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REVIEW

# Geochronology of Neogene magmatism in the Carpathian arc and intra-Carpathian area

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**Abstract:** Neogene to Quaternary volcanism in the Carpathian-Pannonian Region was related to the youngest evolutionary stage of the Carpathian arc and the intra-Carpathian area, with subduction, extension and asthenospheric upwelling as the main driving mechanisms. Volcanism occurred between 21 and 0.1 Ma, and showed a distinct migration in time from West to East. Several groups of calc-alkaline magmatic rock-types (felsic, intermediate and mafic varieties) have been distinguished, and several minor alkalic types also occur, including shoshonitic, K-trachytic, ultrapotassic and alkali basaltic. On the basis of spatial distribution, relationship to tectonic processes and their chemical composition, the volcanic formations can be divided into: (1) areally distributed felsic calc-alkaline formations related to the initial stages of back-arc extension, (2) areally distributed intermediate calc-alkaline formations related to advanced stages of back-arc extension, (3) "arc-type" andesite volcanic formations with a complex relationship to subduction processes, and (4) alkali basaltic magmatism related to post-convergence extension. Petrological data and geotectonic reconstructions, which involve these magmatic groups, place significant constraints on geodynamic models of the Carpathian-Pannonian area. Subduction and back-arc extension were not contemporaneous across the whole Carpathian arc and intra-Carpathian area. Instead, three major geographical segments can be defined (Western, Central, Eastern segments) with a progressively younger timing of subduction roll-back and back-arc extension: 21–11 Ma, 16–9 Ma, 14–0 Ma, respectively. Short-lived subduction-related volcanic activity can be interpreted as either an indication of a limited width of subducted crust (not greater than 200 km) or an indication of detachment of the sinking slab. Interpretation of the areally distributed felsic and intermediate calc-alkaline volcanic formations are considered as being initiated by back-arc extension induced by diapiric uprise of "fertile" asthenospheric material.

**Key words:** Carpathians, intra-Carpathian areas, volcanism, radiometric dating, space-time evolution, geodynamics.

## Introduction

The evolution of magmatism is a key issue in understanding the large-scale geodynamic processes involved in orogenesis in areas of plate convergence. The Carpathian-Pannonian Region (CPR), part of the Alpine-Himalayan orogenic system, resulted from the closure of the former Tethys Ocean. Thus it is a location where a complex array of processes related to plate convergence can be studied. The Carpathian thrust-and-fold belt is a sinuous orogenic segment, situated between the Eastern Alps and Balkans, embracing the intra-Carpathian area, which is mostly occupied by the Pannonian Basin (Fig. 1). It acquired its present form mostly due to the Tertiary orogenic evolution, concluded by collision processes along the European continental margin.

During the past decade, remarkable progress has been made in understanding the geodynamic evolution of the CPR. As magmatism results from processes in the crust and mantle, an investigation of the widespread magmatism that accompanied the Neogene/Quaternary evolution of the region has always been a fundamental part of that effort. Recently published papers have addressed various problems of petrology and geochemistry, as well as the link between geotectonic evolution and magmatism (e.g. Csontos 1995; Lexa & Konečný

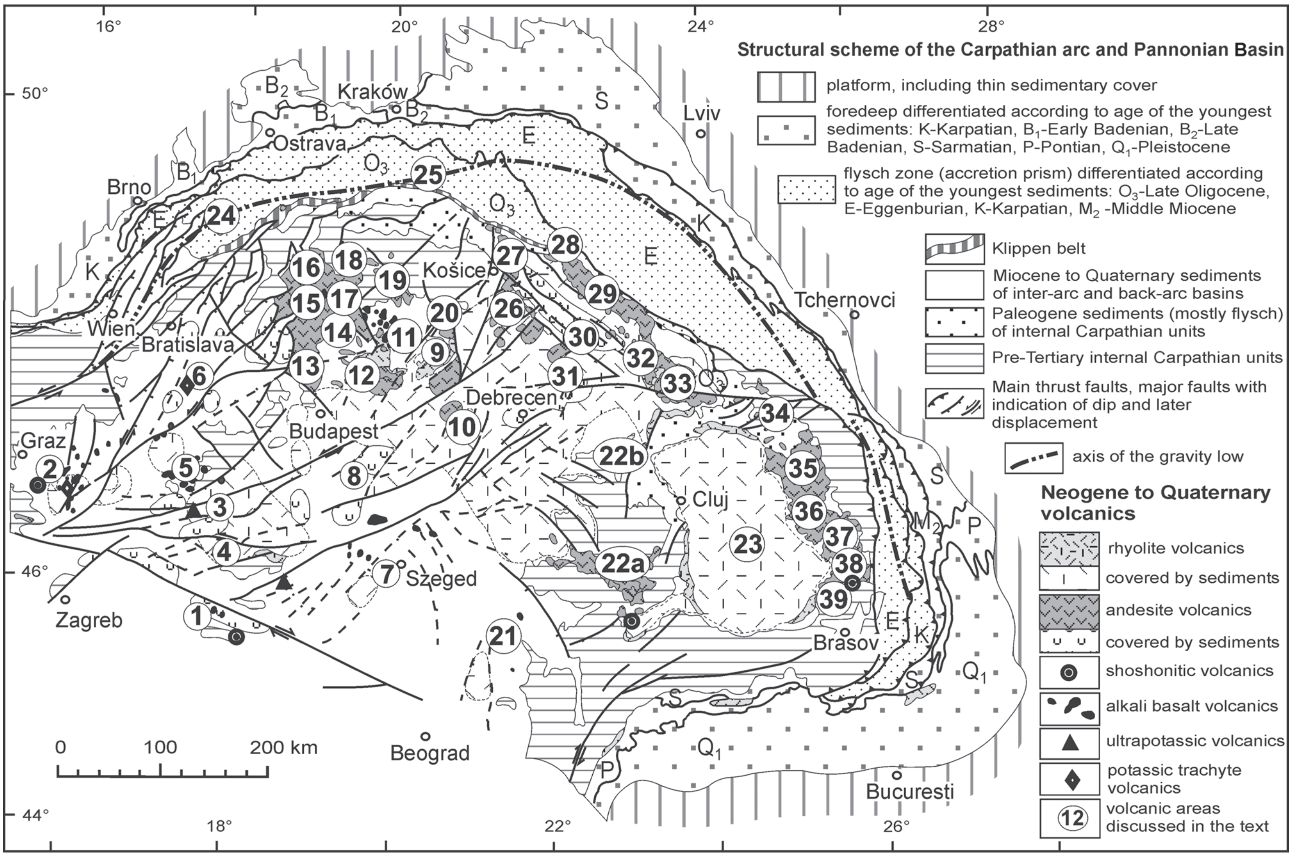


**Fig. 1.** Sketch geological map showing location and distribution of Neogene-Quaternary igneous rocks in the Carpathian-Pannonian Region. Volcanic areas are numbered in Tables 1, 2 and Fig. 2 as following: **Intra-Carpathian area:** (1) Drava-Sava Depression, (2) Styrian Basin, Burgenland, Pohorje, (3) Southern Transdanubia, (4) Mecsek, (5) Transdanubian Central Range and Zala Basin, (6) Danube Basin and Little Hungarian Plain, (7) Southern Danube-Tisza Interfluves region, (8) Northern Danube-Tisza Interfluves region, (9) Bükk Foreland, (10) Central Trans-Tisza region, (11) Nógrád-Southern Slovakia, (12) Cserhát-Mátra, (13) Visegrád-Börzsöny-Burda, (14) Krupinská Planina, (15) Štiavnička stratovolcano, (16) Vtáčnik-Kremnické vrchy, (17) Javorie, (18) Poľana, (19) Vepor region, (20) Borsod Basin, (21) Banat region, (22), Apuseni Mountains, (23) Transylvanian Basin; **Carpathians:** (24) Eastern Moravia, (25) Pieniny, (26) Tokaj-Milic-Zemplín, (27) Slanské vrchy, (28) Vihorlat, (29) Gutin range, (30) Beregovo region, (31) Northern Trans-Tisza region, (32) Oaş, (33) Gutâi, (34) Ţibleş-Toroiaga-Rodna-Bârgău (TTRB), (35) Călimani, (36) Gurghiu, (37) North Harghita, (38) South Harghita, (39) Perşani.

1998; Mason et al. 1998; Nemčok et al. 1998; Seghedi et al. 1998, 2004a,b; Harangi 2001a,b; Konečný et al. 2002b).

A complete knowledge of the space-time distribution and evolution of the magmatism is a key to understanding the general geodynamic development of the CPR. Our previous review (Pécskay et al. 1995a) presented the first synthesis of geochronological data available at that time. Since then a great deal of new analytical data (radiometric, paleomagnetic, geochemical) and geological results (volcanological, paleontological, etc.) has been accumulated. This work concentrated on the gaps revealed by our previous review. These included (a) the buried volcanism within the Pannonian Basin, which has been analysed thanks to the availability of drill-hole material from oil companies, and (b) some of the less well-known areas, such as the Bükk Foreland, Cserhát-Mátra, Transcarpathian segment, Central Slovakia Volcanic Field, Transylvanian Basin, Perşani Mountains, Pieniny and Moravia (Fig. 2). Most of the new results have already been published or are in press (see references in Tables 1 and 2). The main purposes of this paper are (1) to synthesize the new evidence obtained during the past decade and to integrate it with the previously published data, in order to investigate correlations between the different segments of the CPR and (2) to build up an overall picture of the evolution of the Neogene-Quaternary magmatism. Thus, these data are aimed at a better understanding of the geodynamic processes in the area.

