PALEOMAGNETISM OF THE MIOCENE VOLCANISM OF THE OAȘ – GUTÂI MOUNTAINS REVISITED (EASTERN CARPATHIANS, ROMANIA)

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Abstract. In this paper, we reanalyzed the previous paleomagnetic data from the Miocene magmatic rocks from the Oaș and Gutâi Mountains. The paleomagnetic sites were assigned to the correct ages according to the latest model of evolution of the Miocene volcanism in the Oaș and Gutâi Mountains. These new ages of the paleomagnetic sites indicate a good correlation of the stages of magmatic activity in the OGVZ with the Geomagnetic Polarity Time Scale. This correlation confirms that the paroxysm of the volcanic activity is reached during stage two of volcanic activity when the volcanism migrated toward north-east and reached the maximum spatial extension in around 1.3 Ma during Chron C5n (11.0–9.7 Ma). Based on the new age intervals assigned to the paleomagnetic data, we computed a Badenian-Sarmatian paleomagnetic pole for the Gutâi Mountains (13.5–12 Ma) and a Pannonian paleomagnetic pole for the Oaș and Gutâi Mountains (11.7–9 Ma). We reconfirmed the counterclockwise vertical-axis rotation with respect to stable Eurasia of the southern Gutâi Mountains, but with a lower amplitude (-18.4° ± 14.5°). This fast vertical-axis rotation (around 1 Ma) is contemporaneous with the final stage of the clockwise rotation of the Apuseni Mountains and the Transylvanian Basin and the last tectonic movements along the Bogdan Vodă – Dragoș Vodă fault system.

Keywords: paleomagnetism, tectonic displacements, Miocene, Oaș–Gutâi Mountains, Eastern Carpathians.

Résumé. Dans cet article, nous avons réanalysé les données paléomagnétiques antérieures des roches magmatiques du Miocène des monts Oaș et Gutâi. Les sites paléomagnétiques ont été assignés aux âges corrects selon le dernier modèle d'évolution du volcanisme du Miocène dans les monts Oaș et Gutâi. Ces nouveaux âges des sites paléomagnétiques montrent une bonne corrélation des stades d'activité magmatique dans l'OGVZ avec l'échelle de temps de polarité géomagnétique. Cette corrélation confirme que le paroxysme de l'activité volcanique est atteint pendant la deuxième étape de l'activité volcanique lorsque le volcanisme a migré vers le nord-est et a atteint l'extension spatiale maximale vers 1.3 Ma pendant Chron C5n. Sur la base des nouveaux intervalles d'âge attribués aux données paléomagnétiques, nous avons calculé un pôle paléomagnétique badenien-sarmate pour les monts Gutâi (13,5–12 Ma) et un pôle paléomagnétique pannonien pour les monts Oaș et Gutâi (11,7–9 Ma). Nous avons reconfirmé la rotation antihoraire de l'axe vertical par rapport à l'Eurasie stable des monts Gutâi du sud, mais avec une amplitude plus faible (-18,4° ± 14,5°). Cette rotation rapide de l'axe vertical (autour de 1 Ma) est contemporaine de l'étape finale de la rotation horaire des monts Apuseni et du bassin de Transylvanie et des derniers mouvements tectoniques le long du système de failles Bogdan Vodă – Dragoș Vodă.

Mots-clés: paléomagnétisme, déplacements tectoniques, Miocène, Monts Oaș – Gutâi, Carpates orientales.

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1. INTRODUCTION

The Oaş – Gutâi Volcanic Zone (OGVZ) in the Eastern Carpathians records one of the complex and long-lasting periods of Miocene volcanic activity (Kovacs *et al*., 2017) in the Carpathian–Pannonian region (Fig. 1). Paleomagnetism of the Miocene volcanic complex of the Oaş and Gutâi Mountains was studied by Pătraşcu (1993). Even if the paleomagnetic methods and results obtained in this study are still valid, some arguments justify a reevaluation of the interpretation of these results. First of all, since the publication of this study, the model of the temporal evolution of the Miocene volcanism in the Oaş and Gutâi Mountains has evolved and been refined (Kovacs *et al*., 2013; Kovacs *et al*., 2017) in relation to the model used by Pătraşcu (1993). In his work, Pătraşcu (1993) used a time model that involved the development of volcanism between the Sarmatian and the Pontian, while the recent ages showed that it ended in the Pannonian. Second, the statistical criteria for the analysis of the paleomagnetic data have progressed and for this reason a reevaluation of the paleomagnetic data is required. Thirdly, both the methods of evaluating tectonic displacements based on paleomagnetic data and the reference paleomagnetic data have also advanced significantly since the 1993 analysis.

In this paper, we will assign the paleomagnetic sites of Pătraşcu (1993) to the correct ages according to the new model of evolution of the Miocene volcanism in the Oaş and Gutâi Mountains. Based on these new ages attributed to the paleomagnetic sites, we will statistically reanalyze all the paleomagnetic data and recalculate the amplitude of the tectonic movements with respect to the Eurasia plate, the Transylvanian Basin and the Apuseni Mountains.

