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# Geochronology of the Neogene intrusive magmatism of the Oaş–Gutâi Mountains, Eastern Carpathians (NW Romania)

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**Abstract:** Earlier geological work in the Oaş–Gutâi Mts (OG), Eastern Carpathians, has revealed the extensive presence of shallow subvolcanic intrusive bodies, both exposed on the surface and covered by Paleogene-Neogene sedimentary sequences and Neogene volcanic formations. This study is based on detailed mapping and sampling of the OG Neogene intrusive magmatic rocks. Thirty seven representative intrusions (sills, dykes, microlaccoliths, etc.) were selected for radiometric dating. These intrusions show a wide variety of petrographic rock-types: from microgabbros to microgranodiorites and from basalts to andesites. However, the intrusions consist of typical calc-alkaline, medium-K rocks, similar to the volcanic rocks which outcrop in the same areas. The K-Ar age determinations on whole-rock samples of intrusions yielded ages between 11.9 Ma and 7.0 Ma (from Late Sarmatian to Middle Pannonian). The results are in good agreement with the common assumption, based on the biostratigraphic and geological data, that large volumes of intrusions have formed during the paroxysm of the intermediate volcanic activity in the OG. Except for the Firiza basalt intrusive complex of the Gutâi Mts (8.1–7.0 Ma), the OG intrusions show similar K-Ar ages as the intrusions of the "Subvolcanic Zone" and Călimani Mts from Eastern Carpathians. The timing of the OG intrusive magmatism partially overlaps with the timing of the intrusive magmatic activity in the Eastern Moravia and Pieniny Mts. The systematic radiometric datings in the whole OG give clear evidence that the hydrothermal activity related to the epithermal systems always postdates intrusion emplacement.

**Key words:** Neogene, Eastern Carpathians, K-Ar dating, intrusive magmatism, epithermal mineralizations.

## Introduction

The Oaş–Gutâi Mts (OG) belong to the Eastern Carpathian Neogene-Quaternary volcanic chain and spread over the north-western part of the Romanian territory.

An impressive and complex intrusive magmatism developed during the Miocene in the Oaş–Gutâi Mts, exerting a major control in the formation of the well-known gold-silver and base metal hydrothermal ore deposits of the region. The OG Mts contain numerous intrusions which are well documented by field mapping, drilling and underground mining works. The intrusive rocks show crosscut relationships with the biostratigraphically dated Neogene (Badenian, Sarmatian and Pannonian) sedimentary deposits (Marinescu 1964; Sagatovici 1968; Dragu & Edelstein 1968; Edelstein et al. 1971; Dragu 1978; Givulescu et al. 1984; Givulescu 1990; Kovacs et al. 1999) and radiometrically dated Neogene volcanic formations (Edelstein et al. 1992; Pécskay et al. 1994, 1995; Kovacs et al. 1997a). The K-Ar ages of the volcanic rocks from the OG were correlated with the biostratigraphic data (assigned to the Central Paratethys chronostratigraphic stages) and published by Edelstein et al. (1992) and Pécskay et al. (1994).

Geological data on the OG intrusions were previously published by Edelstein et al. (1987), Kovacs et al. (1987) and Kovacs & Fülöp (2003, 2010). The first K-Ar data obtained from the intrusions were presented by Edelstein et al. (1992, 1993), Pécskay et al. (1994, 1995 and 2006) and Kovacs et al. (1997a). The radiometric ages of the hydrothermal mineralizations were published by Lang et al. (1994) and Kovacs et al. (1997b). Results of a systematic geochronological study of the "Subvolcanic Zone" (Poiana Botizei–Ţibleş–Toroiaga–Rodna–Bârgău — PBTTRB) of the Eastern Carpathians were reported by Pécskay et al. (2009).

The aim of this paper is to present the new K-Ar ages (33 determinations) from the intrusive rocks of the OG and to compare them with the radiometric data previously obtained on the volcanic rocks and on the intrusion-hosted hydrothermal mineralizations.

## Geological setting

Like the entire Eastern Carpathian volcanic chain, the Oaş–Gutâi Mts (OG) were built up during the Miocene subduction of the European Plate beneath the two continental blocks/microplates, ALCAPA and Tisza-Dacia/Tisia in the Carpathian-Pannonian Region (CPR) (Csontos 1995; Seghedi et al. 1998 — Fig.1).

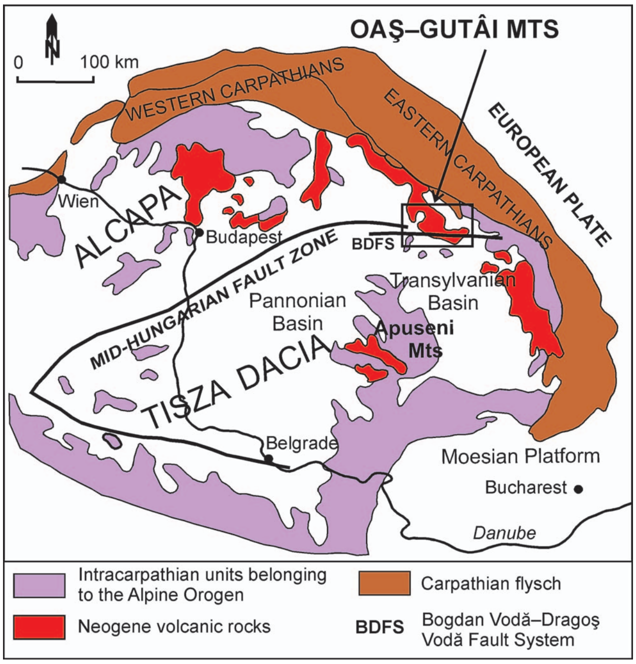


**Fig. 1.** Location of the Oaş–Gutâi Mts on the geotectonic sketch map of the Carpathian-Pannonian Region (compiled and simplified from Săndulescu 1988; Csontos 1995 and Tischler et al. 2007).

Three geological units comprise the OG volcanic area: (1) the pre-Neogene basement, (2) the Neogene sedimentary deposits and (3) the assemblage of Neogene magmatic rocks. The pre-Neogene basement consists of several overthrust units composed of the Paleogene flysch formations (Săndulescu 1984) outcropping extensively in the eastern part of the Gutâi Mts. The Paleogene flysch formations lie beneath the OG volcanic area as shown in drill cores and underground mining works. The Neogene sedimentary deposits comprise Badenian, Sarmatian and Pannonian rocks, and are covered by Neogene volcanic rocks.

Two types of calc-alkaline volcanism took place in the OG during the Miocene: a felsic rhyolitic and explosive, caldera formation-related volcanism (with inception dated at 15.4 Ma, Fülöp 2002), which is partially correlated with the widespread rhyolitic volcanism of the Pannonian Basin (Fülöp 2003; Fülöp & Kovacs 2003) and an intermediate, andesitic volcanism mainly of effusive origin (Kovacs & Fülöp 2003), dated between 13.4–7.0 Ma (Pécskay et al. 1995).

The intermediate volcanism started in the Late Badenian–Sarmatian (13.4–12.1 Ma, Edelstein et al. 1992; Pécskay et al. 1994) in the south-western and south-eastern part of the Gutâi Mts. During the Pannonian, the intermediate volcanism migrated towards the N, NW and NE of the Gutâi Mts (12.0–9.0 Ma, Pécskay et al. 2006; Kovacs et al. 2006). In the Oaş Mts, the intermediate volcanism took place predominantly during the Pannonian, within the time interval of 11.9–9.5 Ma (Kovacs et al. 1997a; Kovacs & Fülöp 2002; Kovacs et al. 2006).

The youngest volcanic products of the OG magmatic activity are represented by the Firiza basalts which form a mafic intrusive complex in the central part of the Gutâi Mts, ranging in age 8.1–7.0 Ma (Edelstein et al. 1993).

The petrography of the intermediate volcanic rocks shows typical calc-alkaline series ranging from basalts to rhyolites. The pyroxene andesites and pyroxene basaltic andesites are predominant.

Both the felsic and the intermediate types of volcanism show typical subduction zone geochemical signatures (Kovacs 2002; Kovacs & Fülöp 2003; Fülöp & Kovacs 2003; Seghedi et al. 2004).

The characteristic tectonic feature of the area is the W-E trending Bogdan Vodă–Dragoş Vodă fault system (BDFS, Fig. 1) located in the southern part of the Gutâi Mts (Săndulescu 1984; Borcoş 1994; Tischler et al. 2007). This fault is interpreted as the extension of the Mid-Hungarian Line (MHL) (Csontos & Nagymarosy 1998; Tischler et al. 2007). Györfi et al. (1999) documented important extensional movements developed along the "Dragoş Vodă fault" and Pécskay et al. (2009) relate the emplacement of the majority of the intrusive bodies from the "Subvolcanic Zone" (which developed in the eastern part of the OG volcanic area) to this strike-slip fault.

The metallogenetic activity developed in connection with the intermediate magmatism in the OG. The typical epithermal mineralizations are dominantly polymetallic and gold-rich veins. Most of the hydrothermal mineralizations from the OG (Baia Mare metallogenetic district) are genetically related to the intrusive magmatism and classified accordingly as "intrusion-related" epithermal systems (Kovacs & Fülöp 2010). The hydrothermal activity in the OG is dated 11.5–7.9 Ma (Lang et al. 1994; Kovacs et al. 1997b), corresponding to the Pannonian.

## General features of the intrusive magmatism

The intrusive magmatism in the OG is associated with the intermediate calc-alkaline volcanism and develops as subvolcanic and shallow-level intravolcanic intrusive bodies with various sizes and mostly irregular shapes. More than 600 intrusions are exposed on the surface and many others are found by underground mining works and drilling. The intrusions develop predominantly in the central and northern part of the Oaş Mts and in the southern and south-eastern part of the Gutâi Mts (Fig. 2). The south-eastern cluster of intrusions liaises with the "Subvolcanic Zone" (PBTTRB) of the Eastern Carpathians. A large number of drill holes intersect the intrusive rocks of the Gutâi Mts and have encountered a total thickness exceeding 3000 m.