## Regional geotectonic setting

The Carpathian orogenic arc forms an arcuate mountain range between the Alps and the Balkans (Fig. 1). It encircles a major basin domain (regarded as the intra-Carpathian area) consisting of an assemblage of intramontane basins, dominated by the Pannonian Basin with a number of small related basins (Danube Basin, Styrian Basin, Great Hungarian Plain) and relatively elevated areas (Transdanubian Central Range, Mecsek Mountains, and the Apuseni Mountains the latter separating the Pannonian Basin from the Transylvanian Basin). This picture is the result of plate-con-

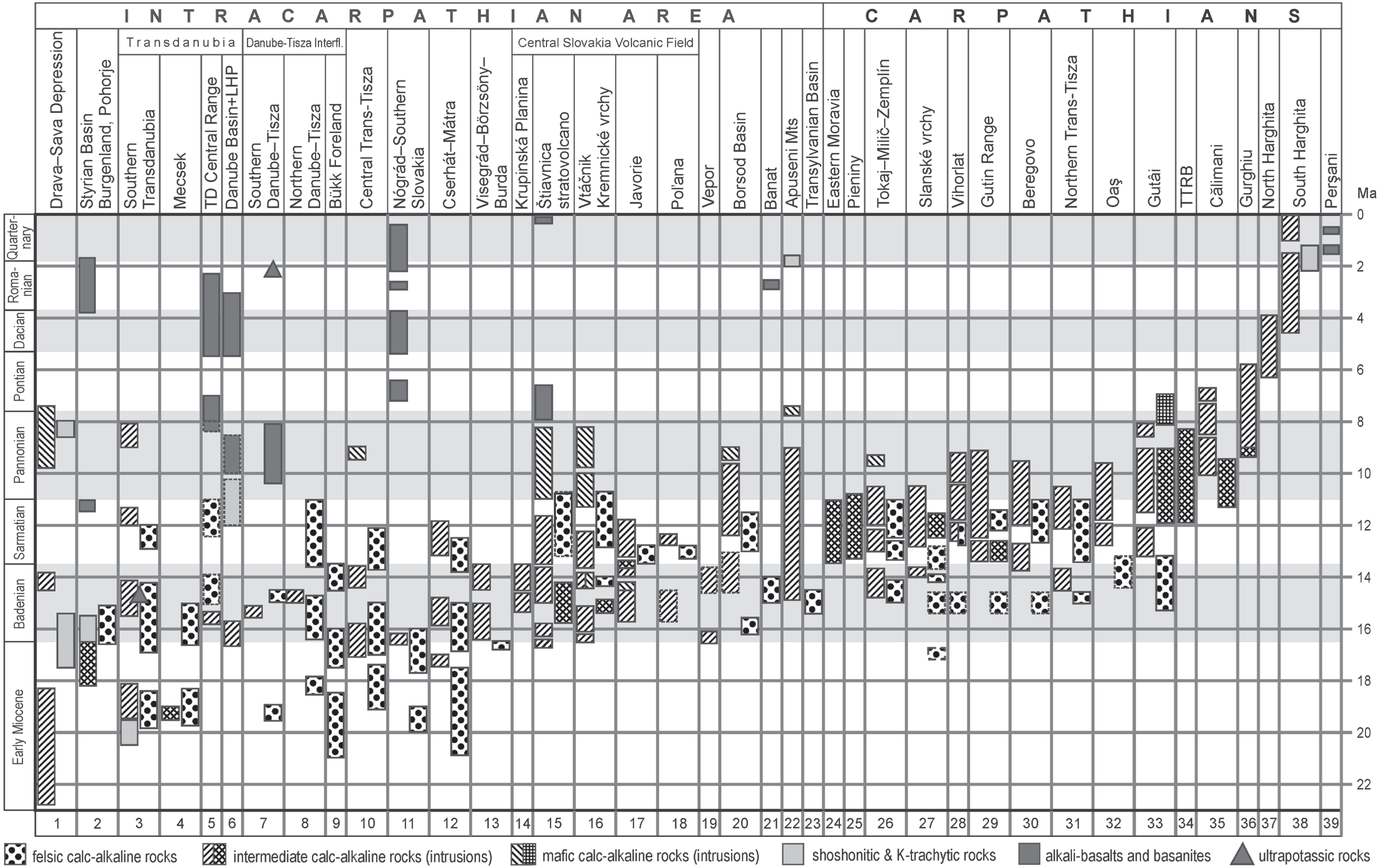


**Fig. 2.** Synopsis of K/Ar ages of magmatic rocks from the CPR shown in Fig. 1. The numbers of the columns correspond to those reported in Fig. 1. The volcanic evolution of each area is described on the basis of radiometric ages (time interval presented in Tables 1 and 2). Where radiometric ages are lacking, available biostratigraphic data have been used for chronological findings.

**Table 1:** Timing of volcanic activity in the intra-Carpathian area, showing age intervals for different rock type groups and volcanic areas. *Continued on the next pages.*

| Volcanic area | Type | Radiometric age (Ma) | Biostratigraphic age | References | Petrography, lithology, volcanic forms |
|---|---|---|---|---|---|
| Drava–Sava Depression **(1)** | SH<br>MCA | 7.4–9.8 | | Pamić & Pécskay 1996 | shoshnitic basalt, calc-alkaline basalt and alkali basalt lava flows |
| | ICA | 13.8–14.5 | *Badenian* | Pamić & Pécskay 1996 | basalt, pyroxene and amphibole-pyroxene andesite and biotite dacite lava flows, domes, breccias and tuffs |
| | SH | 15.4–17.5 | *Karpatian–Early Badenian* | Pamić et al. 1988<br>Pamić & Pécskay 1996 | biotite-pyroxene trachyandesite (banakite) lava flows, pillow lavas, tuffs |
| | ICA | 18.3–22.8 | *Egerian–Eggenburgian* | Pamić et al. 1988<br>Šimunić & Pamić 1993 | pyroxene andesite to biotite-pyroxene dacite necks, lava flows and tuffs |
| Styrian Basin–Burgenland–Pohorje **(2)** | AB | 1.7–3.8<br>11.1–11.5 | | Poultidis & Scharbert 1986<br>Balogh et al. 1994 | cinder cones, tuff cones and lava flows |
| | FCA | 15.1–16.6 | *Early Badenian* | Poultidis & Scharbert 1986<br>Balogh et al. 1994 | rhyodacite tuffs, tuffites |
| | SH | 15.5–16.5 | | Balogh et al. 1994 | shoshonite, trachyandesite, trachyte lava flows, domes ? |
| | ICA | 16.5–18.2 | | Trajanova et al. 2006 | granodiorite and dacite intrusions |
| Southern Transdanubia **(3)** | ICA | 8.0–9.0<br>11.3–12.0 | | Zelenka et al. 2004 | buried andesite lava flows and hyaloclastites<br>buried andesite lava flows |
| | FCA | | *Sarmatian* | Zelenka et al. 2004 | rhyolite tuffs |
| | ICA | 14.1–15.5 | *Badenian* | Zelenka et al. 2004 | andesite hyaloclastites and tuffs |
| | UK | 14.5–15.0 | | Harangi 2001b | buried lava flows ? |
| | FCA | 14.2–16.9<br>18.4–19.9 | *Baden.–Karpatian*<br>*Ottnangian* | Zelenka et al. 2004 | buried rhyodacite domes and tuffs<br>rhyolite domes, ignimbrites, and tuffs |
| | ICA | 18.1–19.5 | | Zelenka et al. 2004 | buried andesite lava flows |
| | SH | 19.5–20.5 | | Zelenka et al. 2004 | sill ?, buried lava flows ? |
| Mecsek **(4)** | FCA | 15.0–16.6<br>18.3–19.7 | *Ottnangian–Eggenburgian* | Hámor et al. 1979, 1987<br>Árva & Máthé 1992 | rhyodacite tuffs, ignimbrite<br>rhyolite tuffs, ignimbrite |
| | ICA | 19.0–19.5 | | Széky-Fux et al. 1991 | andesite sill ? |
| Transdanubian Central Range and Zala Basin **(5)** | AB | 2.3–5.5<br>7.0–8.0 | *Late Pannonian* | Balogh et al. 1986<br>Borsy et al. 1987<br>Balogh & Németh 2005 | alkali basalt maars, tuff cones, cinder cones, lava flows |
| | FCA | 11.0–12.5<br>13.9–15.1 | *Badenian* | Zelenka et al. 2004 | rhyolite extrusive dome<br>rhyolite and dacite tuffs |
| | ICA | 15.5 | *Badenian* | Zelenka et al. 2004 | buried andesite lava flows |
| Danube Basin Little Hungarian Plain **(6)** | AB | 3.0–5.5 | *Pannonian* | Balogh et al. 1986<br>Balázs & Nusszer 1987 | alkali basalt tuff cones, cinder cones, lava flows |
| | SH | | *Pannonian–Late Sarmatian* | Balázs & Nusszer 1987 | buried K-trachyte stratovolcano ? |
| | ICA | 15.7–16.7 | *Early Badenian* | Kantor et al. 1987 | buried hornblende-pyroxene andesite lava flows and hyaloclastite breccias |
| Southern Danube–Tisza Interfluve region **(7)** | UK | 2.0–2.2 | *Early Pleistocene* | Balogh et al. 1986 | dyke ? |
| | AB | 8.1–10.4 | *Pannonian* | Balogh et al. 1986<br>Balázs & Nusszer 1987 | alkali basalt dykes, cinder cones and lava flows |
| | FCA | 14.5–15.0 | | Széky-Fux et al. 1987 | buried rhyodacite tuffs |
| | ICA | 15.1–15.6 | | Széky-Fux & Pécskay 1991 | buried andesite domes |
| | FCA | 19.0–19.5 | | Széky-Fux et al. 1987 | buried rhyolite tuffs |
| Northern Danube–Tisza Interfluve region **(8)** | FCA | 11.0–13.6 | | Széky-Fux et al. 1987 | buried rhyolite tuffs |
| | ICA | 14.5–15.0 | | Széky-Fux & Pécskay 1991<br>Zelenka et al. 2004 | buried andesite lava flows and hyaloclastite breccias |
| | FCA | 14.7–16.4<br>17.9–18.5 | | Széky-Fux et al. 1987 | buried rhyodacite tuffs<br>buried rhyolite tuffs |
| Bükk Foreland **(9)** | FCA | 13.5–14.5<br>16.0–17.5<br>18.5–21.0 | | Márton & Pécskay 1998 | rhyolite tuffs<br>dacite ignimbrite, tuffs<br>rhyolite ignimbrite, tuffs |
| Central Trans–Tisza Region **(10)** | MCA | 9.0–9.5 | | Zelenka et al. 2004 | lava flows ?, dykes ? |
| | FCA | 12.1–13.7 | | Széky-Fux et al. 1987 | buried rhyolite tuffs, domes |
| | ICA | 13.6–14.4<br>15.8–17.1 | | Széky-Fux et al. 1987 | buried andesite domes, dykes<br>buried andesite stratovolcanoes |
| | FCA | 15.0–17.0<br>17.4–19.1 | | Széky-Fux et al. 1987 | buried rhyodacite tuffs<br>buried rhyolite tuffs, domes |
| Nógrád–Southern Slovakia **(11)** | AB | 0.4–2.2<br>2.6–2.9<br>3.7–5.4 | | Balogh et al. 1981<br>Balogh et al. 1986<br>Konečný et al. 2002a | alkali basalt tuff cones, maars, diatremes, cinder cones and lava flows |
| | | 6.4–7.2 | *Pontian* | Vass et al. 1992 | alkali basalt maars and lava flows |
| | ICA | 16.4 | | Pécskay, unpublished | garnet-bearing andesite laccolithes, sills, dykes |
| | FCA | 16.0–16.8 | *Late Karpatian ?* | Hámor et al. 1987 | rhyodacite tuffs |
| | | 16.3–17.7<br>19.0–20.0 | *Ottnangian–Eggenburgian* | Hámor et al. 1987<br>Vass et al. 1987<br>Kantor et al. 1990 | rhyolite tuffs, ignimbrites |

AB — alkali basalts and basanites, UK — ultrapotassic rocks, FCA — felsic calc-alkaline rocks, ICA — intermediate calc-alkaline rocks, MCA — mafic calc-alkaline rocks, SH — shoshonitic and K-trachytic rocks.

