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THE EVOLUTION OF THE NEOGENE VOLCANISM IN THE APUSENI MOUNTAINS (RUMANIA): CONSTRAINTS FROM NEW K-Ar DATA

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Abstract: New K-Ar data from the Apuseni Mountains Neogene volcanic area are presented. When combined with geological and magnetic polarity data, the new data clarify the duration and evolution of this volcanic area. They show that the Neogene volcanic activity took place during the Late Badenian–Pannonian (15–7 Ma). The beginning of calc-alkaline andesitic volcanism (around 15–13 Ma) had an explosive character giving a widespread volcano-sedimentary formation. The volcanic activity reached the paroxysm during the Sarmatian (13.5–11 Ma), when thick lava flows and large volcanic structures were emplaced. This activity decreased in the Pannonian (10–7 Ma) and was restricted to the central and northeastern parts of the studied area. In the central part, the volcanic activity stopped in the Early Pannonian (10 Ma), while in the northeastern part it lasted until the Late Pannonian (7 Ma). The volcanic products are covered by pure sedimentary formations in only a few parts of the area. During all this time, tectonic activity played an important role in the basin's development and volcanic processes.

Key words: Rumania, Apuseni Mountains, Neogene, andesite, K-Ar data, paleomagnetism.

Introduction

The Apuseni Mountains is an isolated massive inside the Carpathian arc (Fig. 1). They had a complex geological history and a different evolution with respect to the Eastern and Southern Carpathians at least before the Tertiary. The Tertiary evolution is characterized by the formation of small intramontane basins associated with important volcanic activity. For many years, the age of these volcanic products was established using geometric relationships, lithofacies correlation, or biostratigraphy of the associated sedimentary deposits. Significant contributions on these topics were made by: Ghiţulescu & Socolescu (1941), Cioflica et al. (1966, 1968), Berbeleac (1966), Antonescu & Mantea (1966), Borcoş & Mantea (1968), Sagatovici (1968), Sagatovici & Ionesi (1971), Sagatovici & Anastasiu (1972), Istocescu (1971) and Ianovici et al. (1969, 1976).

The first K-Ar data on Tertiary volcanic rocks from the Apuseni Mountains (Lemne et al. 1983) marked an important point for the further evolution of models of the magmatic activity (Borcoş et al. 1986, 1989), but some of that data are unacceptable due to the use of an incorrect isochron method. Recently, new good quality K-Ar data from the Apuseni Mountains and some regional correlation of the Neogene volcanic products were published (Roşu et al. 1995; Pécskay et al. 1995a, b). In this study, new uniformly distributed K-Ar ages together with geological background and paleomagnetic data from Neogene volcanic activity of the Apuseni Mountains are correlated and discussed with respect to the evolution of other areas from the Carpatho-Pannonian realm.

Geological settings

The Neogene-Quaternary volcanic activity in the Apuseni Mountains (Fig. 1) took place in three tectonic units: Internal Dacides (in Northern Apuseni Mountains), Transylvanides (in Southern Apuseni Mountains) and Median Dacides (in the southernmost part of the studied area).

The main tectonic structure of the actual Apuseni Mountains was established during the Laramic phase, after which a molasse formation of Maastrichtian–Paleocene age was deposited. It is composed of polymictic conglomerates, sandstones and red shales with alluvial origin, sometimes interbedded with andesites and rhyodacites. This formation was formerly considered of "Tortonian" age (Ghiţulescu & Socolescu 1941) and the volcanic rocks were attributed to the first cycle of the Neogene volcanism (Rădulescu & Borcoş 1967; Ianovici et al. 1976). Using K-Ar dating on andesites and rhyodacites (Lemne et al. 1983) and new geological data, the age was proved to be Maastrichtian-Paleocene (Borcoş et al. 1989). In the Hărţăgani area, the rhyolites — also thought to belong to the first cycle of Neogene volcanism, show a Lower Cretaceous age (124 Ma, Roşu & Ştefan, pers. commun.).