The intrusions show various morphologies (dykes, sills, apophyses of microlaccoliths and subordinately microlaccoliths) and a wide range of sizes (from several meters to several km). The small-sized, up to 500 m diameter intrusive bodies, which cluster locally, are predominant. Large-sized intrusions are also identified. Among these, the sills which reach 6 km in length, exposed in the northern part of the Gutâi Mts outside of the volcanic area in the Neogene sedimentary deposits (Fig. 2), the microlaccoliths from Mesteacăn Valley (Ilba Zone — south-western part of Gutâi Mts — Fig. 3) and Brazilor Valley (Săpînţa Zone — northern part of the Gutâi Mts — Fig. 4) are worth mentioning.

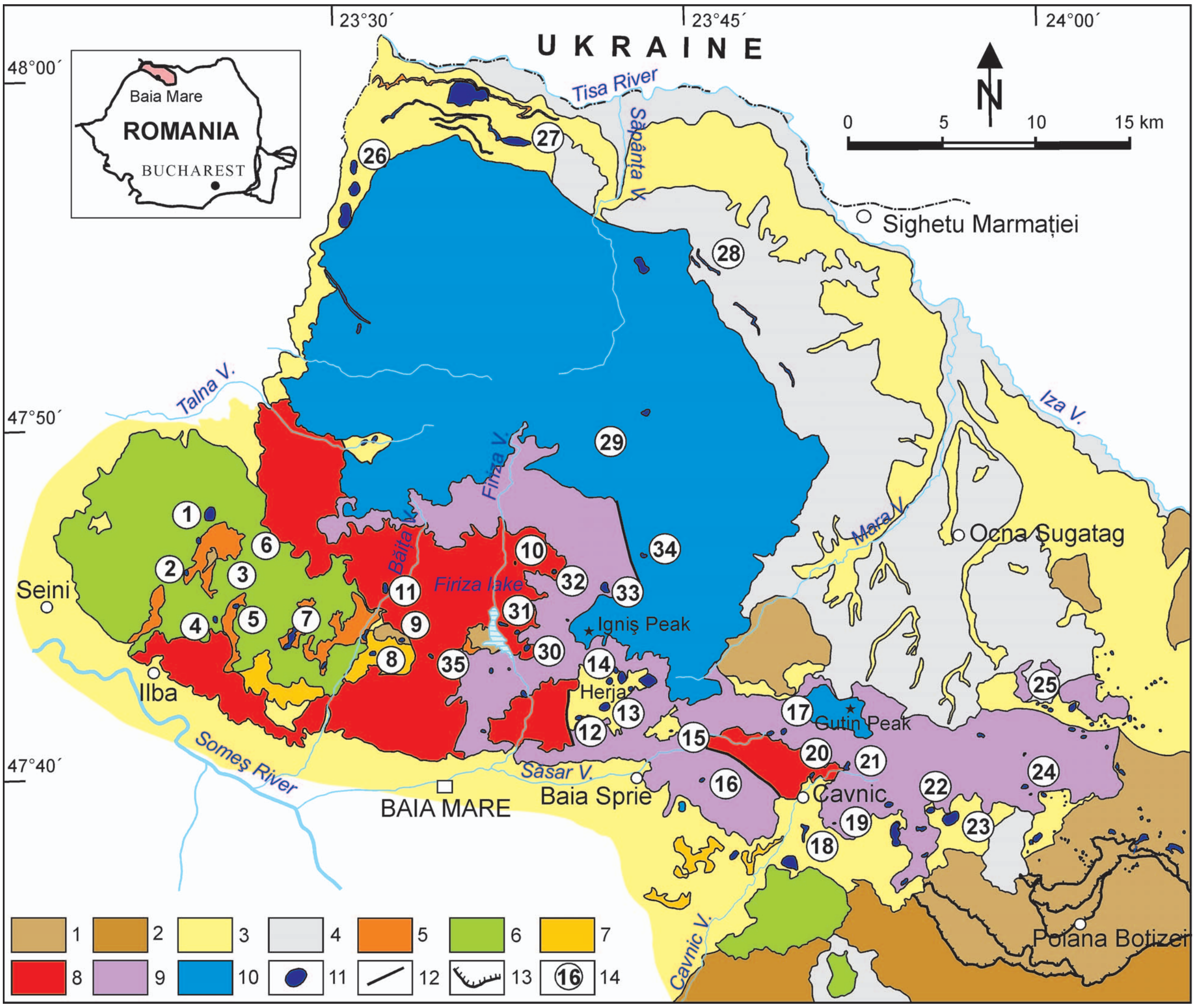


**Fig. 2.** Simplified geological map of the Gutâi Mts (according to Jurje 2012). **1** — Paleogene flysch-type sedimentary deposits; **2** — Oligocene-Miocene sedimentary deposits; **3** — Neogene sedimentary deposits; **4** — Quaternary sedimentary deposits; **5** — Badenian felsic volcaniclastic rocks; **6** — Sarmatian intermediate volcanic rocks; **7** — Pannonian dacite extrusive complexes; **8** — Pannonian quartz andesite volcanic complex; **9** — Pannonian andesite volcanic complexes from the central-south-eastern part of the Gutâi Mts; **10** —Pannonian andesite volcanic complexes from the northern part of the Gutâi Mts; **11** — Intrusive bodies; **12** — Fault; **13** — Overthrusts; **14** — K-Ar sample locations.

Two different types of intrusions can be distinguished on the basis of their genesis and emplacement style: (1) single-stage intrusions comprising a single rock type (often with textural variations); and (2) multistage intrusions composed of two or more petrographic types which show complex relationships (i.e. Brazilor Valley-Săpînţa Zone large intrusion, Fig. 4).

The intrusions investigated in the OG display a wide range of petrographic compositions and textures: microgabbros, diorites/microdiorites, quartz diorites/microdiorites, quartz monzodiorites, microgranodiorites, basalts, basaltic andesites and andesites. The pyroxene andesites and the pyroxene porphyritic microdiorites are the prevalent rock types. The amphibole and the biotite are also present in some intermediate and acidic rocks, besides the pyroxene. The only olivine-bearing rock forms large sills in the northern part of the Gutâi Mts. The Firiza mafic intrusive complex from the central part of the Gutâi Mts is composed of fine porphyritic to aphyric pyroxene basalts. Most of the rock-types show porphyritic texture, with microlithic to microgranular groundmass (basaltic andesites and andesites) and holocrystalline, mainly equigranular groundmass (microdiorites/gabbros, monzodiorites and microgranodiorites). Hornfelses and sometimes skarns formed at the contact of the intrusions with the sedimentary deposits.

Geochemically, the intrusive rocks show a typical calc-alkaline, medium-K character, similar to the volcanic rocks from the OG (Edelstein et al. 1987; Kovacs et al. 1987; Kovacs 2002; Kovacs & Fülöp 2003) (Fig. 5).

The intrusions show complex crosscuting relationships with the Paleogene deposits of the pre-Neogene basement and the Neogene sedimentary deposits. In the southern area of the Gutâi Mts, the Paleogene deposits are crosscut by abundant intrusive bodies as can be seen in the numerous drill holes and underground mining works such as those from Ilba, Herja and Cavnic Zones (Fig. 3 and Fig. 6).

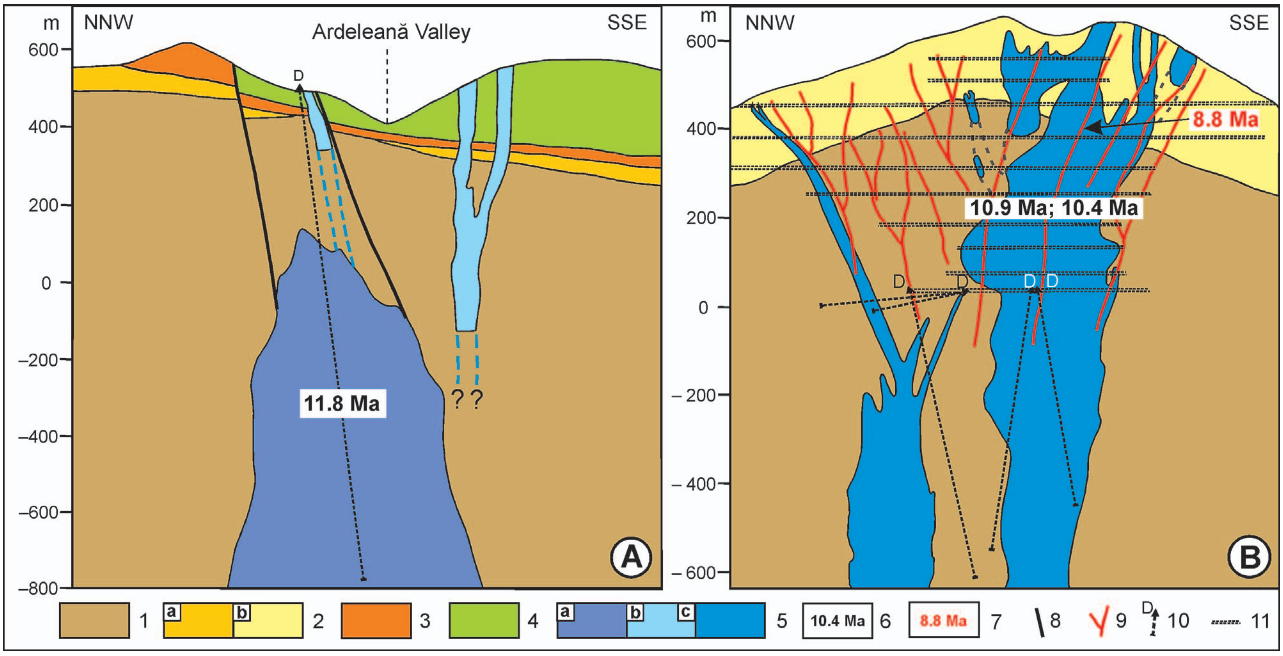


**Fig. 3.** Geological cross-section of the Ilba Zone (Mesteacăn Valley, **A**) and through Herja ore deposit (**B**, from Kovacs & Fülöp 2010). **1** — Paleogene flysch-type sedimentary deposits; **2** — Neogene sedimentary deposits: a — Badenian, b — Pannonian; **3** — Badenian felsic volcaniclastic rocks (mainly rhyolitic ignimbrites); **4** — Sarmatian lava flows (pyroxene andesites); **5** — Intrusive bodies: a — pyroxene monzodiorites, b — pyroxene andesites, c — pyroxene microdiorites; **6** — K-Ar ages of the intrusions; **7** — K-Ar ages of the hydrothermal illite from vein; **8** — Fault; **9** — Hydrothermal veins; **10** — Drill hole; **11** — Gallery.