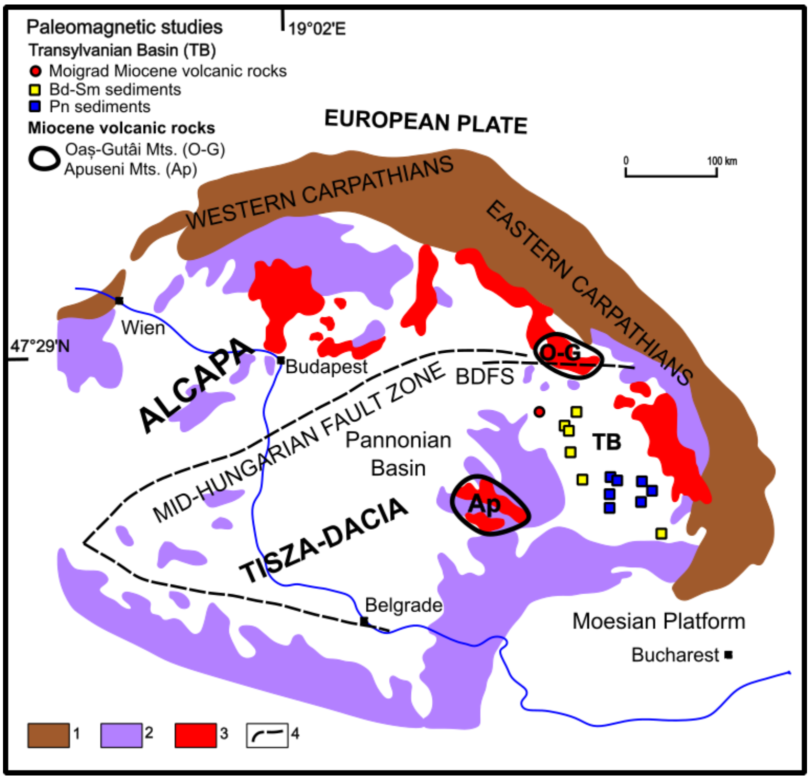

Fig. 1. Location of the paleomagnetic studies discussed in the text on the geotectonic sketch map of the Carpathian-Pannonian Region (modified after Kovacs *et al*., 2013). References for the paleomagnetic studies: Pătraşcu, 1993 (Oaş – Gutâi Mts., Miocene volcanic rocks), Panaiotu, 1999 (Moigrad, Miocene volcanic rocks; Transylvanian Basin, Badenian – Sarmatian sediments), de Leeuw *et al*., 2013 (Transylvanian Basin, Badenian – Sarmatian and Pannonian sediments), Ene *et al*., 2024 (Apuseni Mts., Miocene volcanic rocks). Symbols: 1. Carpathian flysch; 2. Internal units belonging to the Alpine orogeny; 3. Neogene volcanic rocks; 4. Main faults (BDFS = Bogdan Vodă – Dragoş Vodă fault system). For the color version of this figure, the reader is referred to the web version of this article.

2. SPATIAL–TEMPORAL EVOLUTION OF THE OAȘ – GUTÂI VOLCANIC ZONE

According to Kovacs *et al*. (2017), the intermediate/andesitic volcanism in the OGVZ took place between 13.4 – 7 Ma and generated volcanic structures comprising composite volcanoes, extrusive domes and intrusions. This volcanism developed in four stages. The spatial extension of the four stages and their associated volcanic areas are presented in Fig. 2.

The first volcanic stage in the Gutâi Mountains, named G1, took place in the southern part of the mountain between 13.4 and 12.1 Ma. In the Oaș Mountains, this first stage corresponds to a tuff dated at 12.0 Ma. The second stage includes several volcanic complexes in the Gutâi Mountains. It has a total of nine volcanic complexes: G2 (11.6 Ma), G3 (11.8–10.5 Ma); G4 (10.9–10.1 Ma), G5 (11.4–9.5 Ma), G6 (10.3–9.9 Ma), G7 (9.8–9.0 Ma), G8 (9.7–9.3 Ma), G9 (9.3 Ma) and G10 (9.3–9.0 Ma). In the Oaș Mountains, the second stage comprises the following structures: O2 (11.8 Ma), O3 (11.3–11.0 Ma), O4 (10.9–10.5 Ma) and O5 (10.5–9.5 Ma). The volcanism reached its peak during the second stage (11.6–9 Ma) both in the Gutâi and Oaș Mountains when basaltic andesites, andesites and dacites were generated. The end of the volcanic activity is represented by several small volcanic structures representing stage three (G11, 8.5–8.0 Ma) and stage four (G12, 8.1–7.0 Ma).

All these volcanic structures are accompanied by numerous intrusions related to the intermediate volcanism developed across the OGVZ (Kovacs *et al*., 2013). The intrusion has many morphologies and a wide range of sizes from meters to kilometers. The time interval for this intrusive magmatism is between 11.9-9.0 Ma (Kovacs *et al*., 2013).