Between the Maastrichtian–Paleocene molasse deposits and the Miocene ones, there is an important sedimentation gap, due to the tectonic uplift of the whole area. During the Lower Miocene, the main tectonic feature was block faulting, associated with extensions and a strike-slip regime in the Carpatho-Pannonian realm. This regime has created small intramontane basins with temporally independent sedimentologic evolution. In connection with these basins and surrounding areas, a dis-

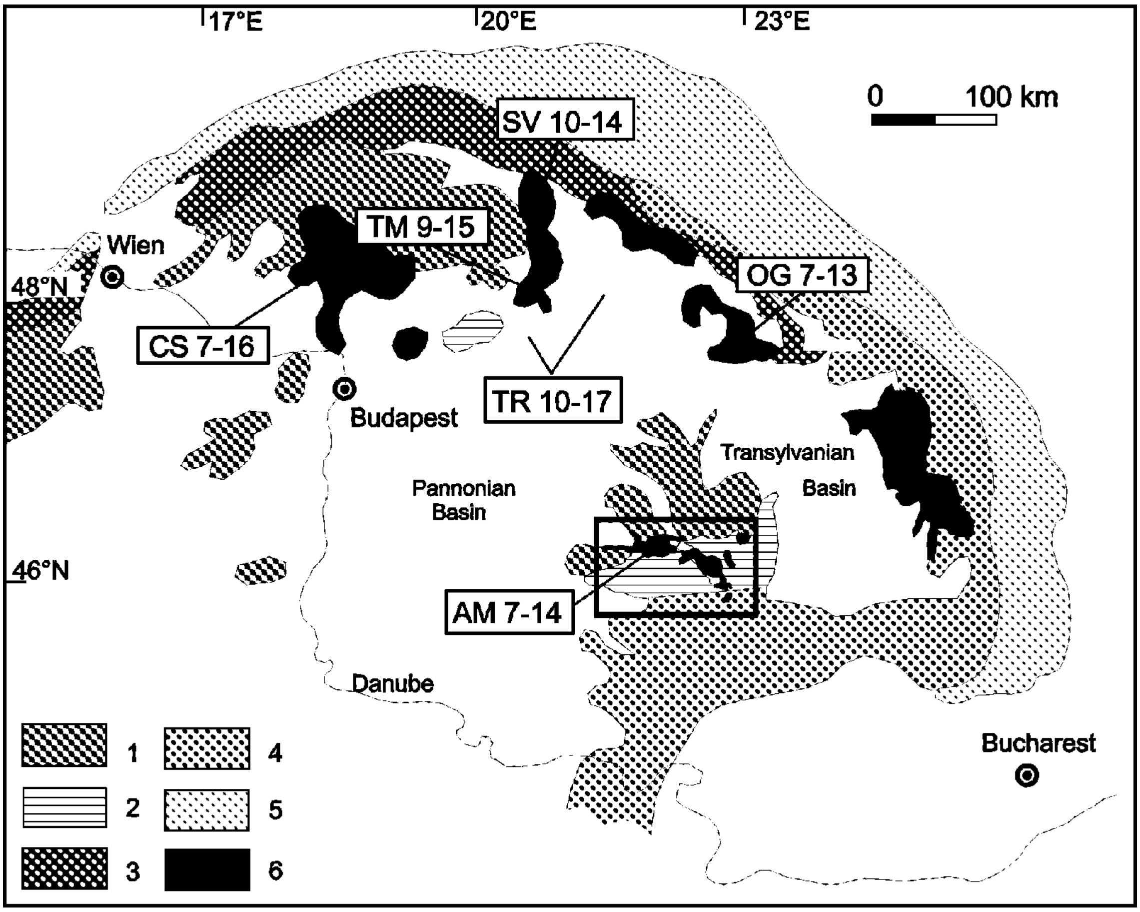

Fig. 1. Location of the Neogene volcanic area from the Apuseni Mountains (box) in the Carpatho-Pannonian region. Areas with coeval volcanic activity: **CS** — Central Slovakia; **TM**-Tokaj-Milic-Zemplin; **SV**—Slanske Vrchy; **TR**—Transtisza Region; **OG**—Oaş-Gutâi; **AM**—Apuseni Mountains. Age of volcanic activity (in Ma) after Pécskay et al. (1995a). Tectonic units (Săndulescu, 1984): **1**—Internal Dacides; **2**—Transylvanides; **3**—Măgura Units; **4**—undifferentiated Middle, Marginal and Outer Dacides; **5**—Moldavides; **6**—Neogene volcanics.

persed Neogene volcanic activity took place. For these reasons, we split the studied area in seven zones (Fig. 2): A (Zarand), B (Ţebea-Brad), C (Hărţăgani-Săcărâmb), D (Deva), E (Zlatna), F (Roşia Montană-Bucium), G (Baia de Arieş).