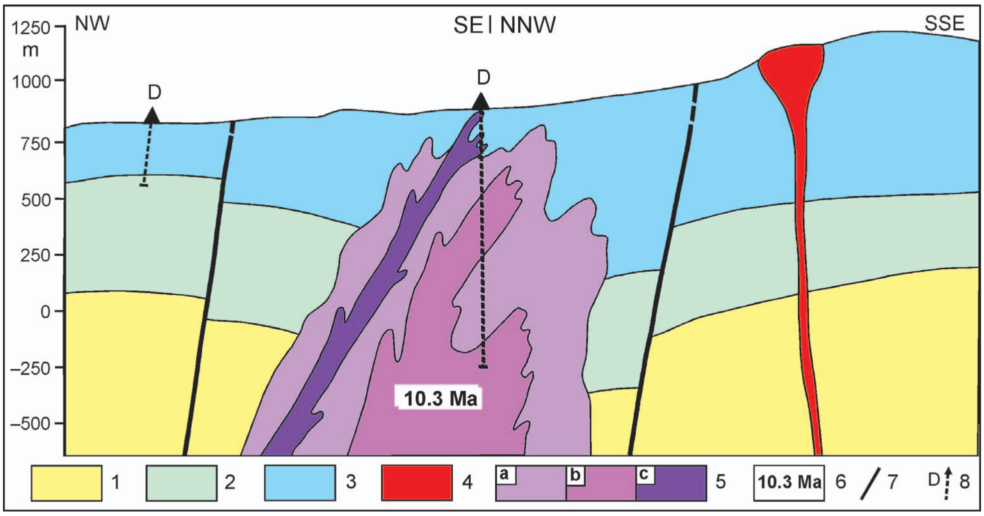


**Fig. 4.** Geological cross-section of the Brazilor Valley — Săpînța Zone. **1** — Pannonian sedimentary deposits; **2** — Pannonian volcaniclastic complex; **3** — Pannonian lava flows (pyroxene andesites); **4** — Biotite dacite extrusive dome; **5** — Multistage intrusive body: a — quartz-bearing pyroxene andesites, b — pyroxene amphibole biotite porphyritic quartzdiorites, c — clinopyroxene basaltic andesites; **6** — K-Ar age; **7** — Fault; **8** — Drill hole.

In the south-eastern part of the Gutâi Mts (Cavnic-Băiuț-Botiza area), which is a transitional area to the "Subvolcanic Zone" of the Eastern Carpathians (Fig. 2), the intrusive bodies exhibit different types of hornfelses developed at the contact with the sedimentary rocks of the overthrusted units of the Carpathian flysch.

The contact relationships of the intrusions with the Neogene sedimentary deposits which are biostratigraphically dated as Badenian, Sarmatian and Pannonian can be identified in underground mines and drill cores throughout the entire area of the OG. The exclusive presence of the Badenian, Sarmatian and Pannonian stages in the OG is based on all the reliable paleontological data of macro- and microfauna and nannoplankton, as well as the palynological data (fossil flora), re-interpreted and correlated by Kovacs et al. (1999). The outcropping intrusive bodies are predominantly hosted by the Pannonian sedi-

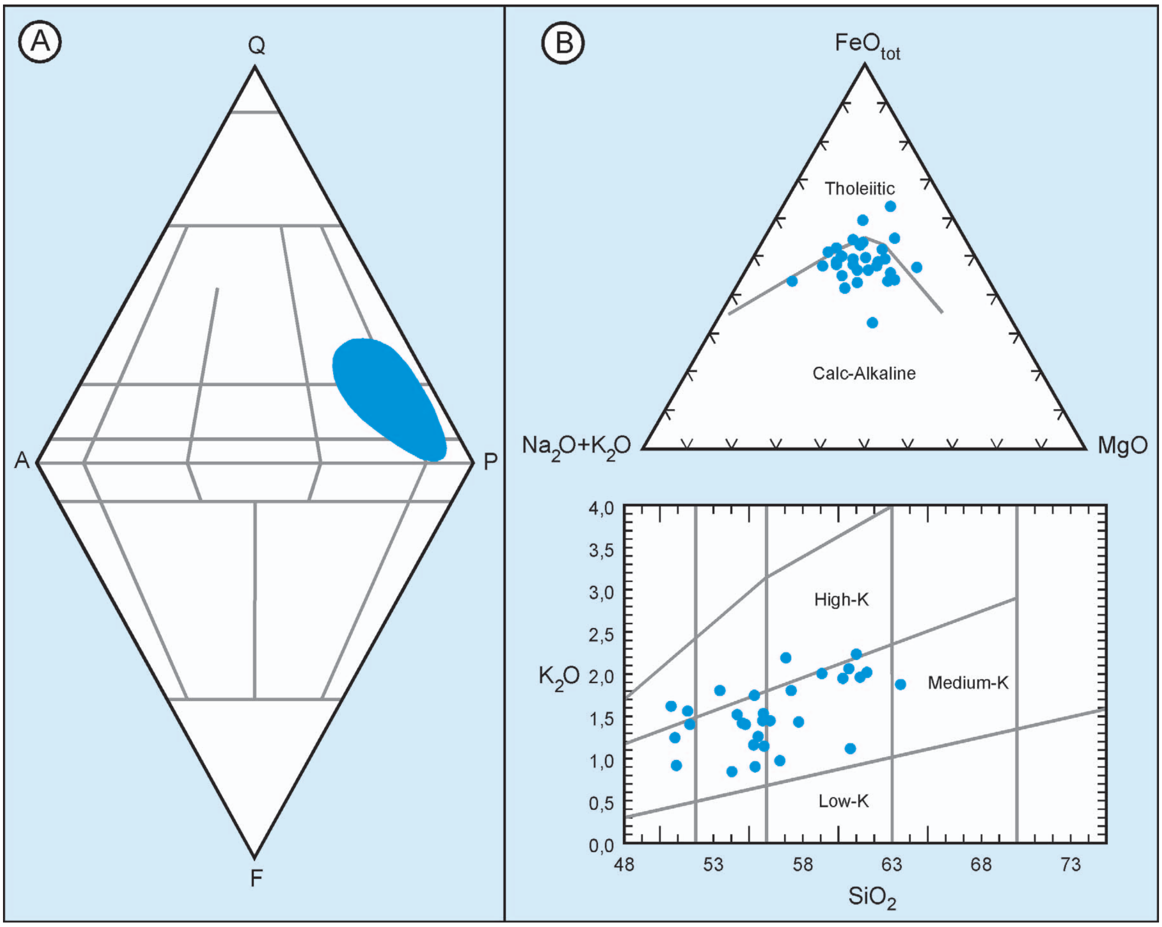


**Fig. 5.** Distribution of the magmatic intrusive rocks of the Oaş–Gutâi Mts in the QAPF diagram (**A**). The emplacement of the radiometric dated samples in the AFM and $K_2O$-$SiO_2$ diagrams (**B**). Geochemical data are from Edelstein et al. (1987), Kovacs et al. (1987), Kovacs (2002), Kovacs & Fülöp (2003).

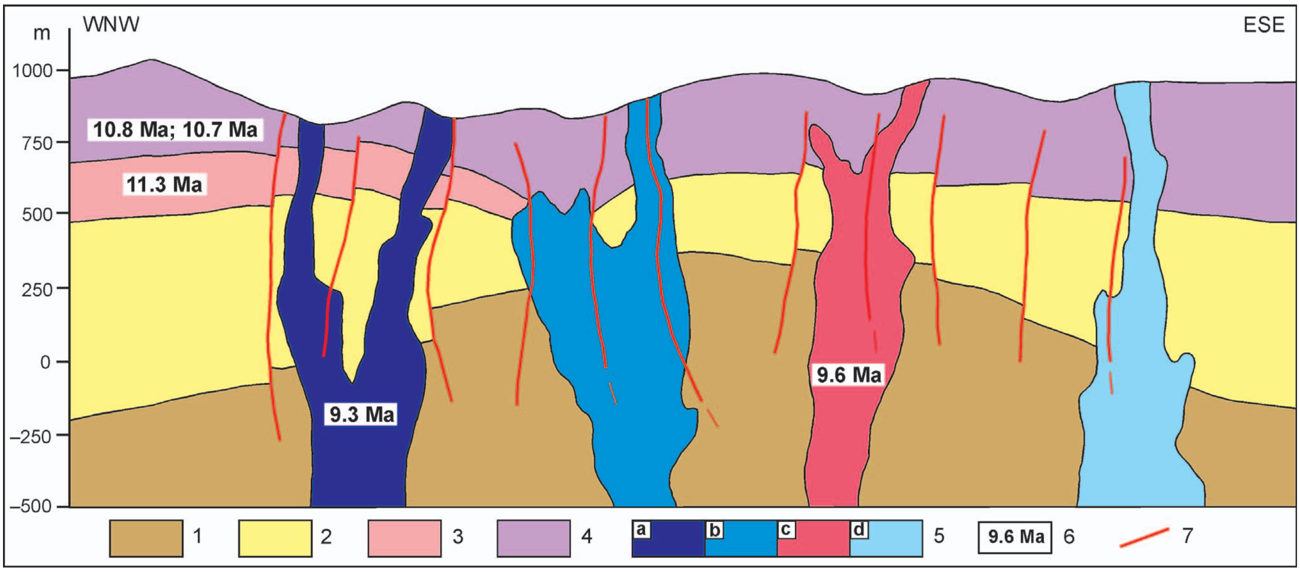


**Fig. 6.** Geological cross-section through the Cavnic polymetallic epithermal ore deposit. **1** — Paleogene flysch-type sedimentary deposits; **2** — Pannonian sedimentary deposits; **3** — Quartz andesite lava flows; **4** — Pyroxene andesite lava flows and associated volcaniclastic rocks; **5** — Intrusive bodies: a — pyroxene microgabbros, b — pyroxene diorites, c — biotite porphyritic quartzdiorites, d — pyroxene andesites; **6** — K-Ar ages; **7** — Hydrothermal veins.