**Table 1:** *Continued.*

| Volcanic area | Type | Radiometric age (Ma) | Biostratigraphic age | References | Petrography, lithology, volcanic forms |
|---|---|---|---|---|---|
| Cserhát–Mátra **(12)** | ICA | 11.8–13.2 | | Zelenka et al. 2004 | andesite lava flows and dykes |
| | FCA | 12.5–13.8 | *Early Sarmatian* | Hámor et al 1987<br>Zelenka et al. 2004 | rhyolite tuffs and ignimbrites |
| | | 15.0–15.6 | | Hámor et al. 1987<br>Zelenka et al. 2004 | rhyolite extrusive domes and tuffs |
| | ICA | 14.8–15.9 | | Póka et al. 2002 | andesite effusive complex with hyaloclastite breccias |
| | FCA | 15.0–16.9 | | Zelenka et al. 2004 | dacite ignimbrites, tuffs |
| | ICA | 17.0–17.5 | *Karpatian* | Hámor et al. 1987<br>Zelenka et al. 2004 | andesite lava flows and hyaloclastite breccias |
| | FCA | 17.5–20.9 | *Ottnangian* | Hámor et al. 1987<br>Zelenka et al. 2004 | rhyolite tuffs and ignimbrites |
| Visegrád–Börzsöny–Burda **(13)** | ICA | 12.6–14.5 | | Korpás & Lang 1993<br>Karátson et al. 2000 | pyroxene andesite stratovolcano including amphibole-pyroxene andesite extrusive domes and related breccias |
| | | 15.0–16.4 | *Early Badenian* | Karátson et al. 2000<br>Báldi & Kókay 1970 | hornblende-pyroxene andesite to biotite-amphibole dacite (often garnet-bearing) extrusive domes, breccias and tuffs |
| | FCA | 16.5–16.7 | *Early Badenian* | Karátson et al. 2000<br>Báldi & Kókay 1970 | dacite tuffs, reworked tuffs |
| Krupinská Planina **(14)** | ICA | 13.5–14.5 | *Middle–Late Badenian* | Konečný et al. 1969<br>Vass et al. 1979 | pyroxene and amphibole-pyroxene andesite pyroclastic volcanoes |
| | | 14.5–15.3 | *Early/Middle Badenian* | Konečný et al. 1969<br>Vass et al. 1979 | amphibole-pyroxene andesite (often garnet-bearing) extrusive domes and related breccias |
| Štiavnica stratovolcano **(15)** | AB | <0.25 | *Late Pleistocene* | Šimon & Halouzka 1996 | nepheline basanite cinder cone and lava flows |
| | | 6.6–8.0 | | Kantor & Wiegerová 1981<br>Konečný et al. 1999 | nepheline basanite and alkali basalt necks and lava flows |
| | MCA | 8.2–11.3 | | Repčok 1982<br>Balogh et al. 1998 | high-alumina basalt and basaltic andesite dykes, necks, lava flows and phreatic tuffs |
| | FCA | 10.7–14.4 | *Late Sarmatian* | Repčok 1981<br>Konečný et al. 1983 | rhyodacite and rhyolite dome/flow complex, dykes and pyroclastic rocks |
| | ICA | 11.4–15.0 | *Early/Middle Sarmatian* | Konečný et al.1969,1983<br>Repčok 1981 | postcaldera pyroxene and amphibole-pyroxene andesite effusive and stratovolcanic complexes |
| | | 14.8–15.8 | *Late Badenian* | Konečný et al.1969, 1983<br>Repčok 1978, 1980, 1981 | caldera filling–biotite-amphibole andesite domes, lava flows and related breccias, pumice tuffs |
| | | 10.5–17.0 | | Bagdasarjan et al. 1970<br>Merlic & Spitkovskaja 1974<br>Repčok 1981<br>Konečný et al. 1983 | diorite, granodiorite and granodiorite to diorite porphyry subvolcanic intrusions affected by younger alterations |
| | | 15.9–16.4 | *Early/Middle Badenian* | Repčok 1980<br>Konečný et al. 1983 | pyroxene and amphibole-pyroxene andesite stratovolcano |
| | | 16.6 | *Early Badenian* | Repčok 1981<br>Konečný et al. 1998 | garnet-bearing hornblende-pyroxene andesite extrusive domes and related breccias, pumice tuffs |
| Vtáčnik–Kremnické vrchy **(16)** | MCA | 8.2–9.8 | | Repčok 1982<br>Balogh et al. 1998 | high-alumina basalt tuff cone, dykes, sills, flows |
| | | 9.8–12.2 | | | small high-alumina basalt stratovolcano |
| | FCA | 10.7–12.9 | *Late Sarmatian* | Bagdasarjan et al. 1970<br>Repčok 1981, 1982<br>Konečný et al. 1969, 1983 | rhyodacite and rhyolite dykes, domes, dome flows and related breccias, pyroclastic rocks |
| | ICA | 12.2–14.5 | *Early to Late Sarmatian* | Bagdasarjan et al. 1970<br>Repčok 1982<br>Konečný et al. 1983<br>Kantor et al. 1990 | pyroxene and amphibole-pyroxene andesite stratovolcanoes |
| | FCA | 14.1–14.3 | *Late Badenian* | Simon et al. 1997 | rhyodacite extrusive domes and tuffs |
| | MCA<br>ICA | 13.8–14.4 | *Late Badenian* | Konečný et al. 1983<br>Šimon et al. 1997 | basalt to felsic andesite graben filling–lava flows, hyaloclastite breccias, pyroclastic rocks |
| | ICA | 15.2–16.3 | | Repčok 1981<br>Konečný et al. 1983 | pyroxene and amphibole-pyroxene andesite stratovolcano and related diorite porphyry subvolcanic intrusions |
| | | 16.2 | *Early Badenian* | Repčok 1981<br>Konečný et al. 1983 | garnet-bearing amphibole-pyroxene andesite extrusive domes and related volcanisedimentary horizon |
| Javorie **(17)** | ICA | 11.8–12.7<br>13.3–13.7 | *Early Sarmatian* | Konečný et al. 1983, 1998 | post-graben pyroxene and amphibole-pyroxene andesite stratovolcanic complex |
| | FCA | 12.5–13.5 | | Konečný & Pécskay, unpublished | dacite and rhyodacite domes and dykes |
| | ICA | 13.2 | | Repčok 1978 | diorite to monzodiorite subvolcanic intrusions, mostly altered |
| | | 13.3–13.6 | | Konečný & Pécskay, unpublished | pyroxene-amphibole and amphibole andesite extrusive domes and related breccias, partially altered |
| | MCA | 14.3–14.4 | | Konečný & Pécskay, unpublished | graben filling–basaltic and pyroxene andesite lava flows and hyaloclastite breccias |
| | ICA | 14.3–15.7 | | Konečný et al. 1969 | pyroxene and amphibole-pyroxene andesite stratovolcano |

AB — alkali basalts and basanites, UK — ultrapotassic rocks, FCA — felsic calc-alkaline rocks, ICA — intermediate calc-alkaline rocks, MCA — mafic calc-alkaline rocks, SH — shoshonitic and K — trachytic rocks.

**Table 1:** *Continued from the previous pages.*

| Volcanic area/segment | Type | Radiometric age (Ma) | Biostratigraphic age | References | Petrography, lithology, volcanic forms |
|---|---|---|---|---|---|
| Poľana **(18)** | ICA | 12.5–12.7 | | Repčok 1982<br>Dublan 1993 | pyroxene andesite stratovolcano with diorite porphyry subvolcanic intrusions |
| | FCA | 12.8–13.2 | *Early Sarmatian* | Repčok 1980<br>Konečný et al. 1983<br>Dublan 1993 | rhyodacite extrusive domes, breccias and related pyroclastic rocks |
| | ICA | | *Middle–Late Badenian ?* | Konečný et al. 1983 | pyroxene andesite stratovolcano |
| Vepor region **(19)** | ICA | 16.2–16.4 | *Late Badenian* | Repčok 1981<br>Sitár & Dianiška 1979 | pyroxene andesite stratovolcano and related epiclastic rocks |
| | | | *Early Badenian ?* | Klinec et al. 1989 | garnet-bearing pyroxene-amphibole andesite extrusive domes and related breccias |
| Borsod Basin **(20)** | MCA | 9.0–9.5 | | Pécskay et al. 1995 | basalt and basaltic andesite dykes |
| | FCA | 11.5–13.0 | *Early Pannonian–Sarmatian* | Hámor et al. 1987<br>Pécskay et al. 1995 | rhyolite and dacite tuffs, reworked tuffs |
| | ICA | 9.5–12.7 | | Pécskay et al. 1995 | andesite domes |
| | | 11.6–14.9 | *Early Sarmatian–Late Badenian* | Hámor et al. 1987 | andesite epiclastic breccias and conglomerates, tuffs |
| | FCA | 15.6–16.2 | *Early–Middle Badenian* | Pécskay et al. 1995<br>Bohn-Havas et al. 1998 | dacite tuffs |
| Banat region **(21)** | AB | 2.5–2.9 | | Downes et al. 1995 | alkali basalt cinder cones and lava flows |
| | FCA | 14.0–15.0 | *Badenian* | Cvetkovic et al., unpublished | rhyolite ignimbrites and tuffs |
| Apuseni Mts **(22)** | SH | 1.6–2.0 | | Pécskay et al. 1995 | shoshonite extrusive dome |
| | MCA | 7.4–7.8 | | Roşu et al. 1997, 2001, 2004 | basalt and basaltic andesite extrusive domes |
| | ICA | 9.0–14.9 | | | andesite stratovolcanic complexes, extrusive domes, diorite to quartz-diorite porphyry intrusions |
| Transylvanian Basin **(23)** | FCA | 14.5–15.4 | *Early Badenian* | Szakács 2000<br>Popescu 1970 | rhyolite tuff complex |

AB — alkali basalts and basanites, UK — ultrapotassic rocks, FCA — felsic calc-alkaline rocks, ICA — intermediate calc-alkaline rocks, MCA — mafic calc-alkaline rocks, SH — shoshonitic and K-trachytic rocks.

vergence processes involving a number of continental fragments or microplates located between the larger Eurasian and African Plates (e.g. Csontos et al. 1992; Csontos 1995). Tertiary translational and rotational movements of these microplates, trapped between the two great continental blocks, formed the Carpathian orogenic system (Panaiotu 1999; Márton & Fodor 2003).