Sedimentary deposits

1. Lower Miocene sedimentary deposits now have a limited occurrence in the C zone, near the Hărţăgani locality. These deposits compose a finning upward siliciclastic unit (beginning with friable conglomerates and grading up to shales) which has a transgressive character. There is no direct biostratigraphic control in these deposits, but they are covered without a significant discontinuity by the Langhian marls.

2. Middle Miocene sedimentary deposits cover a larger area (A, B, C, E zones) and consist of pelagic marls with *Globigerina* (Early Langhian, Cioflica et al. 1966), bioclastic limestones, rhyodacitic tuffs (as ash fall deposition in a distal facies), gypsum layers, and finally thin bedded radiolarites (Early Kossovian, Borcoş et al. 1986).

3. A **volcano-sedimentary formation** of Kossovian - Early Volhynian age (Cioflica et al. 1968; or only Kossovian in the Zlatna area, Borcoş et al. 1986) occurs in A, B, C, E and F zones. In this interval due to an active tectonic block movement, each small basin had its own evolution. For example, in the C zone (Hărţăgani-Săcărâmb area) and partially in B and E zones, the volcano-sedimentary formation consists of silty shales, marls with *Spirialis* (showing a marine influence) and sandstones associated with pyroclastic rocks. The pyroclastic components are dominated by lithoclasts of quartz-hornblende-biotite andesites. In the F zone, the volcano-sedimentary formation was affected by explosive processes during the emplacement of the rhyodacites. A specific feature of the volcano-sedimentary formation appears in the zone A (Zarand Basin), where two different lake facies occur. In the eastern part, at the base of the Tălagiu volcanic edifice, pyroclastic rocks (amphibole-pyroxene andesites) with large vegetal fragments appear. In the western part (Miniş), the basal part of the sequence is dominated by pyroclasts of amphibole-pyroxene andesites mixed with bioclasts (Late Kossovian), while on the top diatomites are associated with