mentary deposits (e.g. the sills from the northern part of Gutâi Mts in Fig. 2 and the intrusions from the Herja-Chiuzbaia area in the south-central part of the Gutâi Mts in Fig. 7).

The intrusive bodies intersect volcanic formations of different ages which can hardly be attributed to any specific, or individual volcanic structure. The intrusions intersect the Badenian rhyolitic ignimbrites, the Sarmatian-Pannonian intermediate volcanics (dominantly andesites), or the Sarmatian and Pannonian volcanic rocks, exclusively. In some cases, the intrusions show complex crosscuting relationships with a volcanic suite consisting of volcanic rocks of different ages and cannot be assigned to a specific volcanic structure (i.e. the basalt intrusions of the Firiza mafic intrusive complex from the Gutâi Mts which pierce quartz andesites of 10.8–10.5 Ma, pyroxene andesites of 10.2 Ma, amphibole-pyroxene andesites of 9.9 Ma and pyroxene andesites of 9.5–9.0 Ma, Edelstein et al. 1992 and Pécskay et al. 1994, 1995). The intrusions also show complex relationships with the vein-hosted mineralizations as identified in the polymetallic and gold-silver epithermal ore deposits from the OG (Edelstein et al. 1987 and Kovacs et al. 1997b). The hydrothermal veins are partially or entirely hosted by intrusions, or developed in the vicinity of intrusions suggesting a genetic relationship (Figs. 3 and 6). None of the ore deposits show any intrusion with crosscuting relationships with the vein-hosted mineralizations.

## Experimental procedures

*Sampling.* For K-Ar dating 37 representative rock samples were collected from different sites in the studied areas (Fig. 2). The samples were taken from quarries, boreholes, mines and from natural outcrops.

A rock piece of about 1 kg was broken out of a larger block, free of xenoliths and joints. Any weathered portions of the samples were eliminated ensuring fresh material for analysis. Most of the samples are fresh rocks under the microscope, only with some secondary minerals (sericite, clay minerals, chlorite and carbonates) in very small quantities. Some of the dated intrusive rocks show propylitic alterations of different intensities (e.g. samples 16.313-5L, 7200K, 14.945-9E, 25.832-94 — Table 1). In most of the altered rocks, the mafic minerals (typically the pyroxene) are almost entirely pseudomorphed by secondary minerals (secondary amphibole and chlorite), and the plagioclase are partially pseudomorphed by sericite/clay minerals (smectites) and/or carbonate.

Appropriate samples were selected for analysis on the basis of the thin section investigations under the microscope. These samples were crushed and sieved to 200–350 μm. The fine dust was elutriated with distilled water and dried at 110 °C for 24 hrs. Most of these samples which are dated herein do not contain a potassium-bearing mineral phase which easily separated. Consequently, these were dated as whole-rock samples. But for the sake of testing the reliability of the radiometric data obtained from whole-rock samples, four K-Ar ages were determined on different magnetic fractions separated from one single rock sample (see No. 2448, Results and discussion for details).

*Potassium determination.* Approximately 0.05 g of finely ground samples were digested in acids (HF, $HNO_3$ and $H_2SO_4$) in teflon beakers and finally dissolved in 0.2 M HCl. Potassium was determined by flame photometry with a Na buffer and Li internal standard using Corning M480 type flame photometer. Multiple runs of inter-laboratory standards (Asia1/95, LP-6, HD-B1, GL-0) indicated the accuracy and reproducibility of this method to be within 2%.

*Argon measurements.* Approximately 0.5 g samples were wrapped in aluminium foil and copper sieve pre-heated for about 24 h at 150–180 °C in a vacuum. Argon was extracted under ultra-high vacuum conditions by RF induction heating and fusion of rock samples in Mo crucibles. The gas was purified by Ti sponge and SAES St 707 type getters, to remove chemically active gas contaminants and some liquid nitrogen in cold trap to remove condensable gases. The extraction line is linked directly to a mass spectrometer (90° magnetic sector type of 155 mm radius, equipped with a Faraday cup, built in ATOMKI, Debrecen, Hungary) used in static mode.

Argon isotope ratios were measured by a $^{38}$Ar isotope dilution mass spectrometric method, previously calibrated with atmospheric argon and international rock standards.

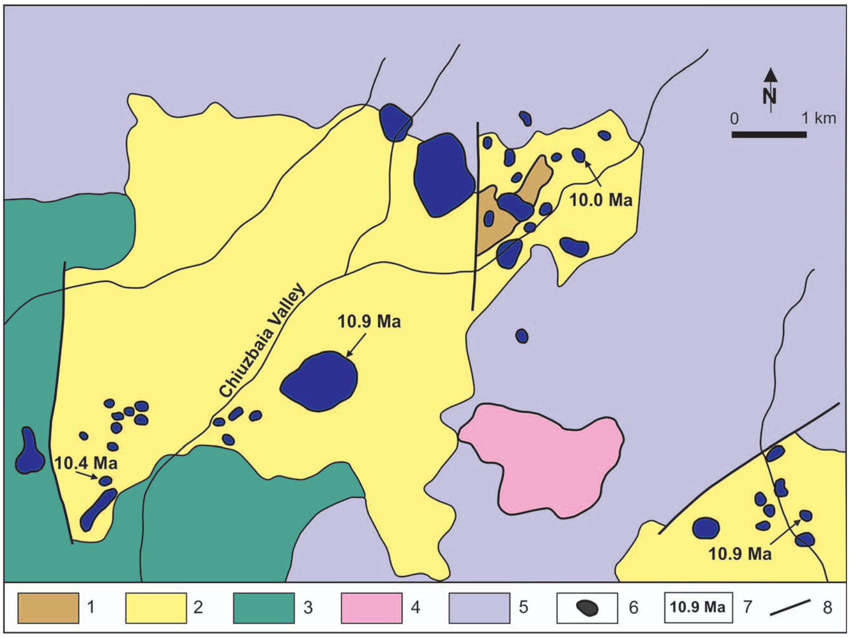


**Fig. 7.** Geological map of the Herja–Chiuzbaia area (simplified after Iştvan et al. 1986). **1** — Paleogene flysch-type sedimentary deposits; **2** — Neogene sedimentary deposits (mainly Pannonian); **3** — Pannonian pyroxene andesite lava flows; **4** — Pannonian rhyolite extrusive dome; **5** — Pannonian pyroxene amphibole andesite lava flows and volcaniclastic rocks; **6** — Intrusive bodies; **7** — K-Ar ages; **8** — Fault.

Experimental details of the K/Ar dating method conducted at ATOMKI Debrecen and the results of calibration are described in Balogh (1985). The ages of the samples are calculated using the decay constants indicated by Steiger & Jäger (1977). The analytical error is given at 68% confidence level (1 σ).

The K-Ar ages are assigned from the chronostratigraphic time scale of Harzhauser & Piller (2007).

## Results and discussion

A systematic geochronological study has been constantly conducted in the OG during the past decades because of the remarkable abundance of intrusions with respect to the volcanic rocks. As a consequence, the numerous K-Ar data now available and still unpublished are subject to interpretation herein and stand in the background of a tentative reconstruction of the evolution of the intrusive magmatism in the OG.

The K-Ar ages determined for the calc-alkaline intrusive rocks of the OG are presented in Table 1. All of the K-Ar ages are consistent with the field relationships, including the ages which show a higher analytical error.