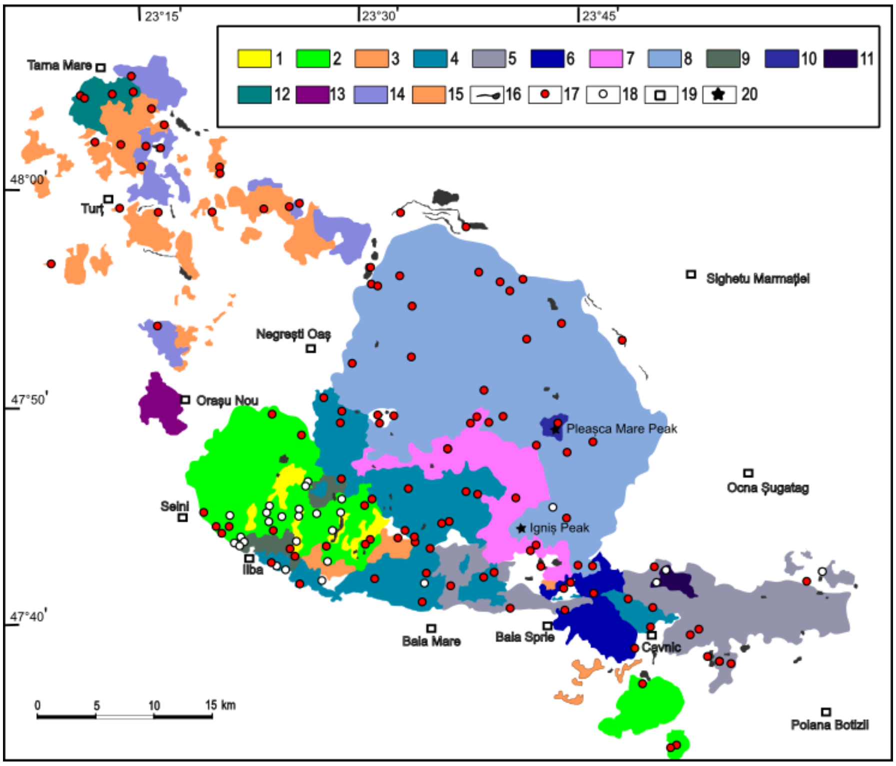

Fig. 2. Position of the paleomagnetic sites (Pătrașcu, 1993) on the geological map of the Oaș – Gutâi Volcanic Zone (simplified after Kovacs *et al*., 2017). Symbols: Felsic/rhyolitic volcanic rocks in Oaș and Gutâi Mts.(1); Intermediate/andesitic volcanic complexes: Gutâi Mts.: Stage one: G1 (2); Stage two: G2 (3), G3 (4), G4 (5), G5 (6), G6 (7), G7 (8), G8 (9), G9 (10), G10 (11); Oaș Mts: Stage two: O2 (12), O3 (13), O4 (14), O5 (15); Intrusions (16); Paleomagnetic sites with normal polarity (17); Paleomagnetic sites with reversed polarity (18); Towns (19); Mountain peaks (20). For the color version of this figure, the reader is referred to the web version of this article.

3. METHODS

In the first step of our analysis, a kmz file was created with the locations of the paleomagnetic sites using the original field notebooks. Since the sampling of the study of Pătrașcu (1993) was done during the late 70th, the geographic coordinates of the sites were obtained from topographic and geological map of the Oaș and Gutâi Mountains. In the second step, we georeferenced the map with the stages of magmatism in OGVZ (Kovacs *et al*. 2017) in Google Earth and superimposed the file with the paleomagnetic sites. Based on this analysis, we assigned each paleomagnetic site to a volcanic stage and structure.

In the third step, we sorted the site-mean paleomagnetic directions (Pătrașcu, 1993) using as a quality parameter the value of the precision parameter $k > 50$ (Johnson *et al*., 2008). Using this new data set of mean site directions, we computed the Virtual Geomagnetic Poles (VGPs) (e.g. Butler, 1992). These VGPs were further sorted eliminating the transitional directions recorded during the change of magnetic polarity. The identification of sites which can be categorized as transitional directions was based on association with low VGP latitudes (< 45°) (e.g. Johnson *et al*., 2008). These sorted data sets were analyzed from the point of view of stability using the reversal test (McFadden and McElhinny, 1990). After which the area means values were calculated using Fisher's statistic (1953). All the directional analysis was performed using the software package Palaeomag-Tools, Version 5.1a (Hounslow, 2006).

The final step in our analysis was to determine relative tectonic motions (vertical-axis rotations and paleolatitudinal displacements) of the Oaș – Gutâi area, Transylvanian Basin and the Apuseni Mountains with respect to the Eurasia plate. These tectonic movements can be determined because paleomagnetic data are a quantitative tool for approximating the paleoposition of tectonic units relative to the Earth's spin axis. To perform this task, we utilized the method of Vaes *et al*. (2023) using the online, open-source environment (APWP-online.org) that provides user-friendly tools to determine relative paleomagnetic displacements. We used the following calculation settings: Number of iterations: 2000; Time window: 10 Ma; Reference location: sampling location of each individual study.