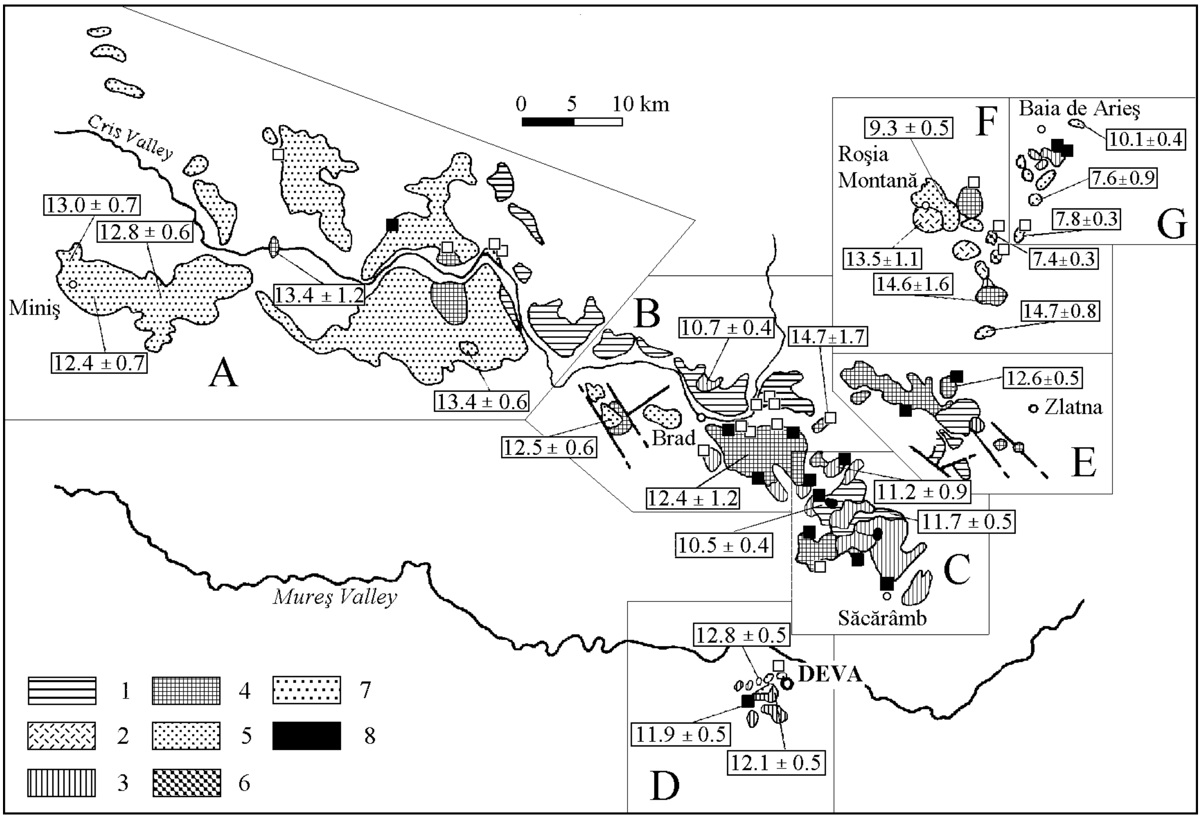

Fig. 2. Sketch map of Neogene volcanic rocks in the Apuseni Mountains and location of analyzed samples. K-Ar ages are in Ma. Paleomagnetic sites: solid squares—normal polarity; open squares—reversed polarity. Sampling areas: **A**—Zarand; **B**—Ţebea-Brad; **C**—Hărţăgani-Săcărâmb; **D**—Deva; **E**—Zlatna; **F**—Roşia Montană-Bucium; **G**—Baia de Arieş. Geological symbols: **1**—volcano-sedimentary formation; **2**—rhyodacites; **3**—quartz-amphibole-biotite-pyroxene andesites; **4**—amphibole andesites; **5**—amphibole (brown) andesites; **6**—basalts; **7**—pyroxene andesites; **8**—alkaline rocks.

pyroxene andesites prevailing pyroclastic rocks (Early Volhynian, Sagatovici & Anastasiu 1972).

Volcanic products

The volcanic products are mainly calc-alkaline andesites in composition and have different structures varying from lava flows, complex stratovolcanoes, and dykes, to intrusive bodies with a subvolcanic character. Often these products are intensely affected by hydrothermal alterations.

In the A zone, lava flows alternating with pyroclastic extrusions formed a stratovolcanic structure, composed of pyroxene andesites and amphibole-pyroxene andesites. In the B, C, D, E zones the volcanic products are dominated by small intrusive bodies. Lava and pyroclastic flows occur only locally. Their composition is mainly constituted by quartz-amphibole-biotite±pyroxene andesites or by amphibole-pyroxene andesites. In the C zone at Hărţăgani (Zâmbriţa Hill) and Săcărâmb (Pârâul lui Toader) two small bodies with more alkaline composition outcrop.

Volcanic products, in the Roşia Montană-Bucium area (F zone) are represented by intrusive bodies (sometimes with intrusive-explosive breccia) and some pyroclastic material with a wide range of compositions: rhyodacites dacites, quartz-amphibole-biotite andesites, amphibole-pyroxene andesites and basaltic andesites. The two small bodies from Detunata, consisting of basaltic andesite with long columnar feature, represent the last volcanic products in this area.

In the G zone, only intrusive bodies appear. They consist of quartz-amphibole-biotite andesites associated with mineralized intrusive breccia and amphibole-pyroxene andesites often with a megaporphyric texture.