Some of the intrusions developed within the hydrothermal alteration areas which are related to the epithermal ore deposits. As a consequence, the isotope system of the original, fresh rock was disturbed. Some examples are: the smectites/illites, sericite and/or chlorites which crystallize frequently from volcanic glass, sometimes also replace the primary magmatic minerals. The presence of the fine-grained clay minerals may also cause a significant increase of atmospheric argon in the

**Table 1:** Analytical results of K-Ar age determinations. **1** — Published by Edelstein et al. (1992); **2** — Published by Edelstein et al. (1993); **3** — Published by Kovacs et al. (1997a). * — Performed in the laboratory of the Geological Survey of Jerusalem. **Rock types:** A — andesite, BA — basaltic andesite, B — basalt, MDi — monzodiorite, mDi — microdiorite, mGr — microgabbro, mQDi — microquartz-diorite, QDi — quartz-diorite. **Minerals:** Am — amphibole, Bi — biotite, Px — pyroxene, Qz — quartz. **Dated fraction:** wr — whole rock, lmf — least magnetic fraction, mmf — most magnetic fraction, pmf — permanent magnetic fraction.

| No. | Sample# | Lab# | Location | Rock type | Dated fraction | K (%) | $^{40}$Ar rad (ccSTP/g) × $10^{-7}$ | $^{40}$Ar rad (%) | K-Ar age (Ma) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2562-7N | 3634 | Carpenului Valley | APx | wr | 1.63 | 7.499 | 35.8 | 11.8±0.5 |
| 2 | 26890-85 | 3255 | Fătuţoaia Valley | BAPx | wr | 1.57 | 7.005 | 15.7 | 11.4±1.0 |
| 3 | F104/966 | 3635 | Drilling 104, Ardeleană Valley | MDiPx | wr | 2.38 | 10.91 | 28.9 | 11.8±0.6 |
| 4 | 16313-5L | 3641 | Baba Griga Valley | BAPx | wr | 0.49 | 2.256 | 7.0 | 11.8±1.8 |
| 5 | 246-5B | 3254 | Cicârlău Valley | BAPx | wr | 1.35 | 6.285 | 18.3 | 11.9±0.9 |
| 6 | 282/F260[1] | 2059 | Firizan gallery | APxQz | wr | 1.78 | 8.103 | 25.2 | 11.7±0.7 |
| 7 | F111/5.5 | 3637 | Drilling 111, Nistru mine | AQzPxAm±Bi | wr | 1.71 | 7.775 | 30.2 | 11.7±0.6 |
| 8 | 25161-91 | 3633 | Căpitanul Mare Valley | AQzPxAm | wr | 2.04 | 9.934 | 53.6 | 12.5±0.4 |
| 9 | 1712-S1 | 3640 | Izvorul Tocastru Valley | AQzPxAm | wr | 1.25 | 5.516 | 15.0 | 11.3±1.0 |
| | | | | | wr | 1.25 | 5.596 | 15.1 | 11.5±1.0 |
| 10 | 3142-90 | 3248 | Valea Neagră (Firiza) | APxAmQz | wr | 1.39 | 6.406 | 25.9 | 11.8±0.6 |
| 11 | 318-91G | 2434 | Coastei Hill (North Băiţa) | APxAm | wr | 1.55 | 6.082 | 18.2 | 10.1±0.8 |
| 12 | 3102-2E | 3267 | Chiuzbaia Valley | APxAm | wr | 1.29 | 5.252 | 20.0 | 10.4±0.7 |
| 13 | 4536-2E | 3258 | Poca Peak | mDiPxAm | wr | 1.24 | 5.296 | 22.1 | 10.9±0.7 |
| 14 | 27455-2 | 3632 | Măgurii Valley | AAmPx | wr | 2.10 | 8.153 | 47.3 | 10.0±0.3 |
| 15 | 4166-2E | 3257 | Ereş Valley | APxAm | wr | 1.92 | 8.173 | 34.2 | 10.9±0.5 |
| 16 | 27129-4 | 3259 | Negreia Valley | BAPx | wr | 1.01 | 4.514 | 25.3 | 11.5±0.6 |
| 17 | 7200K | 3631 | Şuior Quarry | B/BAPx | wr | 0.84 | 3.004 | 13.2 | 9.2±1.0 |
| 18 | 7112-3E | 3268 | Cavnicului Valley | BAPxAm | wr | 1.43 | 5.724 | 20.7 | 10.3±0.7 |
| 19 | 13343-3L | 3262 | Higea Valley | mDiPx | wr | 1.18 | 4.664 | 26.5 | 10.1±0.6 |
| 20 | 14945-9E | 3261 | Gutinului Valley | mGb/BPx | wr | 0.61 | 2.212 | 7.2 | 9.3±1.8 |
| | 7186M | 3630 | Gutinului Valley | mGb/BPx | wr | 0.61 | 2.604 | 10.7 | 10.9±1.4 |
| 21 | 4190-9E | 3639 | Şişca Valley | QDiPxBi | wr | 1.00 | 3.761 | 11.8 | 9.6±1.1 |
| 22 | 25832-94 | 3264 | Roţii Valley | mDiPx | wr | 0.81 | 3.674 | 15.5 | 11.6±1.0 |
| 23 | 2297-4G | 3638 | Strâmbului Valley | mDiPx | wr | 1.04 | 4.745 | 23.8 | 11.7±0.7 |
| 24 | 27199-2L | 3265 | Siva Valley | APxBi | wr | 2.18 | 9.366 | 22.2 | 11.0±0.7 |
| 25 | 5000-2C | 3263 | Ruginoasa Valley | APxBi±Qz | wr | 2.41 | 9.439 | 46.9 | 10.0±0.4 |
| 26 | 6081K | 3266 | Sâmbra Oilor Quarry | APx | wr | 2.06 | 8.475 | 60.4 | 10.6±0.4 |
| 27 | 22569-89 | 3249 | Cherecul Mare (Săpânţa) | BAPx | wr | 1.65 | 6.903 | 45.3 | 10.8±0.5 |
| 28 | 25009-91 | 2448 | Agriş Quarry | BAPx±Ol | wr | 0.99 | 4.438 | 14.5 | 11.5±0.5 |
| | 25009-91 | 2448 | Agriş Quarry | BAPx±Ol | lmf | 0.58 | 2.718 | 39.4 | 12.0±0.5 |
| | 25009-91 | 2448 | Agriş Quarry | BAPx±Ol | mmf | 1.06 | 4.434 | 22.1 | 10.7±0.6 |
| | 25009-91 | 2448 | Agriş Quarry | BAPx±Ol | pmf | 1.06 | 4.438 | 14.5 | 10.7±1.0 |
| 29 | F607/471.5 | 3636 | Drilling 607, Brazilor Valley | mQDiPxAmBi | wr | 2.12 | 8.506 | 36.4 | 10.3±0.4 |
| 30 | 26256-90[2] | 2616 | Berdu Valley | BPx | wr | 1.31 | 3.877 | 15.7 | 7.6±0.7 |
| 31 | 26106-90[2] | 2617 | Vidra Valley | BPx | wr | 0.80 | 2.559 | 8.0 | 8.1±1.4 |
| 32 | 5647-0N[2] | 2447 | Băii Valley | BPx | wr | 1.16 | 3.595 | 20.6 | 7.9±0.6 |
| 33 | 20944-92E[2] | 2635 | Peştilor Valley | BPx | wr | 1.32 | 3.947 | 50.9 | 7.7±0.3 |
| 34 | 20943-92E[2] | 2636 | Runcului Valley | BPx | wr | 1.37 | 3.731 | 24.8 | 7.0±0.4 |
| 35 | 17909-90E[2] | 4348* | Tocastru Peak | BPx | wr | 1.14 | — | 25.1 | 8.0±0.3 |
| 36 | 20S[3] | 2413 | Socea mine | APx | wr | 2.63 | 9.852 | 28.8 | 9.6±0.6 |
| 37 | F236/471[3] | 2920 | Turţ Valley | MDiPx | wr | 1.70 | 7.187 | 28.8 | 10.8±0.6 |

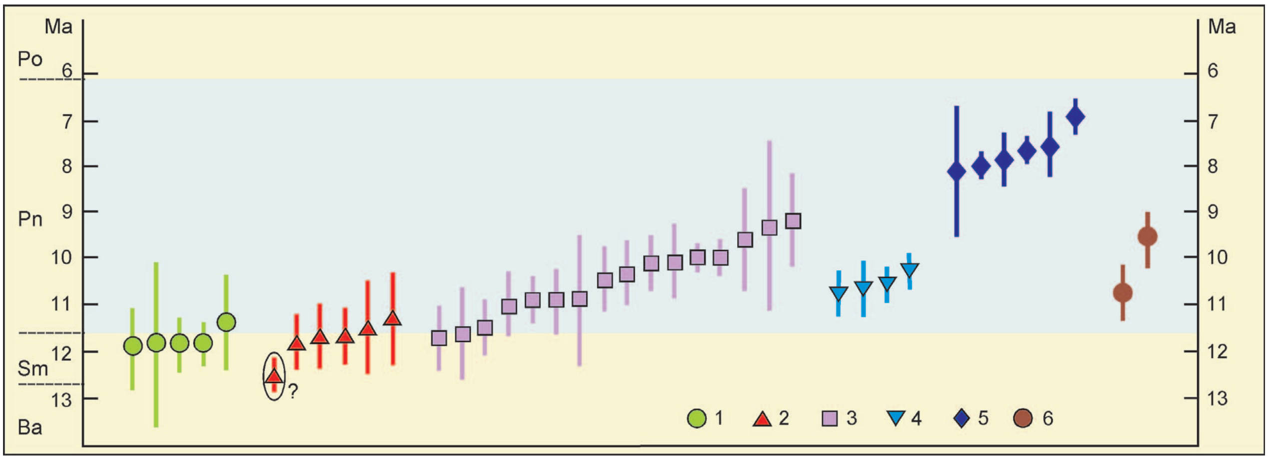


**Fig. 8.** Summary of K-Ar age determinations of the intrusive rocks of the Oaş–Gutâi Mts within the chronostratigraphic scale of Harzhauser & Piller (2007). Individual K-Ar ages are displayed with error bars. **Ba** — Badenian, **Sm** — Sarmatian, **Pn** — Pannonian, **Po** — Pontian. **1** — Sarmatian intrusive rocks; **2** — Pannonian quartz andesite intrusions; **3** — Intrusions associated with the Pannonian volcanic complexes from the central-south-eastern part of the Gutâi Mts; **4** — Intrusive bodies from the northern part of the Gutâi Mts; **5** — Firiza basalt intrusive complex; **6** — Intrusive rocks from the Oaş Mts.

whole-rock sample. This atmospheric argon contamination results in an unusual high analytical error (Walker & McDougall 1982).