4. RESULTS AND DISCUSSIONS

4.1. CORRELATION OF THE STAGES OF MAGMATIC ACTIVITY IN THE OGVZ WITH THE GEOMAGNETIC POLARITY TIME SCALE

The geographical distribution of the 127 paleomagnetic sites in the Gutâi and Oaș mountains is shown in Fig. 2. All paleomagnetic data for these 127 sites are available in the associated database in a xlsx file and their locations in a kmz file. We have included in the geographic area of the Gutâi Mountains the previous paleomagnetic sites from the Igniș and Văratec Mountains (Pătrașcu, 1993) excepting three sites which belong to the subvolcanic zone Poiana Botizei. The distribution of paleomagnetic sites for each volcanic complex and stage versus time are plotted in Fig. 3. In the Gutâi mountains, in the first stage G1 there are 22 paleomagnetic sites (10 sites with normal polarity and 12 sites with reversed polarity). This number is lower than the previous 35 paleomagnetic sites considered to have a Sarmatian age (Pătrașcu, 1993). Most of the sites are distributed in the volcanic complexes of the stage two both in the Gutâi Mountains and the Oaș Mountains. In the Gutâi Mountains in the volcanic complexes G2 to G11 (11.6–9.0 Ma) there are 56 sites with normal polarity and 13 sites with reversed polarity. The intrusions from this area were sampled in 31 sites (30 sites with normal polarity and 1 site with reversed polarity). In the Oaș Mountains the sixteen paleomagnetic sites are distributed in the volcanic complexes O2, O4 and O5 belonging to stage two. The rest of the paleomagnetic sites in the Oaş Mountains were sampled in intrusions (9 sites). All the sites in this area have normal polarity. The third stage (G11) was sampled only in one site which has a normal polarity. The fourth stage (G12) was not sampled for paleomagnetism.

According to the available K-Ar ages (Kovacs *et al*., 2013, 2017), all these volcanic complexes (consisting of extrusive and intrusive structures) from the second and third stages were emplaced during the Pannonian. The new Pannonian age attributed to all paleomagnetic sites sampled in these volcanic complexes is an important correction with respect to the age distribution from Pătraşcu (1993) in which 84 paleomagnetic sites from the OGVZ were considered to be Pontian.

Analyzing the paleomagnetic data represented in figures 2 and 3, a good agreement is observed between the observed magnetic polarities and the ages of the volcanic complexes. The volcanic complexes from the first stage G1 (13.4–12.1 Ma) erupted during the chrons C5AA and C5A (13.3–12.0 Ma) (Ogg, 2020) when 0.43% of their durations the polarity of the Earth magnetic field was normal and 0.56% was reversed. This time distribution of magnetic polarities during these chrons is reflected in the polarity of the paleomagnetic sites: 10 sites with normal polarity and 12 sites with reversed polarity. Most of the volcanic complexes from the second stage (G3, G4, G6, G7, O4 and O5) show a strong bias of the paleomagnetic sites toward the normal polarity (Fig. 2 and 3): 66 sites with normal polarity and only 7 sites with reversed polarity. The same important bias toward the normal polarity was measured in the contemporaneous intrusions with the stage two both in the Gutâi Mountains and Oaş Mountains (Fig. 3).

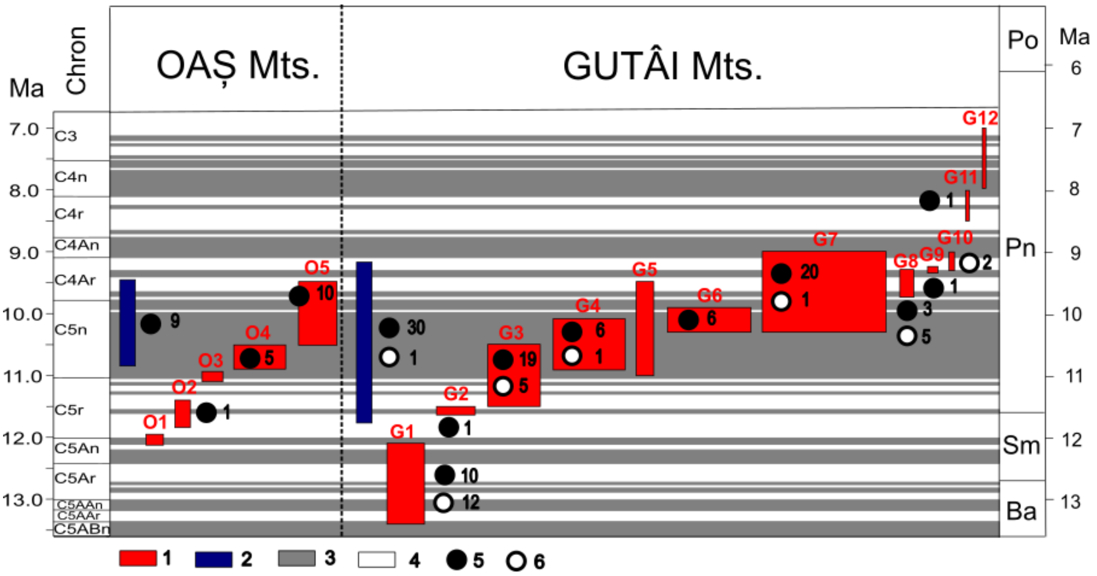

Fig. 3. Correlation between the stages of magmatic activity in the Oaş and Gutâi Mountains (Kovacs *et al*., 2013, Kovacs *et al*., 2017) and the Geomagnetic Polarity Time Scale (Ogg, 2020). Symbols: 1. Time distribution of volcanic complexes. The size of the red rectangles is proportional with the extent of each volcanic complex on Fig. 1 (Kovacs *et al*., 2017); 2. Intrusions; 3. Time interval with normal polarity; 4. Time interval with reversed polarity; 5. Number of paleomagnetic sites with normal polarity; 6. Number of paleomagnetic sites with reversed polarity. Stratigraphic ages: Ba-Badenian; Sm-Sarmatian; Pn-Pannonian; Po-Pontian. Chronostratigraphic scale from Harzhauser and Piller (2007). For the color version of this figure, the reader is referred to the web version of this article.