Geodynamic processes involved subduction (including roll-back and slab break-off), thrust-and-fold orogenesis of the accretionary prism due to collision tectonics, back-arc extension, and lithospheric rotations and escape tectonics as a response to continent/continent collision in the neighbouring orogenic systems of the Alps and Balkans (Royden 1988; Ratschbacher et al. 1991; Nemčok et al. 1998; Seghedi et al. 1998; Panaiotu 1999; Konečný et al. 2002b). The eastward translation of the intra-Carpathian continental blocks (ALCAPA (Alpine-Carpathian-Pannonian) and Tisza-Dacia or Tisia) (Csontos et al. 1992; Csontos 1995) has largely been explained by lithospheric escape tectonics triggered by the N-S squeezing of these terranes between the convergent Northern Europe and Africa and their movement towards the domain under eastward extension (Ratschbacher et al. 1991; Sperner et al. 2002). This eastward-transposed convergence was driven mainly by south-eastward subduction roll-back near the Western margin of the East European Plate in front of the ALCAPA and Tisia blocks (Royden 1993; Seghedi et al. 1998; Wortel & Spakman 2000). Another effect of the convergence was the deformation of the accretionary prism along the subduction boundary to form a typical thrust-and-fold belt, namely the Carpathian orogenic arc. Eastward progression of deformation along the thrust-and-fold system has been reported (Jiříček 1979; Royden et al. 1982; Csontos et al. 1992).

Due to subduction roll-back, extensional tectonics dominated the domain behind the compressional front, including the formation of an extensive back-arc type basin system (the Pannonian Basin with a number of related marginal basins and the Transylvanian Basin) (Royden 1988; Huismans et al. 2001) separated by elevated horst-blocks (Apuseni Mts, Mecsek, Transdanubian Central Range, etc.). Reviews of the geodynamic evolution and magmatism of the CPR system are given by Csontos (1995), Nemčok et al. (1998), Konečný et al. (2002a) and Seghedi et al. (1998, 2004a,b).

## Composition and origin of Neogene-Quaternary magmatism in the Carpathian-Pannonian Region

Various magmatic rocks occur in the CPR, including types from both the calc-alkaline and alkaline series. Transitional types, such as shoshonitic and high-K calc-alkaline rocks, are also present, together with minor amounts of ultrapotassic rocks. The following chemical types of rocks are distinguished into separate groups: (1) felsic calc-alkaline, (2) intermediate calc-alkaline, (3) mafic calc-alkaline, (4) shoshonitic and K-trachytic, (5) ultrapotassic and (6) mafic alkaline (Fig. 3). A special case of adakite-like intermediate calc-alkaline volcanism will also be considered, without being shown separately in the figures.

**Felsic calc-alkaline volcanic formations** are widespread throughout the CPR. They mostly consist of volcaniclastic rocks (rhyolitic to dacitic welded and/or

**Table 2:** Timing of volcanic activity in the Carpathian arc, showing age intervals for different rock type groups and volcanic areas. *Continued on the next page.*

| Volcanic areas | Type | Radiometric age (Ma) | Biostratigraphic age | References | Petrography, lithology, volcanic forms |
|---|---|---|---|---|---|
| Eastern Moravia **(24)** | ICA | 11.0–13.5 | | Pécskay et al. 2002 | biotite-amphibole-pyroxene andesite dykes and sills |
| Pieniny **(25)** | ICA | 10.8–13.3 | | Birkenmajer et al. 1987<br>Birkenmajer & Pécskay 1999, 2000<br>Trua et al. 2006 | amphibole-pyroxene andesite dykes and sills |
| Tokaj–Milič–Zemplín **(26)** | MCA | 9.3–9.7 | | Pécskay et al. 1986 | basalt and basaltic andesite lava flows |
| | ICA | 10.5–12.0 | | Pécskay et al. 1986 | pyroxene andesite lava flows, dacite extrusive domes |
| | FCA | 11.0–12.5 | *Late Sarmatian* | Coň & Slávik 1971<br>Repčok 1977<br>Pécskay & Molnár 2002 | rhyolite extrusive domes, tuffs and ignimbrites |
| | ICA | 12.2–13.0 | *Early–Middle Sarmatian* | Pécskay et al. 1986<br>Pécskay & Molnár 2002<br>Vass et al. 1978<br>Forgáč 1965 | dacite extrusive domes, andesite stratovolcanoes, lava flows with hyaloclastite breccias, subvolcanic intrusions |
| | FCA | 12.5–13.3 | *Early Sarmatian* | Vass et al. 1978<br>Pécskay et al. 1986<br>Forgáč 1965<br>Gyarmati 1977 | rhyolite extrusive domes, tuffs and ignimbrites |
| | ICA | 13.6–14.8 | *Late Badenian* | Bagdasarjan et al. 1971<br>Gyarmati 1977 | pyroxene andesite lava flows |
| | FCA | 14.0–15.0 | *Late Badenian* | Repčok et al. 1988<br>Pécskay et al. 1986<br>Merlic & Spitkovskaja 1974<br>Slávik 1968 | rhyodacite extrusive domes, ignimbrites, tuffs and reworked tuffs |
| Slanské vrchy **(27)** | ICA | 10.5–12.8 | | Vass et al. 1978<br>Repčok et al. 1988<br>Žec & Ďurkovičová 1993 | mostly pyroxene andesite stratovolcanoes including diorite porphyry intrusions |
| | | 11.5–12.5 | | Vass et al. 1978<br>Repčok et al. 1988 | garnet-bearing amphibole-pyroxene andesite intrusions and extrusive domes |
| | FCA | | *Early Sarmatian* | Kaličiak et al. 1991 | rhyolite tuffs |
| | ICA | 13.6–13.9 | *Late Badenian* | Slávik et al. 1976<br>Slávik 1968 | andesite lava flows and epiclastic volcanic conglomerate |
| | FCA | 13.9–14.2 | *Late Badenian* | Kaličiak & Repčok 1987<br>Kaličiak et al. 1991 | rhyolite extrusive domes and tuffs |
| | | | *Early Badenian* | Slávik 1968 | reworked rhyodacite tuffs |
| | | | *Karpatian* | Kaličiak et al. 1991 | rhyolite tuffs, reworked tuffs |
| Vihorlat **(28)** | ICA | 9.2–10.8 | | Slávik et al. 1976<br>Pécskay et al. 2002 | late stage andesite lava flows and necks |
| | | 10.2–11.9 | | Kaličiak et al. 1995<br>Pécskay et al. 2002 | basaltic andesite/pyroxene andesite stratovolcanoes |
| | FCA | 12.5 | *Middle Sarmatian* | Pécskay et al. 2002<br>Brodňan et al. 1959 | rhyodacite and rhyolite extrusive domes and tuffs, reworked tuffs, tuffites |
| | ICA | 11.7–12.6 | *Early–Middle Sarmatian* | Repčok et al. 1988<br>Ďurica et al. 1978<br>Pécskay et al. 2002<br>Brodňan et al. 1959 | amphibole-pyroxene andesite extrusive domes, related breccias and epiclastic volcanic rocks |
| | FCA | | *Early Badenian* | Slávik 1968 | reworked rhyodacite tuffs |
| Gutin Range **(29)** | ICA | 9.1–12.5 | | Pécskay et al. 2000<br>Pécskay et al. 2002 | basaltic andesite/pyroxene andesite stratovolcanoes |
| | FCA | 11.4–12.2 | | Pécskay et al. 2000 | rhyodacite to rhyolite extrusive domes |
| | ICA | 12.7–13.4 | | Pécskay et al. 2000 | andesite/porphyry intrusions |
| | FCA | | *Early–Middle Badenian* | Maleyev 1964 | rhyodacite tuffs, reworked tuffs |
| Beregovo region **(30)** | ICA | 9.5–12.0 | | Pécskay et al. 2000 | basaltic andesite to dacite lava flows and domes |
| | FCA | 11.0–12.7 | *Early Sarmatian* | Széky-Fux et al. 1987<br>Maleyev 1964 | rhyodacite/rhyolite dome-flow complex and related ignimbrites, tuffs |
| | ICA | 12.7–13.8 | *Late Badenian* | Pécskay et al. 2000<br>Maleyev 1964 | andesite lava flows and hyaloclastite breccias |
| | FCA | 14.7 | *Early Badenian ?* | Pantó 1966<br>Széky-Fux et al. 1987 | rhyolite ash-flow tuffs |
| Northern Trans-Tisza region **(31)** | ICA | 10.5–12.2 | | Széky-Fux et al. 1987 | andesite-dacite lava flows and domes |
| | FCA | 11.0–13.5 | *Sarmatian* | Széky-Fux et al. 1987 | buried dacite dome and rhyolite tuffs |
| | ICA | 13.7–14.5 | *Badenian* | Széky-Fux et al. 1987 | andesite lava flows, hyaloclastite breccias, diorite intrusions |
| | FCA | 14.7–15.0 | | Széky-Fux et al. 1987 | rhyolite ignimbrites and dacite tuffs |
| Oaş **(32)** | ICA | 9.5–11.8 | | Pécskay et al. 1995a,b<br>Kovacs et al. 1997a | andesite to dacite lava flows and domes, related hyaloclastite breccias, rhyolite dome complex, intravolcanic and subvolcanic intrusions |
| | | 11.9–12.9 | | | dacite extrusive dome, dacite tuffs |
| | FCA | | *Early Sarmatian* | Fülöp & Crihan 2002 | reworked rhyolite tuffs |

**Table 2:** *Continued from the previous page.*

| Volcanic areas | Type | Radiometric age (Ma) | Biostratigraphic age | References | Petrography, lithology, volcanic forms |
|---|---|---|---|---|---|
| Gutâi **(33)** | MCA | 7.0–8.1 | | Edelstein et al. 1993 | basalt intrusions |
| | ICA | 8.0–8.5 | *Pannonian* | Kovacs 2002<br>Marinescu 1964<br>Edelstein et al. 1992<br>Pécskay et al. 1994, 1995a,b<br>Kovacs et al. 1997b<br>Kovacs et al. 2003 | andesite–dacite extrusive domes/intrusions |
| | | 9.0–11.6 | | | basaltic andesite to rhyolite lava flows and domes |
| | | 9.0–12.0 | | | basaltic andesite to dacites and porphyry micrograbbro to microgranodiorite intrusions |
| | | 12.1–13.4 | *Sarmatian* | | andesite lava flows and dacite extrusive domes |
| | FCA | | *Early Sarmatian* | Stan et al. 1984<br>Fülöp 2002a<br>Fülöp 2003 | rhyolite volcaniclastic mass-flow deposits |
| | | 15.4 | *Early–Late Badenian* | | caldera related rhyolite welded ignimbrites and tuffs |
| Tibles–Toroiaga–Rodna–Bargau **(34)** | ICA | 8.3–11.9 | | Pécskay et al. 1995b | basalt to rhyolite (diorite to granodiorite porphyry) intrusions |
| Călimani **(35)** | ICA | 6.7–7.2 | | Pécskay et al. 1995b<br>Seghedi et al. 2005b | caldera and post-caldera andesite to dacite lava flows, domes and intrusions |
| | | 7.2–8.5 | | | Rusca Tihu andesite stratovolcano |
| | | 8.5–10.1 | | | early stage andesite to dacite domes, shields and lava flows |
| | | 9.4–11.3 | | Pécskay et al. 1995b | basaltic andesite to dacite intrusions |
| Gurghiu **(36)** | ICA | 5.8–9.0 | | Pécskay et al. 1995b<br>Seghedi et al. 2004c | andesite stratovolcanoes, extrusive domes ,caldera |
| | | 9.0–9.4 | | | andesite intrusions |
| North Harghita **(37)** | ICA | 3.9–6.3 | | Pécskay et al. 1995b | mostly pyroxene andesite stratovolcanoes |
| South Harghita **(38)** | ICA | 0.03–1.0 | | Casta 1980<br>Pécskay et al. 1995b<br>Szakács et al. 1993, 2002<br>Moriya et al. 1996 | pyroxene andesite stratovolcanoes and andesite to dacite extrusive domes |
| | | 1.5–4.6 | | | pyroxene-amphibole andesite extrusive dome complex and related pyroclastic rocks |
| | SH | 1.2–2.2 | | Peltz et al. 1987<br>Michailova et al. 1983 | two shallow intrusions |
| Perşani **(39)** | AB | 0.5–0.7<br>1.2–1.5 | | Casta 1980<br>Mihaila & Kreuzer 1981<br>Downes et al. 1985<br>Pécskay et al. 1995b<br>Panaiotu et al. 2004. | phreatomagmatic deposits, maars, scoria cones and lava flows |