Empirically, it was proved that the fresh, well-crystallized intrusive rocks provide suitable material for K-Ar dating (Pécskay et al. 2009) because the intrusive rocks completely retain the radiogenic $^{40}$Ar. Contrary to the fresh rocks, the hydrothermally altered rocks may lose some of radiogenic $^{40}$Ar, giving rise to an apparent K-Ar rock age significantly younger than the ages of the unaltered rock sample, although the fresh and the altered samples are collected from the same intrusive body (e.g. inner and outer parts of a dyke). Additional problems are also encountered in the intrusions emplaced at a greater depth, due to the excess $^{40}$Ar trapped in the phenocrysts, or because of the physical incorporation of fragments of older rocks (McDougall et al. 1969). This may result in an anomalously high apparent age, depending on how inhomogeneous the sample is (e.g. caused by the presence of some xenocrysts or xenoliths). It should be noted that excess argon is particularly common in the hydrothermal system associated with large intrusions (Villa 1998). The presence of excess argon can easily be detected in a mineral fraction or in a whole-rock sample with low potassium content (see Sample No. 28, where the least magnetic fraction which shows the oldest age, most likely contains excess argon released from an older sedimentary rock). The excess argon is less common in shallow intrusions because of the outgassing process which releases it (Kelley 2002).

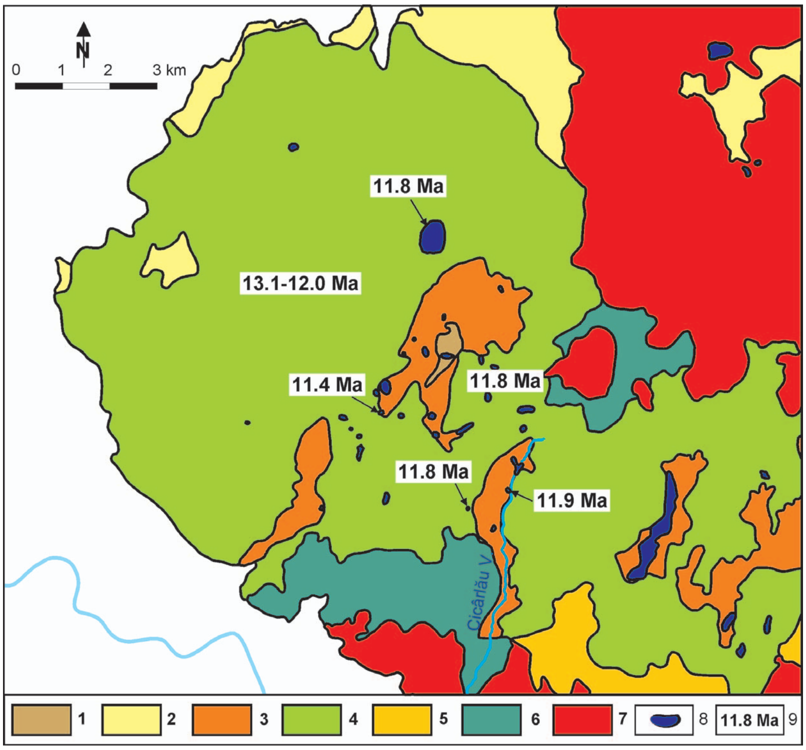


**Fig. 9.** Geological map of the south-western part of the Gutâi Mts (according to Jurje 2012). **1** — Paleogene flysch-type sedimentary deposits; **2** — Neogene sedimentary deposits (mainly Pannonian); **3** — Badenian felsic volcaniclastic rocks; **4** — Sarmatian lava flows (pyroxene andesites) and volcaniclastic rocks; **5** — Pannonian pyroxene dacites; **6** — Pannonian pyroxene andesites; **7** — Pannonian quartz andesite volcanic complex; **7** — Intrusive bodies; **8** — K-Ar ages.

According to the geological data, the intrusive magmatism took place during the Sarmatian and Pannonian in the Gutâi Mts, and during Pannonian in the Oaş Mts. The K-Ar ages obtained during the current geochronological study range between 12.5–7.0 Ma and confirm the geological data. Fig-

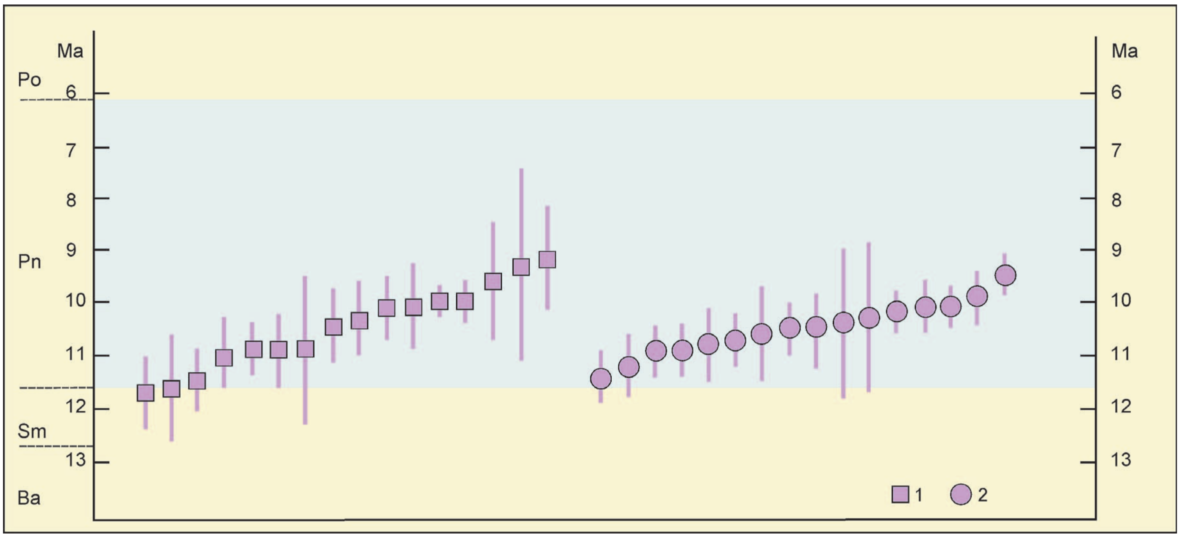


**Fig. 10.** K-Ar age determinations of the intrusive rocks and lava flows assigned to the volcanic complexes of the central-south-eastern part of the Gutâi Mts (the chronostratigraphic scale is the same as in Fig. 8). **1** — Intrusive rocks; **2** — Lava flows.

ure 8 summarizes all the K-Ar ages measured on the intrusive rocks of the OG.

***Sarmatian intrusive magmatism.*** The Sarmatian intrusive bodies show crosscutting relationships with the Paleogene sedimentary deposits and the Badenian and Sarmatian volcanic complexes, only in the south-western area of the Gutâi Mts: for example, the monzodiorite intrusion hosted by the Paleogene basement in the Ardeleană Valley (Fig. 3) and the basaltic andesite intrusion hosted by the Badenian ignimbrites in the Cicârlău Valley (Fig. 9). The five K-Ar ages obtained on these intrusions range between 11.9–11.4 Ma (Table 1, Fig. 8), which is in accordance with the geological data and confirms the younger age of the intrusions in comparison with the spatially associated Sarmatian lava flows (13.1–12.0 Ma, Edelstein et al. 1992 and Pécskay et al. 1995; Fig. 9). Consequently, the intrusive magmatism relatively occurred during a short time interval: approximately around the Sarmatian/Pannonian boundary (Harzhauser & Piller 2007).

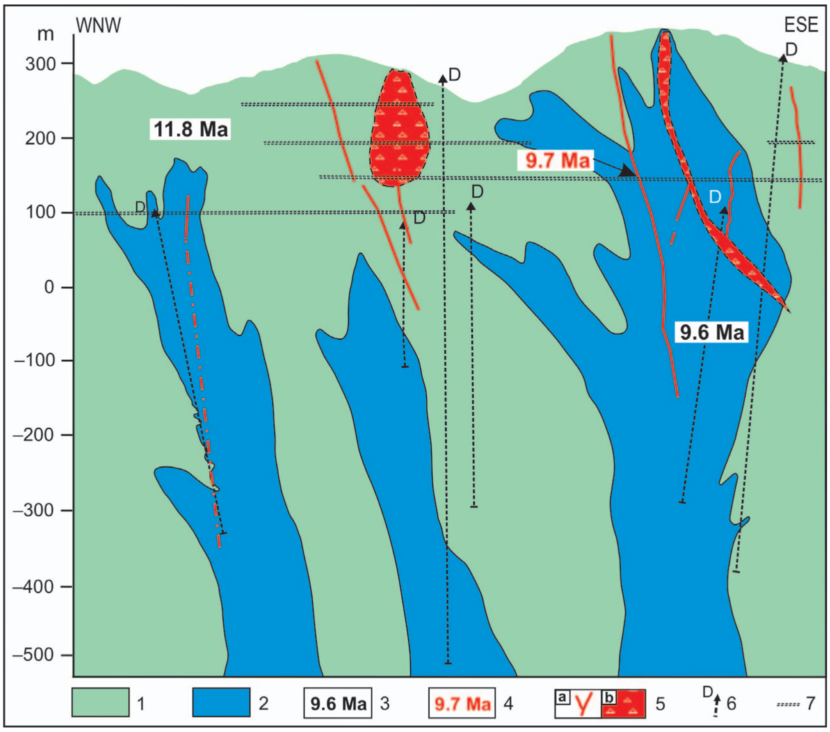


**Fig. 11.** Geological cross-section through the Socea polymetallic epithermal ore deposit (Oaş Mts). **1** — Pannonian andesite volcanic complex; **2** — Intrusive bodies (pyroxene microdiorites and andesites); **3** — K-Ar ages of the intrusions and the lava flows; **4** — K-Ar ages of the adularia from the hydrothermal veins; **5** — Hydrothermal mineralizations: a — veins, b — breccia pipe/dyke; **6** — Drill hole; **7** — Gallery.