Post-volcanic sediments

The main character of these formations is the absence of any pyroclastic material. They do not have a large areal extension, because even after the emplacement of the volcanic products, the block assemblage still functioned, leading to the formation of small asynchronous basins. In the Zarand Basin (A zone), the volcanics are covered first by epiclastic sediments (sands, marls) and bioclastic limestones of Late Volhynian age (Sagatovici 1968; Sagatovici & Ionesi 1971) and later, more extended (including also the B zone) by Pannonian-Pontian and Quaternary deposits. Around Deva town (D zone), the sediments have Volhynian–Late Bessarabian age (Lupu et al. 1982). In the eastern and northeastern part (E, F, G zones) there are no relations with younger sedimentary deposits.

Methods

Measurement of K-Ar ages was carried out in the Institute of Nuclear Research of the Hungarian Academy of Sciences Debrecen, Hungary. All the K-Ar ages were measured on whole rock samples because of the mineralogy and texture of the magmatic rocks. The samples were degassed in a conventional extraction system using induction heating and were measured by mass spectrometric isotope dilution with a ^{38}Ar spike. The recording and evolution of the Ar spectrum were controlled by microcomputer. Potassium analyses were made using standard flame photometric techniques. The K and Ar determinations were checked regularly against interlaboratory standards. Atomic constants suggested by Steiger & Jäger (1977) were used for calculating the age. All analytical errors represent one standard deviation. Details of the instruments, the applied methods and results of the calibration have been described elsewhere (Balogh 1985). For stratigraphic classification, we use the internationally accepted time scale compiled for Central Paratethys by Vass & Balogh (1989).

Results and discussions

The sample locations are presented in Fig. 2 and the results of the K-Ar age determination are given in Table 1. These ages are represented in Fig. 3 together with the geological constraint for the ages.

The starting point of the volcanic activity in the Apuseni Mountains is around Early Kossovian, and the products are mainly volcano-sedimentary deposits. From the K-Ar ages, these deposits are synchronous with the emplacement of some intrusive bodies in the B and F zones: at Curechi (B zone) 14.7±1.7 Ma and at Bucium (F zone): 14.6±1.6 Ma, 14.7±0.8 Ma. Unfortunately, these bodies have no relationship with the volcano-sedimentary formation. The confidence limit of the K-Ar data for these rocks is so large (1.6–1.7 Ma) mainly because the rocks are propilitized. In other areas there are volcanic bodies direct related to the volcano-sedimentary formation and their K-Ar ages agree with the biostratigraphic data. For example in the F zone, the volcano-sedimentary formation is pierced by the Brazi dacitic body (13.5±1.1 Ma) and in the central part (B, C, E zones) is pierced or covered by the quartz-amphibole-biotite±pyroxene andesites of: 13.6±0.9 Ma at Săcărâmb, 12.9±0.5 Ma at Brad (Lemne at al. 1983).

After deposition of the volcano-sedimentary formation in A, B, E and F zones, the amphibole andesites or amphibole-pyroxene andesites volcanic activity followed. Their K-Ar ages are in agreement with biostratigraphic markers: Volhynian in Zarand area (13.4±1.2 Ma), Middle Sarmatian in Brad area (12.4±1.2 Ma) and in Zlatna area (12.6±0.5 Ma).

Around Deva (D zone) the amphibole-biotite andesites (11.9±0.5 Ma) are intruded by microdiorites (12.1±0.5 Ma) having the same composition. The two data overlap with each other, suggesting the short time span between the two volcanic events. These data agree with the age of the post-volcanic sedimentary cover (Volhynian–Early Bessarabian, Lupu et al. 1982). In the same area, some subvolcanic bodies consisting of amphibole andesites with megaporphyric texture have a K-Ar age of 12.8±0.5 Ma.