Taking into account the K-Ar ages, the geographical distribution of the magnetic polarities and the correlation with the Geomagnetic Polarity Time Scale (Fig. 2 and 3), we suggest the following scenario of evolution of the spatial and temporal of volcanic activity during stage two. The volcanism started in the southern part of the Gutâi Mountains during G2 and mainly G3 (e.g. the sites with reversed polarity erupted during Chron C5r). The paroxysm of the volcanic activity is reached during G3, G4, G5, G6, G7, O4, O5) when the volcanism migrated toward north-east and reached the maximum spatial extension. This period of intense volcanism corresponds to the Chron C5n (11.056-9.786 Ma) when the geomagnetic field was dominant with normal polarity around 1.3 Ma (Fig. 3). The end of the stage two is reflected in the reappearance of reversed polarity (Fig. 2 and 3) in agreement with younger K-Ar ages in those areas. From the spatial point of view this final part of the stage two is restricted to the several small areas in the central (Igniș Peak, G7) and in the southern part of the Gutâi Mountains (G8, G10).

4.2. DIRECTIONAL ANALYSIS

Based on the age intervals assigned to the paleomagnetic sites in 4.1, we split the site-mean directions (Pătrașcu, 1993) in two groups (Fig. 4). The first group corresponds to the paleomagnetic sites sampled in the magmatic rocks from the first stage (G1 in Fig. 2) from the southern part of the Gutâi Mountains. The age of this group is between 13.5 Ma and 12 Ma (the Badenian – Sarmatian group). The second group of directions is composed by sites sampled in the second and third stage of volcanism both in the Oaș and Gutâi Mountains. The age of this group is from 11.7 Ma to 9.0 Ma (the Pannonian group).

The directions from these two groups were transformed to equivalent VGPs. For the subsequent analysis we removed from these data the site-mean directions with precision parameter k less than 50 (Johnson *et al.*, 2008). This step eliminated one direction from the Sarmatian group and 15 sites from the Pannonian group. The precision parameters k of these disregarded directions range from 17 to 48. According to Gerritsen *et al.* (2022), the directions with k in this interval can be safely used to compute the paleomagnetic pole. Their conclusion is also evident from our data (Fig. 4) since the eliminated directions are similar to the remaining directions.

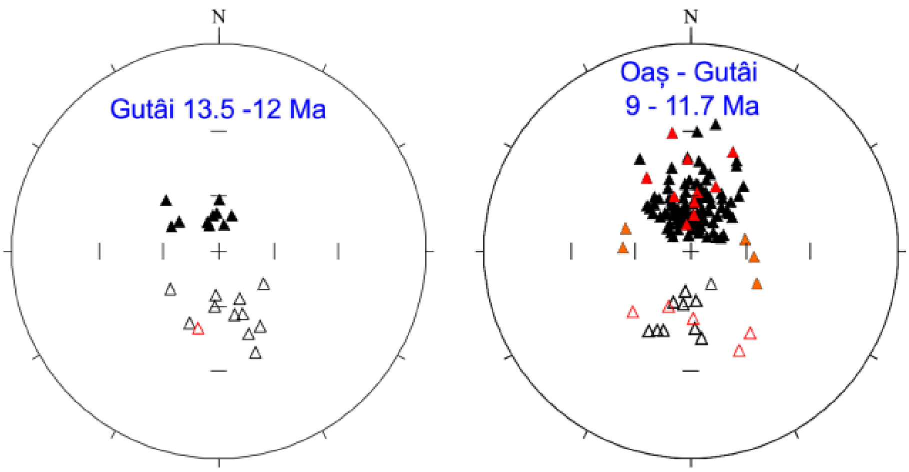

Fig. 4. Equal-area projections with site-mean directions from the Oaș and Gutâi Mountains magmatic rocks. Symbols: full = lower hemisphere; open = upper hemisphere; red symbols = sites with precision parameters k < 50; orange symbols = sites with VGP paleolatitude < 45°. For the color version of this figure, the reader is referred to the web version of this article.

Based on these two selected data sets, we computed the equivalent VGPs. These VGPs were further sorted removing the VGPs with latitude less than 45° N or S. Such VGPs are considered as transitional VGPs during a reversal or a geomagnetic excursion. They are usually disregarded from the computation of the paleomagnetic pole (e.g. Johnson *et al.*, 2008). This step removed 5 sites from the

Pannonian group. After this selection, the two VGPs set were tested and both are compatible with a Fisherian distribution. Finally, we inverted the reversed VGPs to their normal equivalents and computed for the two groups the paleomagnetic poles (mean of VGPs calculated using Fisher's statistics (1953)).