***Pannonian intrusive magmatism.*** The intrusive bodies crosscut the successions of Paleogene to Pannonian sedimentary deposits and Badenian to Pannonian volcanic rocks in both the Oaş and Gutâi Mts. The Pannonian intrusive magmatism is well expressed in the Gutâi Mts and well documented in the abundant drill cores and underground mining works.

Six intrusions related to the Pannonian quartz andesite volcanic complex from the central-southern part of the Gutâi Mts were sampled. Five samples yielded consistent K-Ar ages (11.8-11.3 Ma) and one sample (Căpitanul Mare Valley, No. 8 in Fig. 2) shows a slightly older age (12.5 Ma; Table 1, Fig. 8). The radiometric data indicate that a Late Sarmatian–Early Pannonian intrusive event developed in association with the quartz andesite complex of the Gutâi Mts.

Numerous intrusive bodies show relationships with the Pannonian volcanic complexes developed in the central-south-eastern part of the Gutâi Mts and the Pannonian sedimentary deposits (Fig. 2). The Pannonian intrusions pierce the whole succession of Paleogene and Neogene deposits (e.g. Herja-Chiuzbaia area — Figs. 3 and 7 and Cavnic area — Fig. 6). Fifteen intrusions of the area, with different sizes, shapes and petrography were dated. The K-Ar ages are shown in Table 1 and Fig. 8. The radiometric ages range between 11.7–9.2 Ma and the majority are younger than 10.5 Ma. In Figure 10, the K-Ar ages of the intrusive rocks are compared with the K-Ar ages of the lava flows from the same area, which are assigned to the volcanic complexes of the central-south-eastern part of the Gutâi Mts. The contact relationships of the intrusions and the volcanic successions are constrained by poor field evidence (e.g. Cavnic area — Fig. 6) but the K-Ar ages suggest that the intrusions are slightly younger than the volcanic rocks. However, the K-Ar ages overlap the range of the analytical errors.

In the northern part of the Gutâi Mts, outside the volcanic area, several intrusive bodies crosscut the Sarmatian and Pannonian sedimentary deposits (Fig. 2). Three radiometric age determinations were conducted on the samples collected from these intrusive rocks and the results show similar ages: 10.8, 10.7 and 10.6 Ma, respectively (Table 1 and Fig. 8). In the Brazi Valley, a large multi-stage intrusion was reached by a drill hole (Fig. 4). The core sample (No. 3636, Table 1) with higher K content (K: 2.12 %) gave a slightly younger age (10.3 ± 0.4 Ma) demonstrating that this intrusion was also emplaced in the Pannonian.

The two K-Ar ages of the intrusive rocks from the Oaş Mts (10.8 and 9.6 Ma, Fig. 8., Kovacs et al. 1997a) reflect similar ages as the majority of the Pannonian intrusion ages from the Gutâi Mts.

The radiometric datings of adularia and illite related to the hydrothermal mineralizations, performed using conventional K-Ar and Ar-Ar step degassing techniques (Lang et al. 1994; Kovacs et al. 1997b) indicate that the mineralizations are younger than the emplacement of the intrusions in all the metallogenetic fields of the OG (Figs. 3b, 11 and 12).

The Ilba-Nistru base metal metallogenetic field from the south-western part of the Gutâi Mts shows an 11.9–11.4 Ma

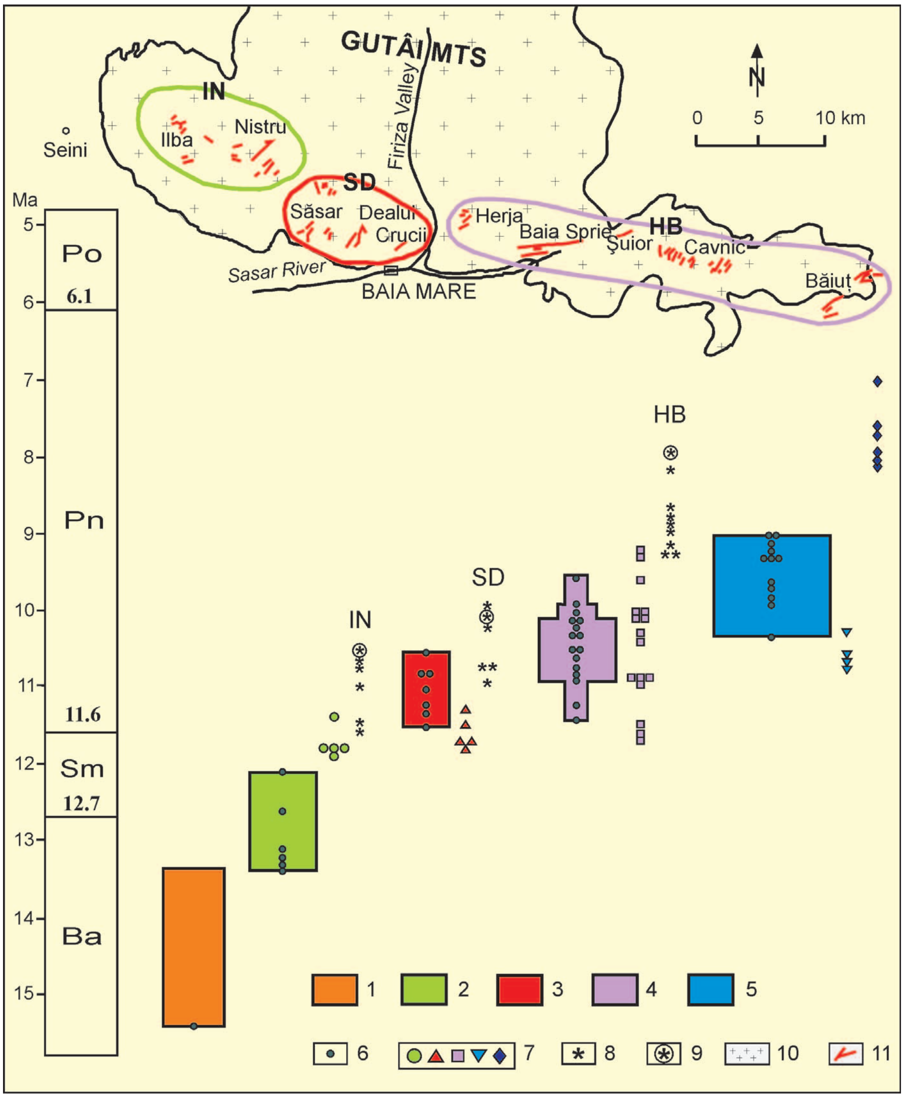


**Fig. 12.** Comparative K-Ar and Ar-Ar ages of the intrusions, lava flows and hydrothermal mineralizations from the Gutâi Mts. The time interval defined by the K-Ar age determinations of the volcanic complexes is illustrated on the Y axis. The different volcanic complexes are illustrated according to their relative sizes. **1** — Badenian felsic volcaniclastic rocks; **2** — Sarmatian lava flows (pyroxene andesites); **3** — Pannonian quartz andesite volcanic complex; **4** — Pannonian volcanic complexes from the central-southeastern part of the Gutâi Mts; **5** — Pannonian volcanic complexes from the northern part of the Gutâi Mts; **6** — K-Ar ages of the lava flows; **7** — K-Ar ages of the intrusive rocks (Symbols as in Fig. 8); **8** — K-Ar ages of adularia and illite from hydrothermal mineralizations; **9** — Ar-Ar ages of adularia; **10** — Neogene volcanic rocks from the Gutâi Mts; **11** — Hydrothermal veins. **IN** — Ilba-Nistru base metal metallogenetic field, **SD** — Săsar-Dealul Crucii gold-silver metallogenetic field, **HB** — Herja-Băiuţ base metal + gold metallogenetic field (Herja, Baia Sprie, Şuior, Cavnic, Băiuţ ore deposits).

time interval for K-Ar ages for the intrusive rocks, an 11.6–10.7 Ma time interval for the K-Ar ages of adularia and illite (Lang et al. 1994; Kovacs et al. 1997b) and 10.6 Ma for the Ar-Ar age of adularia (Lang et al. 1994).

The comparative K-Ar and Ar-Ar ages of the intrusions, lava flows and hydrothermal mineralizations from the Gutâi Mts are exhibited in Figure 12. The age distribution of intrusions and volcanic complexes demonstrates that the intrusive magmatism started at the end of the Sarmatian in connection with and subsequently following the intermediate volcanism. The ages of the intrusions associated with the Sarmatian volcanic complexes are younger than the age of the lavas. Regarding the intrusions assigned to the Pannonian volcanic rocks, their age relationship cannot always be constrained. As a consequence, the apparent age may not be truly representative for the age of the emplacement of the intrusion. In this case, the presence of some excess Ar results in slightly older analytical ages than the real geological age.

The Firiza basalt intrusive complex does not show connections with any mineralizations. However, in each of the investigated ore deposits, the intrusions are older than the mineralizations. There is a gap of 0.5–1.5 Myr between the intrusive and the hydrothermal events, reflected mostly by the Ar-Ar ages of the adularia separated from veins.

The comparison of the K-Ar ages of the intrusive magmatism from the Romanian Eastern Carpathians is displayed in Figure 13. The time intervals constrained for the emplacement of the intrusions in the OG vs. Poiana Botizei and Ţibleş of the "Subvolcanic Zone" are similar except for the Firiza basalt intrusive complex from the Gutâi Mts. During the time interval 9.2–8.1 Ma, when the intrusive activity of OG was interrupted, in the Rodna-Bârgău area, the intrusive magmatic activity just started.

The new radiometric data emphasize a younger intrusive magmatic activity for the OG compared to other volcanic zones in the Carpathian-Pannonian Region. With respect to the timing of the intrusive magmatism from the Eastern Moravia and Pieniny Zones, this overlaps partially with the timing of the intrusive magmatism from the OG (Fig. 14).