AB — alkali basalts and basanites, UK — ultrapotassic rocks, FCA — felsic calc-alkaline rocks, ICA — intermediate calc-alkaline rocks, MCA — mafic calc-alkaline rocks, SH — shoshonitic, K — trachytic rocks, and TTRB — Tibles-Toroiaga-Rodna-Bargau.

non-welded ash-flow tuffs, fallout tuffs and their reworked counterparts) and a minor amount of extrusive rocks (rhyolite to dacite domes and dome/flow complexes). Owing to their wide dispersion over very large areas, the felsic explosive products are present throughout most of the Pannonian and Transylvanian Basins, as well as at their margins. Their thickness and characteristics vary strongly from one area to another. Conventionally, in Fig. 1 we consider only felsic tuff complexes at least 10 m thick. The cardinal problem is to establish the volcanic source areas of these felsic explosive products. Some of them have been tentatively identified (e.g. Szakács et al. 1998; Fülöp 2003), but their location is still mostly unknown. The eruptive centers were probably located in the intra-Carpathian area and to a lesser extent along the Carpathian volcanic arc itself.

Felsic calc-alkaline volcanism was spatially associated with early extension and basin formation in the intra-Carpathian area (e.g. Pécskay et al. 1995a). Their Sr, Nd, and Pb isotopic compositions (Salters et al. 1988; Fülöp & Kovacs 2003; Seghedi et al. 2004a) indicate a dominant crustal component. Crustal anatexis was most probably induced by extension-related diapiric uprise of the asthenospheric mantle associated with the emplacement of mantle-derived basaltic magmas at the base of a thick continental crust (e.g. Harangi 2001a; Konečný et al. 2002a). Downes (1996) and Seghedi et al. (1998) have proposed an alternative model involving lithospheric delamination, bringing hot asthenospheric material into direct contact with crustal material. Whatever the origin, the presence of felsic calc-alkaline volcanic formations implies extension affecting relatively thick continental crust and related diapiric uprise of asthenospheric mantle.

**Intermediate calc-alkaline volcanic formations** are present along the whole Carpathian magmatic arc and are widespread in the intra-Carpathian region too. The volcanic edifices are monogenetic and composite stratovolcanoes, effusive domes, lava flows, as well as subvolcanic intrusive complexes. According to their distribution in the Carpathian orogenic arc, two main categories have been distinguished by Lexa et al. (1993) and Lexa & Konečný (1998): (1) areally distributed volcanic formations in the intra-Carpathian area considered as emplaced in back-arc basins; (2) roughly linearly distributed volcanic formations along the internal side of the Carpathian orogenic arc. However, in places it is difficult to distinguish between these two categories, especially where a well-defined volcanic area, such as the Tokaj area, extends from near the "arc" zone to well inside the "back-arc" region. Some volcanic areas, such as the Central Slovakia Volcanic Field, Börzsöny, Cserhát, Mátra, Apuseni

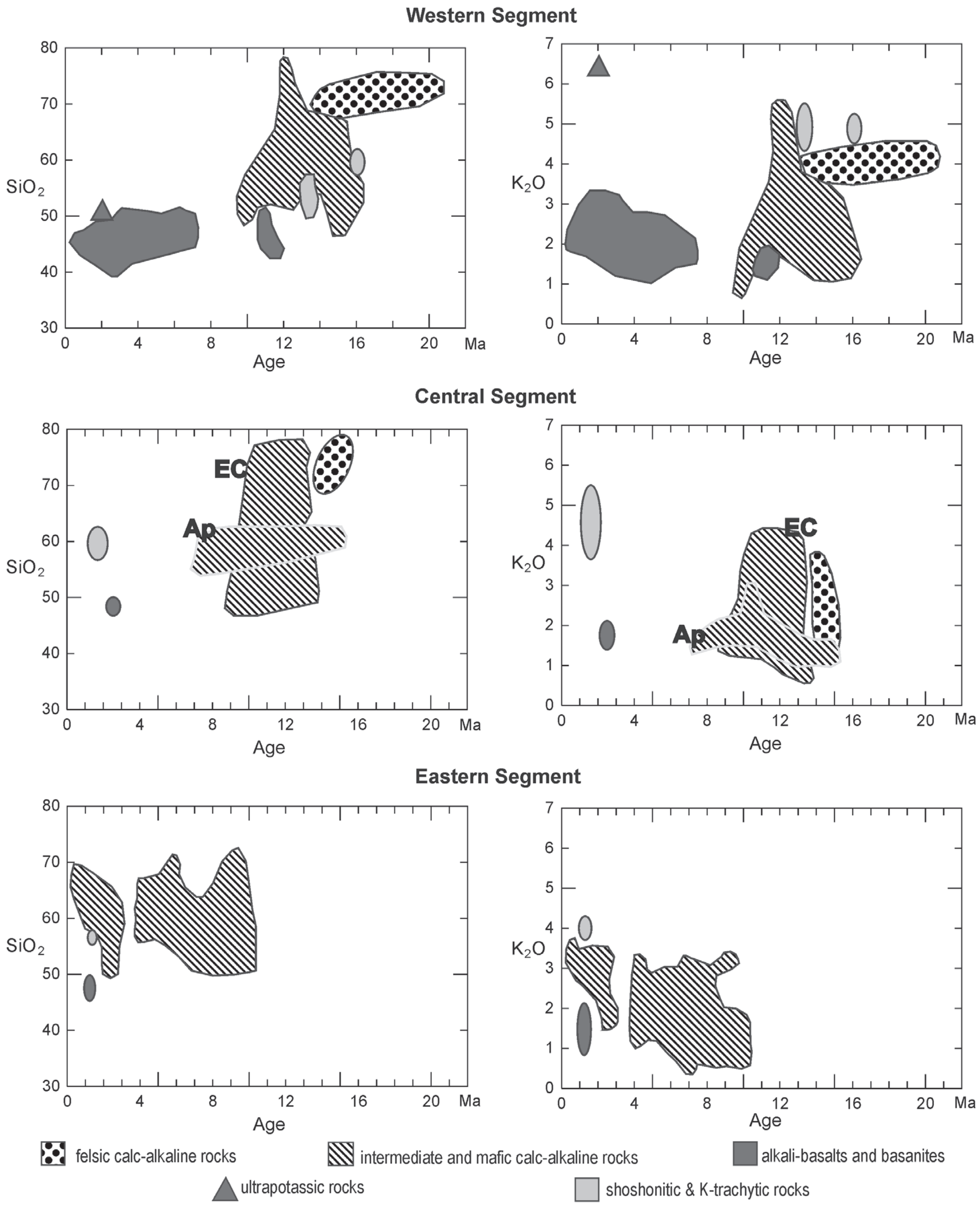


**Fig. 3.** $SiO_2$ and $K_2O$ vs. Age (Ma) for **Western, Central, Eastern segments,** showing the main chemical types of rocks which characterize the CPR magmatism. The mafic calc-alkaline rocks have been separated, and included in the intermediate calc-alkaline group, as well as differentiated felsic products considered to derive from this group. The intrusive roks have been not separated. Geochemical data from Embey-Isztin et al. (1993); Dobosi et al. (1995); Downes et al. (1995a,b); Konečný et al. (1995); Kaličiak & Žec (1995); Žec (1995); Harangi et al. (1995a,b, 2001) Harangi (2001b), Mason et al. (1996); Seghedi et al. (1995, 2001, 2004a,b); Kovacs (2002); Fülöp & Kovacs (2003); Roşu et al. (2001, 2004). Age data according to this work and included references. Figure $SiO_2$ vs. age (Ma) is simplified after the fig. 3 of Seghedi et al. (2005a). Abbreviations: **Ap** — magmatic rock from Intracarpathian Apuseni area; **EC** — magmatic rocks from East Carpathians arc area.

Mountains and some areas with buried volcanic formations, are clearly disconnected from the Carpathian arc *s.s.* Nevertheless, despite these uncertainties, we are able to clearly identify a relatively continuous volcanic arc along the northern and eastern margin of the ALCAPA and Tisia microplates (Fig. 1). This volcanic arc is situated close to the Carpathian orogenic arc and displays a pronounced segmentation, which roughly corresponds to the boundaries of different plate or lithospheric blocks (Seghedi et al. 1998, 2004a; Konečný et al. 2002).

The areally distributed andesitic volcanism has been interpreted as belonging to an advanced stage of back-arc extension in the intra-Carpathian area (Lexa & Konečný 1998). Volcanic formations include intermediate to basaltic andesites with substantial occurrences of subvolcanic intrusive rocks and differentiated rocks with rare late-stage rhyolites. They are mostly of the medium- to high-K type, showing compositional features comparable to andesites of active continental margins (Lexa & Konečný 1998). Trace element distribution and Sr, Nd, Pb and O isotopic compositions (Salters et al. 1988; Downes et al. 1995a; Roşu et al. 2001) support a primary basaltic magma source in the enriched asthenosphere (or lithosphere in the case of adakite-like rocks from Apuseni Mountains), with subsequent contamination by crustal materials. Further evolution of magmas involved both high- and low-pressure fractionation, assimilation and mixing (Lexa et al. 1998a,b). Magma generation was initiated by decompression partial melting of the enriched asthenosphere and/or lithosphere, due to asthenosphere upwelling and/or related lithosphere delamination (Lexa & Konečný 1998; Roşu et al. 2001). The areally distributed andesite volcanism (including adakite-like lithologies) implies an advanced stage of back-arc extension that affected progressively thinning crust, together with advanced diapiric uprise of asthenospheric mantle, which was affected by a preceding stage of subduction responsible for enrichment including volatile components.

The andesite volcanic formations situated along the Carpathian arc are dominated by basaltic andesites and andesites with subordinate differentiated rocks and/or subvolcanic intrusions. They are mostly of medium-K type, similar to andesites of evolved island arcs and continental arcs. Their geochemical characteristics and spatial distribution were controlled indirectly by subduction (Mason et al. 1996; Seghedi et al. 1998, 2001, 2004a, 2005a; Kovacs 2001, 2002). Nemčok et al. (1998) and Mason et al. (1998) argued that volcanic formations of this type may be generated by detachment of the subducting lithospheric slab. This “arc-type” andesite volcanism implies (1) subduction roll-back processs, (2) breakoff or delamination processes, (3) the duration at which subducting lithosphere may have reached the magma generation window and/or the time of detachment of the lithospheric slab.