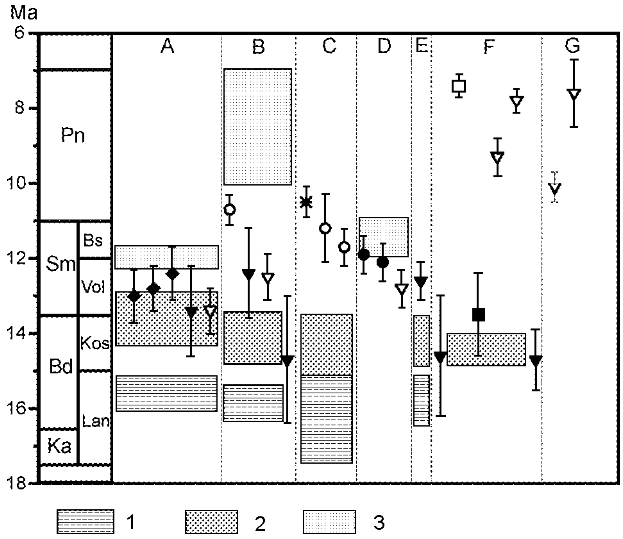

Fig. 3. Distribution of K-Ar data in the Apuseni Mountains and their stratigraphic confinement. Geological constrains for the age of the volcanism: **1**—pre-volcanic sedimentary deposits; **2**—volcano-sedimentary formation; **3**—post-volcanic sedimentary deposits. Petrotypes: solid diamond—pyroxene andesites; solid inverse triangle—amphibole-pyroxene andesites; open inverse triangle—amphibole(brown)-pyroxene andesites; open circle—quartz-amphibole-biotite-pyroxene andesite; solid circle—amphibole-biotite andesite; star—trachyandesites; solid square—dacites; open square—basaltic andesites. Period: Ka—Karpatian; Bd—Badenian; Sm—Sarmatian; Pn—Pannonian; Lan—Langhian; Kos—Kossovian; Vol—Volhynian; Bs—Bessarabian.

K-Ar data from B and C zones, taken from quartz-amphibole-biotite±pyroxene andesites ("Cetraş type") show a Late Sarmatian–Early Pannonian age: 11.7±0.5 Ma, 11.2±0.9 Ma and 10.7±0.4 Ma.

The last volcanic products are asynchronously distributed in the whole studied area and they are represented by different petrotypes. In the Zarand area (A zone), the last products are pyroxene andesites: 13.0±0.7 Ma; 12.8±0.6 Ma; 12.4±0.7 Ma and they are covered by Upper Volhynian sediments. In the B zone, the pyroclastic deposits with clasts of quartz-amphibole-biotite±pyroxene andesites are the final phases of volcanic activity here (10.7±0.4 Ma). In Hărţăgani–Săcărâmb area (C zone) the volcanic activity stopped in the Early Pannonian with trachy-andesites (Zâmbriţa Hill 10.5±0.4 Ma). In F and G zones, the last phase of volcanic activity is dominated by amphibole-pyroxene andesites (with brown hornblende). Their K-Ar ages group around two intervals: 9–10 Ma and 7–8 Ma. This type of andesite with brown hornblende was used for a long time as a marker to identify the final stage of the volcanic activity in the Metaliferi Mountains (Rădulescu & Borcoş 1967; Ianovici et al. 1969, 1976). Our K-Ar ages show that this is no longer true since the same type of andesite also occurred in the first stages of the volcanic activity: 13.4±0.6 Ma in Zarand area, 12.5±0.6 Ma in Ţebea–Brad area. In F zone, a short time after these andesites, the volcanic activity stopped with the basaltic andesites from Detunata (7.4±0.3 Ma).

Table 1: K–Ar datings of Neogene calc-alkaline volcanic rocks in the Apuseni Mountains.