The spatial distribution of the intrusions in the Gutâi Mts suggests the emplacement control exerted by the major transcrustal Bogdan Vodă-Dragoş Vodă fault, as well as the tectonic alignments followed by most of the hydrothermal veins. The inception of the intrusive phases can be related to the change of the regional tectonic regime from transpressional to transtensional at ca. 12 Ma, as it was stated in the case of the "Subvolcanic Zone" of the Eastern Carpathians (Pécskay et al. 2009). The intrusive magmatism ended around 9 Myr ago, except for the mafic phase of the Gutâi Mts (Firiza basalt intrusive complex) which terminated around 7 Myr.

In the Oaş Mts the intrusive magmatism developed exclusively in the Pannonian, whereas in the Gutâi Mts the intrusive magmatism started in the Late Sarmatian, post-dated the Sarmatian volcanism and ended in the Pannonian. In the Gutâi Mts the intrusive magmatism developed simultaneously with the intermediate volcanism during the Pannonian and, similar to the volcanism, migrated from the South towards the East and North of the Gutâi Mts. The time and space distribution confirms the connection between the intermediate volcanism and the intrusive magmatism which developed contemporaneously with the paroxysm of the OG volcanism.

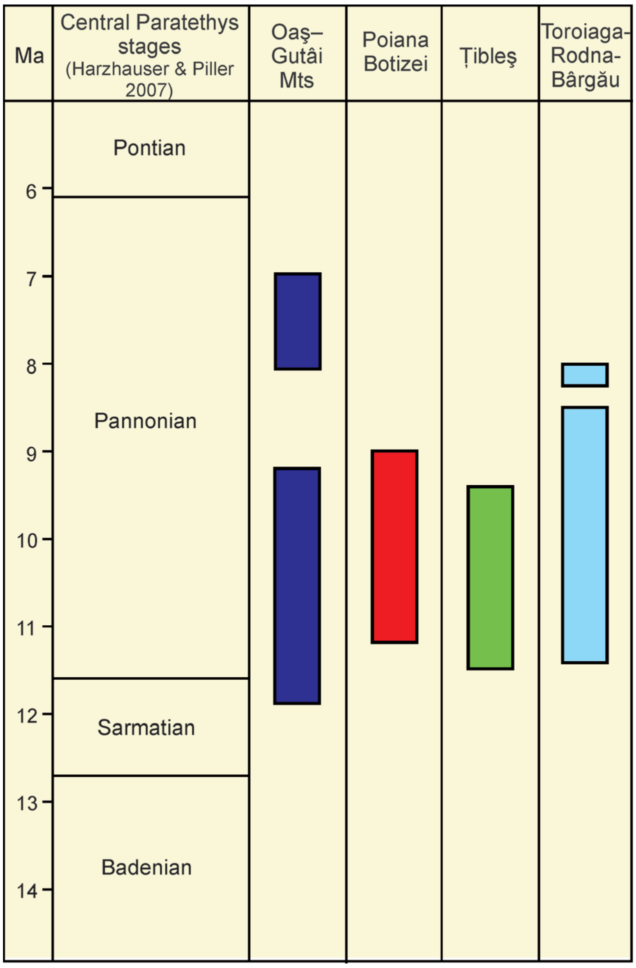


**Fig. 13.** Comparative radiometric data on the intrusive rocks of the Oaş–Gutâi Mts and of the "Subvolcanic Zone" (Poiana Botizei–Ţibleş–Toroiaga–Rodna-Bârgău — PBTTRB) of the Eastern Carpathians.

## Conclusions

The K-Ar determinations performed on the intrusive rocks from the Oaş–Gutâi Mts improve the geochronological database with respect to the evolution of the Neogene volcanism and the associated metallogenetic activity. The radiometric data confirm that the intrusive magmatism was strictly connected with the intermediate calc-alkaline volcanism.

On the basis of the K-Ar data, the stratigraphic position of the dated intrusive rocks is placed in the time interval between the Late Sarmatian and Middle Pannonian (11.9–7.0 Ma). Two distinct phases of intrusive magmatism can be distinguished: a first phase (11.9–9.2 Ma) which post-dated the Sarmatian volcanism and overlapped the paroxysm of the OG volcanism and a second phase (8.1–7.0 Ma) restricted to the Firiza basalts from the Gutâi Mts which are the youngest magmatic rocks from the OG.

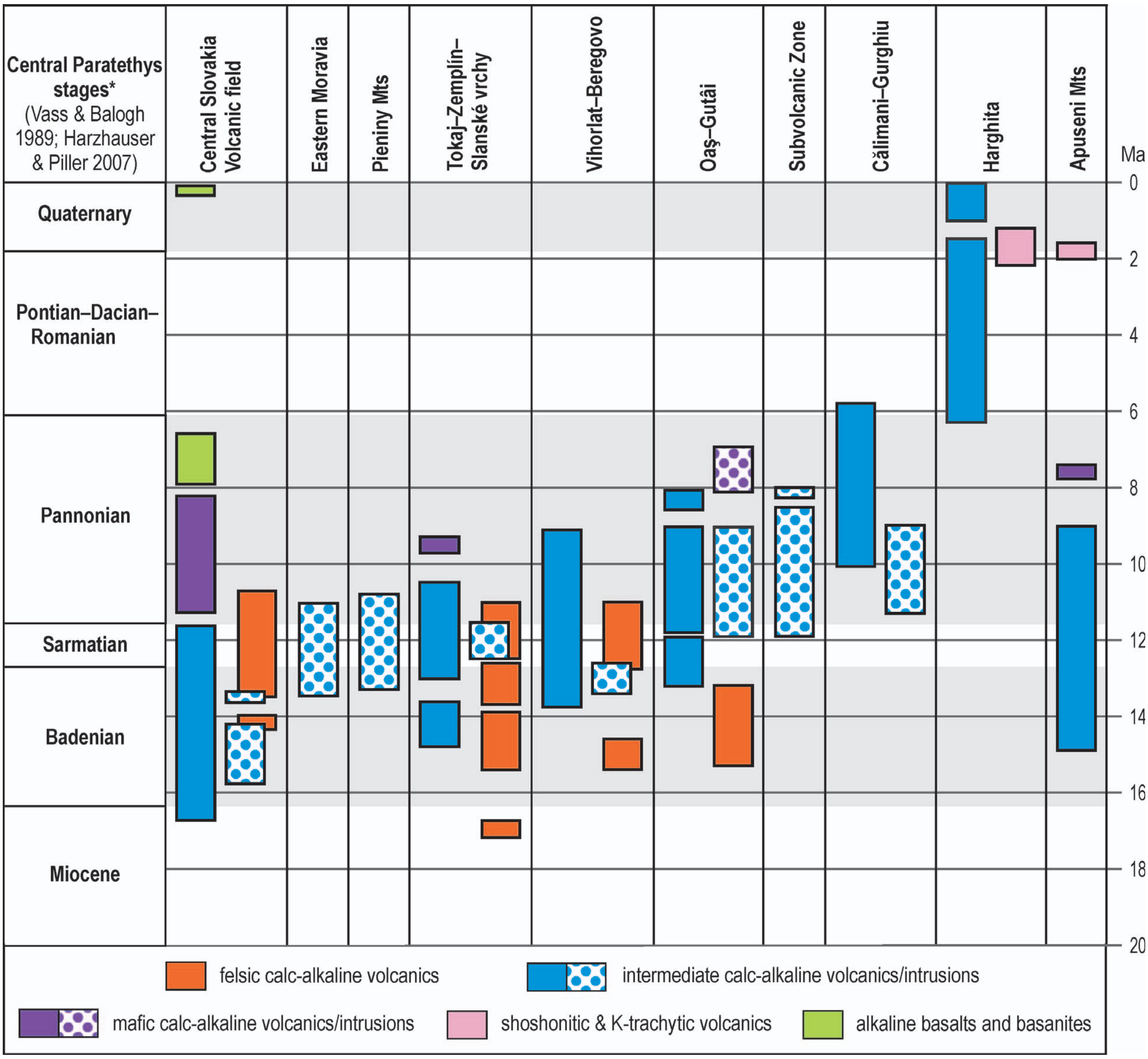


**Fig. 14.** Timing of the extrusive and intrusive magmatism in the main volcanic zones of the Carpathian-Pannonian Region. Except for the intrusions of OG, the radiometric data are from Pécskay et al. (2006, 2009). * The column with the Central Paratethys stages represent a combination of the chronostratigraphic scales of Vass & Balogh (1989) and Harzhauser & Piller (2007). The Quaternary boundary is from Vass & Balogh (1989).

The timing of the OG intrusive magmatism overlaps with the timing of the intrusive magmatism in the "Subvolcanic Zone" of the Eastern Carpathian volcanic arc and partially overlaps with the intrusive magmatism of the Eastern Moravia and Pieniny Mts, except for the late intrusive phase of the Firiza basalts.

The intrusions are older than the epithermal mineralizations of all the ore deposits from the OG, as well as other areas of the Carpathian-Pannonian Region (Pécskay & Molnár 2002; Birkenmajer et al. 2004). There is a gap of 0.5–1.5 Myr between the emplacement of the intrusions and the hydrothermal events.

The distribution of most of the intrusions in the southern part of Gutâi volcanic area, along the transcrustal Bogdan Vodă–Dragoş Vodă fault system (BDFS), suggests that this major tectonic system exerted structural control on the emplacement of the intrusions. The onset of the intrusive magmatism in the OG was probably constrained by the change of the regional tectonic regime from transpressional to transtensional along the major BDFS, around 12 Ma, as in the case of the intrusive magmatism from the "Subvolcanic Zone" of the Eastern Carpathians, as suggested by Pécskay et al. (2009).

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