**Shoshonitic rocks** are present in very small volumes and occur in the western part of the CPR (Poultidis & Scharbert 1986; Pamić & Pécskay 1994, 1996; Pamić et al. 1995), as a single occurrence in the Apuseni Mts (Savu 1994; Roşu et al. 2001), and associated with adakite like rocks in South Harghita (Seghedi et al. 2004a). Shoshonitic/high-K andesites have also been described in Moravia (Přichystal 1998). Their generation is still debated by petrologists (e.g. Mason et al. 1998; Roşu et al. 2001). **K-trachytic and ultrapotassic rocks** have been found mainly in the south-western corner of the CPR, except the K-trachytic occurrences reached by the boreholes in the Little Hungarian Plain (Harangi et al. 1995b) (Fig. 1). A lithospheric origin for these magmas is generally accepted (Harangi et al. 1995b).

**Alkalic volcanic formations** include nepheline basanites, alkali basalts and their differentiated counterparts such as nepheline tephrites, trachybasalts, trachyandesites and hawaiites (Embey-Isztin et al. 1993; Dobosi et al. 1995; Downes et al. 1995; Harangi et al. 1995a). They are spread over most of the western CPR as isolated clusters of outcrops organized in more or less extended monogenetic volcanic fields of maars, diatremes, tuff cones, cinder/spatter cones and lava flows. These occurrences are located in the back-arc setting; however, one example (Perşani Mts, Romania) is situated very close to the Carpathian volcanic arc *s.s.* Petrological aspects of the alkalic volcanic formations were recently evaluated by Embey-Isztin et al. (1993), Dobosi et al. (1995), Downes et al. (1995b), Harangi et al. (1995), Harangi (2001b) and Seghedi et al. (2004b). Alkali basalts and nepheline basanites are products of decompression partial melting of depleted asthenospheric mantle. Magma composition was controlled mostly by the degree of partial melting, with less important fractionation processes leading to trachytic and potassic compositions. Alkali basalt volcanism implies (1) an extension environment, (2) a local asthenospheric uprise with a vertical displacement able to generate alkali basalt magmas, and (3) an asthenosphere source that was not affected or slightly affected by subduction processes.

## Selection criteria and methodology

There are several approaches to dating volcanic rocks and/or formations; however, no single one of them is dependable enough for as to disregard the other’s. Only an internally consistent set of data obtained by different methods gives us a trustworthy age assignment. However, such an ideal situation cannot always be achieved and the possibility of error in the age assignment thus increases. In discussion of individual volcanic areas we shall indicate those ages that are uncertain due to poor quality of data, insufficient data or controversial results. With the exception of simple and solitary magmatic bodies, like isolated intrusions, extrusive domes, lava flows and tuff horizons, a paleovolcanic reconstruction and identification of lithostratigraphic units are the essential first steps. Without these steps we would not know what is actually being dated (unknown relationship of the dated sample to other rocks in the area) and we would not be able to confront the results of individual age determinations. Paleovolcanic reconstruction and definition of lithostratigraphic units open the way to the next important step — establishment of the succession using cross-cutting and/or superposition relationship of lithostratigraphic units. The age assignment of lithostratigraphic units based on other methods should always respect the established succession. It is important to note, that paleovolcanic reconstruction and definition of lithostratigraphic units has not been carried out in all the volcanic areas we are discussing in this paper — where absent, the succession is not well defined or it is based solely on the results of K-Ar dating. As biostratigraphic data are often scarce or absent, our essential approach to the age assignment of volcanic rocks and units is K/Ar dating, carried out in the laboratory of the Institute of Nuclear Research of the Hungarian Academy of Sciences in Debrecen. During the years 1995–2002 all together 1000 samples have been dated. Published data have been utilized, considering reasonable quality regarding the geological context (mostly whole rock K/Ar data and some FT datings, especially in Slovakia). Results of dating on individual samples may not always be indicative of the age of the rock. The "isotopic clock" might be affected by younger processes, such as alteration, loss or incorporation of excess radiogenic argon, etc. Several ways have been used to eliminate possible errors in the age assignment of rocks. First of all, we have always selected fresh samples not affected by weathering or alteration. Also we do not generally depend on single sample age determination. A consistent set of results diminishes the possibility of error in the age assignment. In the case of controversial results we have eventually dated various gravity and magnetic fractions of the samples and constructed isochrons to eliminate the influence of radiogenic argon loss or excess.

Where available, radiometric dating is supplemented by biostratigraphic data on underlying, interbedded and/or overlaying sedimentary rocks. While biostratigraphic data for the early Middle Miocene, based on nannoplankton zonation, are dependable, data for younger stages based on faunal assemblages sensitive to environmental (salinity) changes in the Paratethys sea are less dependable (also owing to a lack of good regional correlation). The same applies to palynology, based on climatic changes. Biostratigraphic data are correlated with radiometric data using the time-scale of Vass & Balogh (1989) and Berggren et al. (1995). In some areas we are also able to use the results of paleomagnetic measurements. Remanent magnetic polarities of rocks contribute to the division into lithostratigraphic units, however, designation to individual subchrons is usually difficult for several reasons: 1) incomplete record of the reversals succession in volcanic formations with long lasting breaks in activity and erosion; 2) in some areas poor knowledge of succession of sampled volcanic rocks; 3) confidence limits of K/Ar ages are sometimes larger than the duration of a particular subchron. However, in several situations, magnetic polarity time scale combined with K/Ar ages has refined timing and duration of volcanic activity beyond the resolution of radiometric data alone (Roşu et al. 1997; Panaiotu et al. 2004). Balla (1984) suggested and Márton & Márton (1996) and Panaiotu (1999) proved extensive rotations of crustal blocks (ALCAPA and Tisia) during Early and Middle Miocene times. So the extent of the clockwise and counterclockwise rotations, respectively, of the lithospheric blocks can be converted into relative age assignments.

Individual rocks samples were crushed and sieved to separate the fraction 250–500 μm for Ar analysis. It was degassed by high frequency induction heating, the usual getter materials (titanium sponge, CaO, SAES getter and cold traps) being used to clean argon. A $^{38}Ar$ spike was introduced to the system from a gas pipette before the degassing started. Cleaned argon was directly introduced into the mass-spectrometer. The mass spectrometer was the magnetic sector type of 150 mm radius and 90° deflection. It was operated in a static mode. Recording and evaluation of the Ar spectra was controlled by a microcomputer. To determine potassium content 0.1 g of pulverized samples were digested in HF with addition of sulphuric and perchloric acids. The digested sample was dissolved in 100 ml 0.25 mol/l HCl. After a subsequent fivefold dilution 100 ppm Na and 100 ppm Li were added as a buffer and internal standard. K concentrations were measured by the digitized flame photometer OE-85 manufactured in Hungary. The inter-laboratory standards Asia 1/65, LP-6, HD-B1, and GL-O as well as atmospheric Ar were used to control the measurements. Details of the instruments, applied methods, and calibration results have been published by Balogh (1985) and Odin et al. (1982).

## Space-time evolution of magmatism in the Carpathian-Pannonian Region

In this paper we consider the large-scale space distribution of the volcanics according to the geographical units as in Fig. 2, which are not related to any specific geotectonic model. The divisions are presented for the Carpathians (Alpine folded thrust belt) and intra-Carpathian area (encompassed by the sygmoidal Carpathian arc) from the West toward the East. The below discussed volcanic areas are listed in Figs. 1 and 2 and summarizing information on time intervals of volcanic activity is given in Tables 1 (intra-Carpathian area) and 2 (Carpathian arc *s.s.*), including data sources.

Fig. 2 provides a synopsis of the K-Ar ages of magmatic rocks from the CPR (see also Fig. 1). The evolution of each individual volcanic area is described on the basis of time intervals presented in Tables 1 and 2. Fig. 2 shows mafic calc-alkaline rocks (important for the magmatic evolution of some areas) that cannot be shown on Fig. 1, due to their small volume. In Fig. 1 we have also not separated intrusive rocks from volcanic ones. Due to the lack of radiometric ages, in some cases only biostratigraphic data have been used for chronological discussion (Tables 1, 2). The paleomagnetic method contributed to the refinement of age estimation by applying correlations through magnetic polarities and marker horizons related to the rotation of microplates (Fig. 4).

All the data used, both analytical (radiometric, paleomagnetic, geochemical) and geological (volcanological, paleontological), support the simplified geographical division used in this paper, as expressing significant differences in the evolution of the CPR. This enables us to distinguish three main segments, conventionally shown on Fig. 4: the **Western, Central** and **Eastern segments**, which show progressively younger timing of subduction roll-back and back-arc extension: 21–11 Ma, 16–9 Ma, 14–0 Ma, respectively. Below we present in a greater detail the pattern in the temporal distribution of magmatism in these three segments. Numbers in brackets indicate relevant volcanic areas on Figs. 1 and 2.