No	Sample	Locality	Rock type	K(%)	$^{40}Ar_{rad}$ (%)	$^{40}Ar_{rad}$(ccSTP/g)	K-Ar age(Ma)
A. Zarand							
1*	2688	Dieci	α px am	1.01	16.2	5.293×10^{-7}	13.4±1.2
2*	2686	Talagiu	α px am (br)	1.27	48.6	6.623×10^{-7}	13.4±0.6
3*	2685	Camna	α px	1.22	33.7	6.195×10^{-7}	13.0±0.7
4*	2687	Chişindia	α px	1.18	43.3	5.897×10^{-7}	12.8±0.6
5*	2684	Miniş	α px	1.27	28.3	6.144×10^{-7}	12.4±0.7
B. Ţebea-Brad							
6*	3352	Curechi	α am px	1.18	12.2	6.757×10^{-7}	14.7±1.7
7*	2683	Barza	α am px	1.44	14.4	6.977×10^{-7}	12.4±1.2
8*	3356	Caraciu	α am(br) px	0.97	34.7	4.714×10^{-7}	12.5±0.6
9*	2682	Brad	α q am bi ± px	1.22	54.4	5.096×10^{-7}	10.7±0.4
C. Hărţăgani -Săcărâmb							
10	3357	Duba	α q am bi ± px	1.19	18.9	5.210×10^{-7}	11.2±0.9
11	3501	Cetraş	α q am bi ± px	1.05	51.5	4.793×10^{-7}	11.7±0.5
12*	3350	Zâmbriţa	trachyandesite	2.46	61.7	1.011×10^{-7}	10.5±0.4
D. Deva							
13	3524	Nucet	α am ± bi	1.40	71.0	6.482×10^{-7}	11.9±0.5
14	3525	Pârâul Băilor	md am ± bi	1.68	61.8	7.921×10^{-7}	12.1±0.5
15	3526	Serhediu	α am (gr+ br)	1.14	56.9	5.671×10^{-7}	12.8±0.5
E. Zlatna							
16	3527	Trâmpoiele	md am px	1.75	64.7	8.621×10^{-7}	12.6±0.5
F. Roşia Montană-Bucium							
17*	3351	Tăul din Brazi	ν	1.25	17.5	6.583×10^{-7}	13.5±1.1
18*	2689	Citera	α am px	1.21	12.8	6.916×10^{-7}	14.6±1.6
20	3530	Bucium S	md am px	0.94	33.3	5.401×10^{-7}	14.7±0.8
21*	3355	Rotunda	α am(br) px	1.41	33.7	5.095×10^{-7}	9.3±0.5
22	3502	Geamăna W	α am(br) px	1.27	55.8	3.883×10^{-7}	7.8±0.3
23*	3349	Detunata	α β	1.30	37.3	3.602×10^{-7}	7.4±0.3
G. Baia de Arieş							
24	3528	Bulzu	α am br px	1.51	50.2	5.942×10^{-7}	10.1±0.4
25	3503	Surligata	α am br px	1.20	12.3	3.533×10^{-7}	7.6±0.9

Abbreviations: α = andesites; αβ = basaltic andesites; ν = dacites; md = microdiorites; q = quartz; am = amphibole (gr = green; br = brown); bi = biotite; px = pyroxene
*Data from Pécskay et al. (1995b)

Correlation of magnetic polarity data and K-Ar ages

The distribution of the localities sampled for paleomagnetic studies and their magnetic polarity is presented in Fig. 2. The paleomagnetic data are from Pătraşcu et al. (1994), Panaiotu et al. (1995). To correlate the observed magnetic polarities with the polarity time scale (Cande & Kent 1995) a histogram of K-Ar ages was computed using the method of Vandamme et al. (1991) (Fig. 4). Each datum is a given unit weight and represented by a Gaussian distribution with standard deviation equal to the age uncertainty. This flattens the large uncertainty data and emphasizes the most precise results. The histogram represents the sum of all individual Gaussian distributions. The shape of this histogram reveals three distinct phases of volcanic activity. In the same figure the histogram of K-Ar data from Oaş-Gutâi area (Pécskay et al. 1995b) is also represented. The shapes of these histograms show that the time of the main volcanic activity is different even the volcanism covers the same period: Sarmatian–Pannonian. This distribution of K-Ar data is also reflected in the distribution of magnetic polarity data.

Reinterpreting the paleomagnetic data from Oaş–Gutâi area (Pătraşcu 1993), according to the new K-Ar data (Pécskay et al. 1995b), is obvious that the strong bias toward normal polarity for the Pannonian sites correlates with the peak of the volcanic activity around 10.5 Ma. On the polarity time scale this peak corresponds to the chron C5n (9.7–10.9 Ma) with normal polarity, which is long enough to explain the strong bias towards normal polarity. Sites with reversed polarity were found only in the areas with ages around 12–13 Ma or around 9 Ma, in agreement with the polarity time scale. In the Apuseni Mountains the distribution of magnetic polarity data is different. From 29 localities sampled in Lower Sarmatian–Lower Pannonian rocks, 15 localities have normal polarity and 14 localities have reversed polarity