Since the paleomagnetic sites sampled in lava flows or shallow intrusions represent a spot reading of the geomagnetic field, the VGPs used to compute the paleomagnetic pole must be tested if the paleosecular variation (PSV) of the geomagnetic field is averaged. We tested our VGPs sets using the method of Deenen *et al*. (2011). Deenen *et al*. (2011) provided a N (number of sites)-dependent A95 (95% confidence circle around the paleomagnetic pole) envelope, bounded by an upper limit A95max, and a lower limit A95min that helps to ascertain whether or not a distribution has sufficiently well-sampled PSV and therefore geomagnetic field behavior. The results of this computation are presented in Table 1. The A95 of both the Sarmatian and Pannonian paleomagnetic pole pas this test suggesting that PSV was averaged by both sets.

Another test to prove if the PSV was adequately sampled, is the reversal test that verify if the means of normal and reversed VGPs are antipodal. We have applied the reversal test of McFadden and McElhinny (1990). Both the Sarmatian group and the Pannonian group passed the reversal test with classification C.

The paleomagnetic poles from Gutâi and Oaș Mountains (Table I) pass the reliability criteria of Meert *et al*. (2020): number of sites > 8, number of samples > 25, $10 \leq K \leq 70$. A site is defined by Meert *et al*. (2020) as a spot reading of the magnetic field with minimum of 3 samples per site. Most of the sites from Pătrașcu (1993) pass this criterion. Gerritsen *et al*. (2022) have shown that even sites with a lower number of samples three can be used to compute a reliable paleomagnetic pole, so we used also the sites of Pătrașcu (1993) with two block samples per site. Overall, both the Badenian – Sarmatian paleomagnetic pole and the Pannonian paleomagnetic pole have achieved the goal of averaging secular variation and can be used for the tectonic analysis.

Table I

Paleomagnetic poles for the Oaș-Gutâi Mts., the Transylvanian basin and the Apuseni Mts.

Name	Min age (Ma)	Max age (Ma)	N	K	A95	plat	plon	A95min	A95max
OG-Pn	9.0	11.7	106	14	3.8	88	110.2	1.8	4.3
G-Bd-Sm	12.0	13.5	21	12	9.5	79.8	286	3.5	12.0
AP-Bd-Sm	12.8	14.7	15	22	8.3	52.2	97.6	4.0	14.8
AP-Pn1	10.3	12.8	28	19	6.3	88	239	3.1	10.0
AP-Pn2	7.2	9.4	7	11	18.6	84.3	132.5	5.5	24.0
TB-Pn	9.6	11.2	7	67	7.4	77.7	167.1	5.5	24.0
TB-Bd-Sm	12.3	14.3	6	79	7.6	65.8	133	5.8	26.5
MO	11.4	14	3	50	17.5	45.3	53.8	7.7	41.0

Name: OG-Pn = Oaș-Gutâi Pannonian magmatic rocks, G-Bd-Sm = Gutâi Badenian – Sarmatian magmatic rocks, AP-Bd-Sm = Apuseni Badenian – Sarmatian magmatic rocks, AP-Pn1 = Apuseni Pannonian 1 magmatic rocks, AP-Pn2 = Apuseni Pannonian 2 magmatic rocks, TB-Pn = Transylvanian Basin Pannonian sediments, TB-Bd-Sm = Transylvanian Basin Badenian – Sarmatian sediments, Mo = Moigrad magmatic rocks; N = number of sites; K = precision parameter (Fisher, 1953); A95 = 95% confidence circle (Fisher, 1953); plat = latitude of paleomagnetic pole; plon = longitude of paleomagnetic pole; A95min and A95max = bounds of A95 for PSV (Deenen *et al*., 2011). The minimum and maximum age for each paleomagnetic pole are shown in the columns Min age and Max age, respectively,

4.3. TECTONIC DISPLACEMENTS

Paleomagnetic poles can be used to estimate paleogeographic displacements of a terrain relative to the Earth's spin axis (e.g. Butler, 1992). These tectonic movements are usually separated in vertical-axis rotations and paleolatitudinal motions. Usually, the paleomagnetic pole from the studied rock unit is compared with a reference paleomagnetic pole of a neighboring stable tectonic plate, provided by the apparent polar wander path (APWP) of that plate. This approach will provide the relative tectonic displacement relative to the stable tectonic plate and not to the Earth's spin axis. For this study, the stable tectonic plate is Eurasia and its APWP is from Vaes *et al*. (2023). To calculate the tectonic motions of the Oaș and Gutâi Mountains after the emplacement of the Miocene magmatic rocks, we used the the online, open-source environment APWP-online.org (Vaes *et al*., 2024).