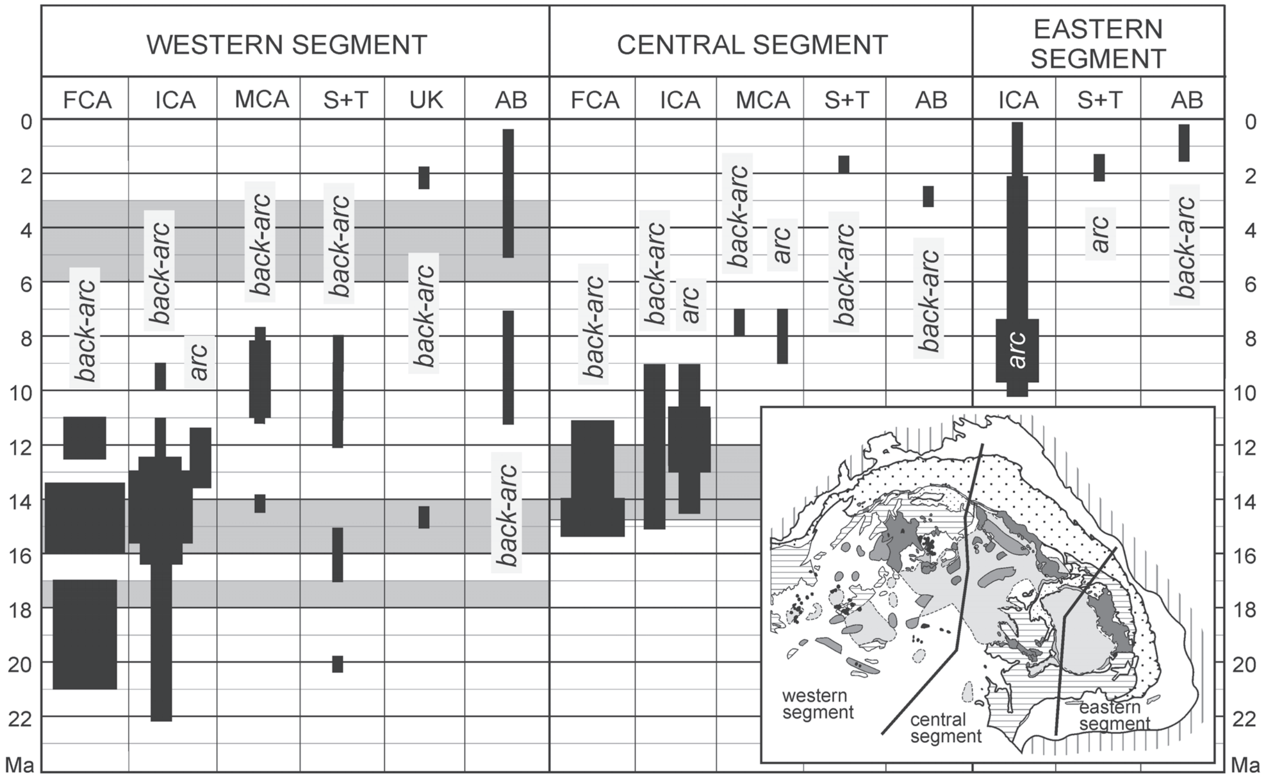


**Fig. 4.** Summary of radiometric ages of the rock types groups and the timing of rotations (shaded areas), based on paleomagnetic measurements in the Western, Central and Eastern segments. The bar width suggests relative volume of magmatic products. Back-arc and arc geotectonic setting are distinguished. Rock types: **FCA** — felsic calc-alkaline, **ICA** — intermediate calc-alkaline, **MCA** — mafic calc-alkaline, **S+T** — shoshonitic and trachytic, **UK** — ultrapotassic, **AB** — alkali basalts. Inserted scheme corresponding to the Fig. 1 shows extent of the segments.

### *Western segment (1–20, 24, 25)*

The **Western segment** is characterized by the widest extent and greatest variety of magmatism in the intra-Carpathian area, and also by the oldest volcanic activity in the whole CPR. Volcanic formations reached about one thousand meters in thickness in the Pannonian Basin. The Neogene volcanic products extend over the intra-Carpathian area in a great volume and thickness (1–20), while occurrences in the Carpathian arc are sporadic (24, 25). The following relationship can be observed between the distribution, volume of volcanic rocks and their corresponding age interval:

- At **23–21 Ma** the oldest calc-alkaline magmatic activity, characterized by relatively small volumes, took place in the southernmost part of the segment, at the southern margin of the Pannonian Basin along the Drava-Sava fault system (1). This magmatism was explained as related to slab break-off due to the convergence between Apulia and Tisia (Pamić & Balen 2001). So we do not consider this magmatic activity as related to the evolution of the Carpathian-Pannonian system.
- From **21 to 17 Ma** a felsic calc-alkaline volcanic activity occurred in the south-central part of the segment. This volcanism was mostly of a highly explosive nature giving rise to voluminous tuff horizons (3, 4, 7, 8, 9, 10, 11 and 12). Rare shoshonitic and intermediate calc-alkaline activity took place in the southern part of the Pannonian Basin (3). They have been interpreted as related to the same slab break-off as the calc-alkaline magmatic activity mentioned above (Pamić et al. 2002).
- From **17** to **11 Ma** intermediate to felsic calc-alkaline volcanic activity covered most of the intra-Carpathian area with its voluminous products, showing a northward age progression (1–20). This magmatism displays an important local petrological complexity in the western corner of the intra-Carpathians, consisting of simultaneous activity of felsic and intermediate calc-alkaline, shoshonitic, K-trachytic and ultrapotassic volcanic rocks during the interval 17.5–15.5 Ma (1, 2, 3, 6). During the interval 13.5–11 Ma, sporadic high-K (to slightly shoshonitic) andesite activity occurred in the westernmost segment of the Carpathian volcanic arc *s.s.* in eastern Moravia and the Pieniny areas (24, 25).
- Between **12 and 8 Ma** intermediate calc-alkaline volcanic activity diminished and finally ceased (3, 15, 16 and 20). In certain areas calc-alkaline magmatism ended with the eruption of mafic magmas (1, 10, 15, 16 and 20). In the western part of the segment, K-trachytic and shoshonitic volcanism was also active (1, 6), as well as the first eruption of alkali basalt and ultrapotassic lavas, post-dating the calc-alkaline activity (2, 6, 7).
- From **8 to 0.01? Ma** only alkali basalt and rare ultrapotassic volcanic activity took place, forming monogenetic volcanic fields (5, 6, 11) as well as sporadic isolated occurrences (2, 7, 15).

*Central segment (21, 22, 26–34)*

The **Central segment** is characterized by mostly calc-alkaline magmatism and by the shift of volcanism to the Carpathian arc and the intra-montane basins of the Apuseni Mountains. Volcanic formations in the Carpathian arc are extensive and voluminous, and show a systematic age progression towards the suture zone. Volcanic activity was more or less contemporaneous along the arc; however, its peak migrated gradually from the northwest to the southeast. Ages of the volcanic formations in the intra-Carpathian area overlap with ages of volcanic rocks in the Carpathian arc (26, 30–33). In the intra-Carpathian area volcanism took place only in Banat and the Apuseni Mountains, showing a longer interval in the south-easternmost parts. The following relationship between the distribution, volume of volcanic rocks and their corresponding age interval has been observed:

- The oldest volcanism in the segment (**15.5–14.5 Ma**) is represented by extensive and voluminous rhyodacite tuffs, rhyolite ignimbrites and reworked tuffs (locally named Hrabovec, Novoselica, and Dej tuffs) with sources in the Carpathians (Gutâi Mountains (33)), but also probable sources in the intra-Carpathian northern Trans-Tisza area (31).
- At **14.5–9 Ma** alternating andesite, dacite and rhyolite volcanic activity took place in the internal part of the Carpathian arc and neighbouring intra-Carpathian basins (26, 30–33), sometimes terminating with sporadic mafic volcanism (26, 33). The morphologically conspicuous alignment of composite andesitic volcanoes Vihorlat–Gutin–Gutâi (28, 29 and 33) (with minor differentiated rocks) yields ages in the interval 12.5–9 Ma. However, older rocks dominate in the northwest (28), while younger rocks dominate in the southeast (33).
- From **14.9 to 9 Ma** intermediate andesite volcanic activity took place in the intra-Carpathian area of the Apuseni Mountains (22), terminating with eruption of intermediate adakite-like calc-alkaline products and sporadic, slightly younger (**7.8–7.4 Ma**) basic magmas.
- During **11.9–8.3 Ma** basalt to rhyolite (diorite to granodiorite porphyry) intrusions characterize the Ţibleş-Toroiaga-Rodna-Bârgău alignment (34), overlapping with the ages of the intrusive rocks in the Gutâi Mountains (33) to the northwest and extending southward below the overlying volcanic successions of Călimani and Gurghiu (35, 36).
- Between **2.5 and 1.5 Ma** sporadic shoshonites were erupted at the southern edge of the Apuseni Mountains (22) and alkali basalt activity took place in the intra-Carpathian Banat area (21).

*Eastern segment (35–39)*

The **Eastern segment** shows the youngest, mostly intermediate calc-alkaline magmatic activity related to the Carpathian arc. This is represented by the conspicuous chain of andesite composite volcanoes of the Călimani–Gurghiu–Harghita (CGH) mountain range, showing a rapid age progression from north to south (Rădulescu et al. 1972; Peltz et al. 1987; Pécskay et al. 1995b). The following relationship can be determined between distribution, volume of volcanic rocks and ages:

- At **10–0.03 Ma** the CGH volcanic chain (35–38) was generated, characterized by dominantly intermediate calc-alkaline volcanism with minor basalts and differentiated rocks. Southward progression of volcanic activity is recorded in overlapping ages of andesite stratovolcanoes: Călimani (35) from 10.1 to 6.7 Ma, Gurghiu (36) from 9.0 to 5.8 Ma, Northern Harghita (37) between 6.3 and 3.9 Ma and Southern Harghita (38) between 4.6 and 1.5 Ma. The Ciomadul dome/flow complex at the southern end of the chain yields ages of 1.0–0.03 Ma.
- Between **2.2 and 0.03 Ma** volcanic activity at the southern end of the CGH chain showed one of the most complex petrological features in the CPR. Three different magma types were erupted simultaneously very close to each other: intermediate calc-alkaline showing adakite-like features, shoshonitic and alkali basaltic.

## Discussion

As magmatic activity is closely related to geotectonic processes, the complex magmatic evolution of the CPR implies an equally complex geotectonic evolution. As magmatic activity and geotectonic phenomena are related via processes of magma generation, the space-time distribution of magmatism places severe constraints on the geotectonic evolution. In addition to Figs. 1 and 2, the space-time distribution of volcanic formations defining the magmatic evolution of the CPR is summarized within the three major segments (Western, Central and Eastern) in Fig. 4 and illustrated in Fig. 5, where a schematic reconstruction of the volcanic activity in a series of 2 Ma intervals is reported.

The Neogene to Quaternary geodynamic evolution for the whole area was determined by the interplay between south-westward subduction and its compensation by back-arc extension and related asthenospheric mantle uprise (e.g. Huismans et al. 2001). Both of these processes have been recorded by the relevant volcanic activity. While the subduction-related volcanism appeared after the subducted slab reached the depth of magma generation window around 120–150 km (e.g. Gill 1981; Sekine & Willey 1982), the extension-related volcanism mainly reflects the uprise of asthenospheric mantle. However, we also need to take into account that subduction beneath the CPR also implies roll-back and slab breakoff processes (e.g. Csontos 1995; Seghedi et al. 1998; Nemčok et al. 1998). If we analyse the magmatic evolution of the three major geographical segments of the CPR (Figs. 4, 5) the following picture can be depicted:

**In the Western segment** the felsic and intermediate calc-alkaline volcanism was related to a back-arc setting, which implies asthenospheric mantle uprise. This process is related to subduction started at the beginning of Early Miocene (~21 Ma). Volcanic activity reached its paroxysm at 17–12 Ma, waning at ~8 Ma. Between 21 Ma and 11.5 Ma, the felsic and intermediate calc-alkaline volcanic activities were contemporaneous. From a geodynamic