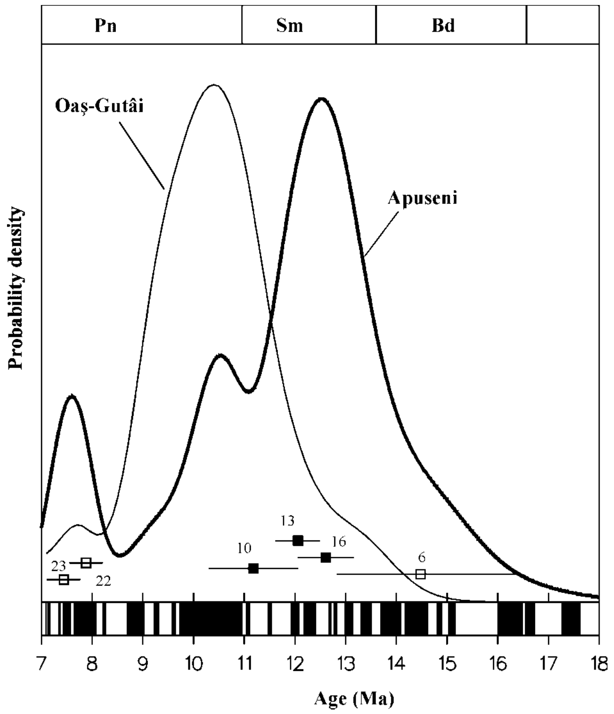

Fig. 4. Histograms of K-Ar data from the Apuseni Mountains (heavy line) and Oaş-Gutâi Mountains. Numbering of paleomagnetic sites according to Table 1: solid square—normal polarity; open square—reversed polarity. Polarity time scale: black—normal polarity; white—reversed polarity.

(Pătraşcu et al. 1994; Panaiotu et al. 1995). This distribution of polarity data agrees with the main peak of volcanic activity during the Sarmatian when there was a relatively high frequency of reversals. The four K-Ar ages from the sites sampled for paleomagnetism have too large uncertainties to assign each site to a certain subchron on the polarity time scale. Since the sequence of the volcanic activity in the area sampled for paleomagnetism cannot be always perfectly known, it is not possible to establish how many reversals are present in this area.

The last peak on the histogram corresponds to Late Pannonian. The two sites sampled for both K-Ar data and paleomagnetism (Detunata and Geamăna W) have a reversed polarity. Since the interval of the volcanic activity suggested by the K-Ar data is dominated by normal polarities, the most probable interpretation is that the volcanic activity took place during the chron C3Br (7.1–7.4 Ma) or subchron C4n.1r (7.5–7.6 Ma).

Conclusions

The present K-Ar data and biostratigraphic data show that the Neogene volcanic activity in the Apuseni Mountains took place between Kossovian–Pannonian. The beginning of calc-alkaline andesitic volcanic activity had an explosive character. The biostratigraphic age of the volcano-sedimentary formation range from Early Kossovian–Early Sarmatian in the central part and Late Kossovian–Early Sarmatian in the Zarand area. The volcanic activity reached its paroxysm during Early–Middle Sarmatian. The evolution was relative short in the Zarand and Deva areas where the volcanism stopped in the Late Sarmatian. During the Pannonian the volcanic activity decreased and was restricted to some small areas from the central and northeastern parts of the studied area. In the central part (Ţebea–Brad and Hărţăgani–Săcărâmb areas) the volcanic activity stopped in the Early Pannonian, while in the northeastern part (Roşia Montană–Bucium and Baia de Arieş areas) it lasted until the Late Pannonian.

The andesitic volcanism from the Apuseni Mountains is coeval with the volcanic activity from the Western Carpathians: Central Slovakia and Tokaj–Milic–Zemplin areas and from the Eastern Carpathians: Oaş–Gutâi area (Pécskay et al. 1995b). Both K-Ar data and polarity magnetic data show that the main phase of volcanic activity took place during the Sarmatian in the Apuseni Mountains and the Early Pannonian in the Oaş–Gutâi area.

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