Since the study of Pătrașcu (1993), numerous papers have shown that the Bogdan Vodă – Dragoș Vodă fault system (Fig. 1) is the boundary between the ALCAPA (Alpine–Carpathian–Pannonian) and Tisza-Dacia megatectonic units in the northern part of Romania (e.g. Marton *et al*., 2007 and references therein). To constrain the timing of the relative rotation during Miocene between these megatectonic units, we also reviewed the paleomagnetic results from the Transylvanian Basin and the Apuseni Mountains and compared them with the recent reference APWP of Eurasia proposed by Vaes *et al*. (2023). Following the paper of de Leeuw *et al*. (2013), we computed, using the results from the sedimentary formation of the Transylvanian Basin (Fig. 1), a Pannonian and a Badenian-Sarmatian paleomagnetic pole (Table I). The Badenian-Sarmatian paleomagnetic pole was calculated combining the results of de Leeuw *et al*. (2013) with two sites from Panaiotu (1999). At these data, we added a paleomagnetic pole computed from three sites sampled in a cluster of small intrusive bodies at Moigrad at the northern edge of the Apuseni Mountains (Fig. 1). The paleomagnetic data from the Moigrad area are from Panaiotu (1999) and the K-Ar age is 12.4 ± 1.3 Ma (Roșu *et al*., 2004). Since the paleomagnetic pole from the Moigrad area is based on only three sites is very probable that the PSV is not average. Both the site-mean paleomagnetic data from the sedimentary data and the Moigrad area are available in the database associated at this paper. The paleomagnetic poles for the Apuseni Mountains (Fig. 1, Table I) are based on the data presented by Ene *et al*. (2024).

Table II

Tectonic displacements

Name	Age (Ma)	Min_age (Ma)	Max_age (Ma)	N	R (°)	delta_R (°)	L (°)	delta_L (°)
O-G-Pn	10.5	9	11.7	106	-4.8	7.9	1.1	5.6
G-Bd-Sm	12.5	12	13.5	21	**-18.9**	**14.6**	-2.9	10.6
AP-Bd-Sm	13.3	12.8	14.7	15	**45.0**	**14.7**	2.3	10.6
AP-Pn1	11.6	10.3	12.8	28	-9.0	11.4	1.7	8.2
AP-Pn2	8.5	7.2	9.4	7	-2.6	25.8	-0.7	18.6
TB-Pn	10.4	9.6	11.2	7	3.2	17.6	-9.2	13.0
TB-Bd-Sm	12.8	12.3	14.3	6	**22.2**	**18.3**	-10.9	13.6
Mo	12.7	11.4	14	3	**77.9**	**58.6**	**26.8**	**21.7**

N = number of VGPs; R = vertical-axis rotation; delta_R = confidence interval for rotation; L = latitudinal displacemen; delta_L = confidence interval for latitudinal displacement. Bold data are statistically significant. For name see Table I. For each name, the mean age, the minimum age and maximum age are shown in the columns Age, Min_age and Max_age, respectively.

The results for the tectonic displacements of all these geological terrains are presented in Table II and Fig. 6 and 7. As expected for such young rocks and the tectonic history of the Carpatho-Pannonian area, the latitudinal displacement is not statistically significant, excepting the data from the Moigrad area. We think that the Moigrad results are an artifact produced by the insufficient sampling of the secular variation.

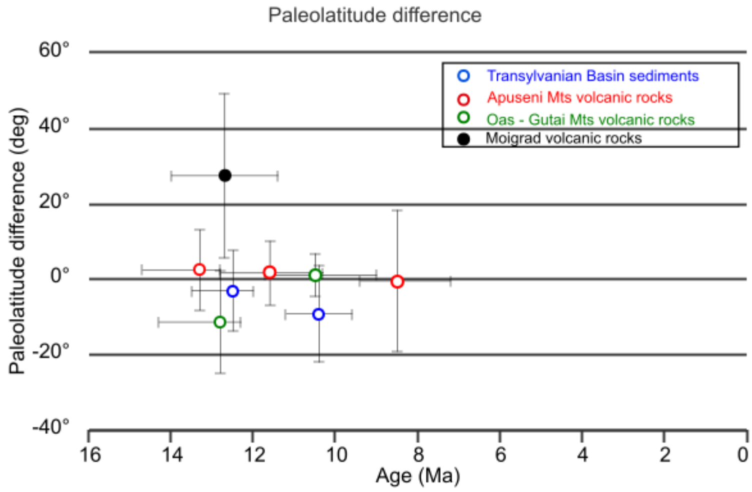

Fig. 6. Plot of the latitudinal displacement relative to the Eurasia – using the global APWP of Vaes *et al*. (2023). Full symbols mark significant rotations. For the color version of this figure, the reader is referred to the web version of this article.