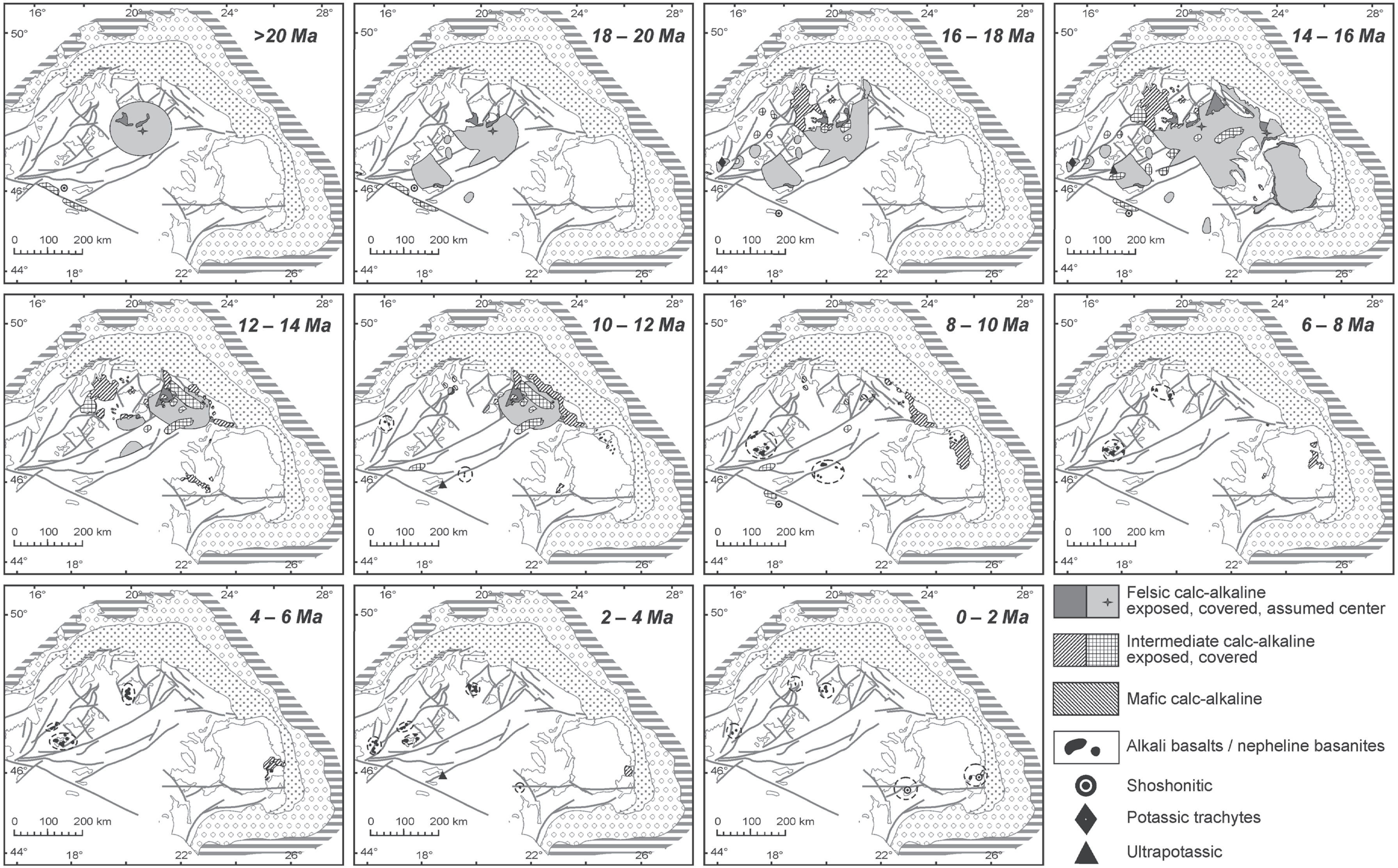


**Fig. 5.** Evolutionary scheme of the Neogene-Quaternary volcanism in the Carpathian-Pannonian Region.

point of view, the sporadic andesitic magmatism in the Carpathian arc (13–11 Ma) is poorly understood. This timing corresponds to the termination of subduction (and slab detachment?) as recorded by the end of inversion of the outer flysch basin (e.g. Oszcypko 1998; Konečný et al. 2002; Seghedi et al. 2004a).

**In the Central segment** the back-arc felsic and intermediate calc-alkaline volcanism implies that asthenospheric mantle uprise and related subduction roll-back, which started at ~15.5 Ma, reached a maximum intensity at 14–11 Ma and finished around 9 Ma. A striking feature of this segment is that voluminous (caldera-type?) felsic volcanic activity took place between 15 and 14 Ma (Pécskay et al. 2001; Fülöp 2003), the products of which accumulated in the north-eastern Pannonian Basin and the Transcarpathian Basin) and Transylvanian Basin. Activity in the Apuseni area, characterized by typical calc-alkaline to adakite-like calc-alkaline magmas, developed during Middle Miocene times (14 Ma), reaching a maximum intensity between 13 and 10 Ma and finishing between 8 and 7 Ma. This magmatic activity was not connected with the contemporaneous roll-back processes and generation of magmas of the arc area. Since the Apuseni magmatism was generated in an extensional regime (Royden 1988; Csontos & Nagymarosy 1998; Ciulavu 1999), lithospheric decompressional melting during eastward translation and clockwise rotation of the Tisia intra-Carpathian block has been invoked by Seghedi et al. (1998) and Roşu et al. (2001). In the southern part of the Apuseni area, the presence of ~2.5 Ma alkalic basalts and ~1.5 Ma shoshonites suggests a hot mantle upwelling in a local extensional environment (Seghedi et al. 1998, 2004a; Roşu et al. 2001).

**In the Eastern segment,** the magmatic activity was dominated by intermediate calc-alkaline volcanic rocks. The magmatism is clearly post-collisional since it developed after the main Sarmatian collision event (Săndulescu 1984; Maţenco 1997). The age progression of volcanic activity along this segment is obvious (Fig. 2) and is explained by roll-back and simultaneous along-arc breakoff processes (Mason et al. 1998; Seghedi et al. 1998). In the southernmost part of the segment magmas of different composition (adakite-like calc-alkaline, shoshonitic and alkali basaltic) were generated between 2 and 0.03 Ma. Breakoff and tearing of the slab at shallow levels, followed by asthenosphere uprise, have been suggested (Seghedi et al. 2004a).

Accordingly, the Tertiary evolution of volcanic activity of the Carpathian arc and intra-Carpathian area controlled by geotectonic evolution was not contemporaneous, but shows a progression from West to East in definable segments (Konečný et al. 2002; Seghedi et al. 2004a). Marked southward progression of volcanic activity within the **Eastern segment** cannot be explained successfully by the variable onset of subduction, but it rather reflects a southward progression of the slab tear-off (Wortel & Spakman 2000). Such model implies that the required magma generation depth was reached only during the process of slab detachment (Downes 1996; Nemčok et al. 1998). Detachment-driven magma generation would also explain a rather short duration of magmatic activity. The detachment-driven magma generation might indeed be a more common process than previously thought, as a short duration of volcanic activity is characteristic also for the western segment and a part of the north-eastern segment of the volcanic arc *s.s.*

On the basis of our data, the time that elapsed between the onset of volcanic activity in the back-arc region and that in the volcanic arc reflects the time required for the subducting slab to achieve a roll-back induced vertical position. Involvement of the detachment process in magma generation would decrease the estimate of the subduction rate. The Carpathian volcanic arc is situated mostly rather close to the trace of the related subduction zone (Fig. 1), indicating that magma generation window was reached, when the subduction zone was almost vertical. The process of slab verticalization is documented in the Central segment, where successive volcanic alignments show a pronounced migration of volcanic activity towards the subduction zone during Sarmatian time (13.5–11 Ma) (Lexa & Kaličiak 2000; Pécskay et al. 2001; Seghedi et al. 2001). Volcanic activity in individual volcanic areas of the arc was coeval with the latest time of thrusting in front of the accretion prism at that segment, indicating that during volcanism the subduction zone was almost vertical and was in its final stage of activity.

Termination of subduction and related back-arc extension was immediately reflected in a change of volcanic activity. Voluminous calc-alkaline magmas were replaced by sporadic alkaline magmas. Apparently the change in geodynamic processes also radically changed the pattern of asthenospheric mantle flow as since that time diapiric uprise in the mantle was tapping depleted mantle material.

The main periods of block rotations proved by paleomagnetic measurements (shaded areas on Fig. 4), clearly indicate that the sense, amplitude and duration of lithospheric movements are variable within each segment. These features suggest the eastward progression of deformation along the thrust-and-fold system owing to progression in interaction between the upper and lower plates (Panaiotu 1998; Márton & Fodor 2003).

The first period of rotation (18–14 Ma in the Western segment and 15–12 Ma in the Central segment) was clearly related to subduction (Panaiotu 1998; Márton & Fodor 2003). The sense, amplitude age and duration of block rotations were variable for each segment. However the intensity and volume of magmatic activity appear to be correlated in time with periods of block rotations (Fig. 4). During the volcanic activity, rotations affected only the Western and Central segments. Rotation has been detected only on rocks of the first period of volcanism in more internal areas with respect to the subduction front. The connection between block rotations and volcanism suggests a different mechanism for magmagenesis within each individual segment as supported by the geochemical data (Seghedi et al. 2004a, 2005a). The youngest phase of rotation in the Transdanubian Central Range area (5) was associated with increasing compression/inversion in the Pannonian Basin and adjacent areas (Márton & Fodor 2003). Alkali basalts of the Transdanubian Central Range are inside the area affected by this rotation or at its margins.

## Conclusions

Neogene to Quaternary volcanism in the Carpathian-Pannonian Region was related to the youngest evolutionary stage of the Carpathian arc and intra-Carpathian area, with subduction of the crust underlying former outer flysch basins as the main driving mechanism. Volcanic activity took place in the time interval 21 to 0.01 Ma, showing a pronounced migration in time from West to East. According to the compositional characteristics, spatial distribution and relationship to tectonic phenomena, the volcanic formations can be divided into three segments, each one with its own timing: (1) a **Western segment** characterized by areally distributed felsic calc-alkaline volcanic formations related to initial stages of back-arc extension active between 21 and 12 Ma and by areally distributed intermediate calc-alkaline volcanic formations related to advanced stages of back-arc extension between 19 and 8 Ma, (2) a **Central segment** where felsic volcanic activity was generated between 15 and 11 Ma, as well as the main intermediate calc-alkaline activity between 15 and 9 Ma, both in the Carpathian arc and in the intra-Carpathians (Apuseni Mts), and (3) an **Eastern segment** generated between 10 to 0.3 Ma. Alkali basaltic volcanism generally post-dated the calc-alkaline one, erupting between 12 and 0.1 Ma in the west, except for the southern part of the East Carpathians, where they were contemporaneous, between 2.5 and 0.5 Ma. Comparison of the duration of volcanic activity within different areas of CPR shows that both calc-alkaline and alkaline basaltic volcanic activities were longer-lasting in the back-arc region than in the arc region. The very short-lived volcanic activity in most of the segments of the arc can be interpreted as an indication of either a limited width of the subducted crust (probably not more than 200 km), or a detachment of the sinking slab from the platform margin at the time of volcanic activity. According to Fig. 4: (1) a decreasing role of the back-arc extension related felsic and intermediate calc-alkaline volcanism and (2) an increasing role of the slab detachment driven intermediate calc-alkaline volcanism with time from the West towards the East, can be highlighted.

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