The counterclockwise vertical-axis rotation is significant for the Badenian – Sarmatian paleomagnetic pole (13.5–12.0 Ma) from the Gutâi Mountains (Table II and Fig. 7). The result is similar to that presented by Pătrașcu (1993), but the amplitude of the relative rotation with respect to stable Eurasia is significant lower (-18.4° ± 14.5°) than (-30.2° ± 9.6°). This difference reflects the new age intervals assigned to the paleomagnetic sites that has reduced the number of Badenian – Sarmatian sites, the new reference APWP of stable Eurasia and the new method to compute vertical axis rotation. The rotation took place very fast (less than 1 Ma) since the Pannonian paleomagnetic pole from Oaș-Gutâi Mountains (11.7–9 Ma) do not show a significant rotation (Table II and Fig. 7). The rotation of the Miograd area, even it has large confidence limits due to insufficient average of the PSV, shows the extent of the area affected by the clockwise rotation. The counterclockwise rotation is contemporaneous with the final stage of the clockwise rotation of the Apuseni Mountains and the Transylvanian Basin. Significant vertical-axis rotations of the Apuseni Mountains and the Transylvanian Basin ended during the Pannonian (~ 11 Ma in the Apuseni Mountains). This fast differential vertical-axis rotation between the Gutâi area and the Transylvanian Basin correlate well with the last tectonic movements (sinistral transtension between 12 to 10 Ma) along the Bogdan Vodă – Dragoș Vodă fault system (Tischler *et al*., 2007). Marton *et al*. (2007), based on several remagnetized sites, suggest a counterclockwise rotation (around 30°) post-12 Ma for the Maramureș area (to the east of the Gutâi Mountains) in the vicinity of the Bogdan Vodă fault, both north and south of the fault. The origin of this remagnetization is not very clear, so its interpretation must be viewed with caution.

Our analysis requires a minor change in the paleomagnetic database used to reconstruct the tectonic evolution of the Mediterranean region of van Hinsbergen *et al*. (2020). Namely, in their Supplementary information 2, the entry for the Tisza-Dacia tectonic unit called TD - Ignis volcanics, which is based on all the paleomagnetic data of Pătrașcu (1993), must be replaced with the mean direction and the paleomagnetic pole of our Pannonian group. Our Badenian – Sarmatian paleomagnetic data from the Gutâi Mountains must be introduced in the paleomagnetic database of van Hinsbergen *et al*. (2020) at the entry for the tectonic units ALCAPA, since at that time Gutâi Mountains were part of this tectonic unit (e.g. Marton *et al*., 2007).

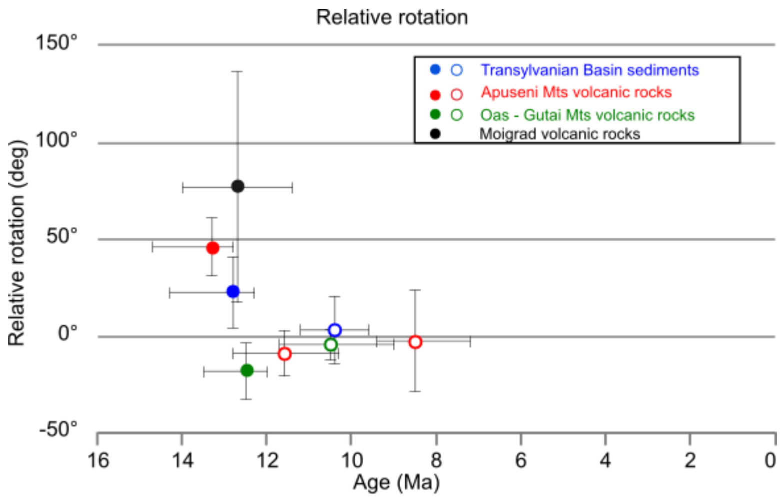

Fig. 7 Vertical axes rotations relative to Eurasia – using the global APWP of Vaes *et al*. (2023). A positive value indicates a clockwise rotation since that time. Full symbols mark significant rotations. For the color version of this figure, the reader is referred to the web version of this article.

5. CONCLUSIONS

In this paper, we reanalyzed the previous paleomagnetic data from the Miocene magmatic rocks from the Oaş and Gutâi Mountains. The paleomagnetic sites of Pătraşcu (1993) were assigned to the correct ages according to the latest model of evolution of the Miocene volcanism in the Oaş and Gutâi Mountains (Kovacs *et al*., 2017). These new ages of the paleomagnetic sites show a good correlation of the stages of magmatic activity in the OGVZ with the Geomagnetic Polarity Time Scale. This correlation confirms that the paroxysm of the volcanic activity is reached during stage two of volcanic activity when the volcanism migrated toward north-east and reached the maximum spatial extension in around 1.3 Ma during Chron C5n. Based on the new age intervals assigned to the paleomagnetic data, we computed a Badenian-Sarmatian paleomagnetic pole for the Gutâi Mountains (13.5–12 Ma) and a Pannonia paleomagnetic pole for the Oaş and Gutâi Mountains (11.7–9 Ma). We reconfirmed the counterclockwise vertical-axis rotation with respect to stable Eurasia of the southern Gutâi Mountains (Pătraşcu, 1993), but with a lower amplitude (-18.4° ± 14.5°). This fast vertical-axis rotation (around 1 Ma) is contemporaneous with the final stage of the clockwise rotation of the Apuseni Mountains and the Transylvanian Basin and the final tectonic movements along the Bogdan Vodă – Dragoş Vodă fault system.

Data availability statement. Paleomagnetic site-mean data from the Oaş and Gutâi Mountains, the Transylvanian Basin and the Miograd area are publicly available on Zenodo repository: https://doi.org/10.5281/zenodo.14054128. The paleomagnetic site-mean data from the Miocene magmatic rocks from the Apuseni Mountains, Table S3 of Ene *et al*. (2013), are available at https://doi.org/10.6084/m9.figshare.c.6951429.v1.

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