PALEOMAGNETIC CONSTRAINTS FOR THE TIMING OF VOLCANISM FROM THE SOUTH GURGHIU AND HARGHITA MOUNTAINS

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The volcanism in the Carpathian-Pannonian Region was active since the Early Miocene (between 21 and 0.1 Ma), through various phases in variable geotectonic and magmatic settings, with a distinct migration in time from North-West to the South-East (Lexa *et al.*, 2010). The Gurghiu–Harghita volcanic area has been ascribed to the East Carpathians volcanic arc (Călimani–Gurghiu–Harghita volcanic areas), corresponding to the central and southern Tisia block. This part is characterized by the presence of large amounts of calc-alkaline rocks formed between 6 and 3.5 Ma. After this period, the activity continued south-eastwards into the South Harghita area, between 3.5 and 0.2 Ma, with contemporaneous eruptions of calc-alkaline, shoshonitic and alkali basaltic lavas (Seghedi *et al.*, 2004).
Palaeomagnetic studies of igneous rocks cover the Harghita Mountains and the southern part of the Gurghiu Mountains. Over the entire area 206 sampling sites were analyzed. The polarities distribution highlights the fact that, in most volcanic structures, the main eruption period lasted for less than 1 Ma; accordingly, the time-interval suggested by the polarities distribution is shorter (~0.8 Ma) than the one inferred from K-Ar age determinations (*e.g.* Pécskay *et al.*, 1995; Seghedi *et al.*, 2004).

Key words: volcanic rocks, magmatism, paleomagnetism, magnetic polarities, K-Ar age measurements, Carpathians.

1. INTRODUCTION

Magnetostratigraphy is based on the fact that the Earth's magnetic field polarity changes through time at a non-constant frequency and on the fact that sediments and volcanic rocks have the capability to record and retain the magnetic field present at the moment of their formation. The fossil magnetism naturally present in a rock is termed the natural remanent magnetization (NRM). The primary magnetization is the component of the NRM that was acquired when the rock was formed, and may represent all, part, or none of the total NRM.

Palaeomagnetic studies of igneous rocks provided the first reliable information on polarity reversals. K/Ar dating combined with magnetic remanence measurements on igneous rocks, performed for the first time by Cox *et al.* (1963) and McDougall and Tarling (1963, 1964), resulted in the beginning of development of the modern geomagnetic polarity timescale (GPTS). These studies established that rocks of the same age carry the same magnetization polarity, at least for the last few million years. Polarity zones do not always correlate with rock K/Ar ages by not implying a stratigraphic superposition. Doell and Dalrymple (1966) designated the long intervals of geomagnetic polarity of the last 5 Myrs as magnetic epochs, and named them after pioneers of geomagnetism (Brunhes, Matuyama, Gauss and Gilbert).

Previous paleomagnetic studies of the volcanic rocks from the East Carpathians conducted in the 1970 have mainly addressed the central section of the Călimani–Gurghiu–Harghita (CGH) volcanic chain. The study published by Pătraşcu (1976) has proposed a division of the volcanic areas into distinct domains as a function of the recorded paleomagnetic polarities. Yet when the distribution of newly acquired K-Ar age data (Peltz *et al.*, 1987, Pécskay *et al.*, 1995, Seghedi *et al.*, 2004) was correlated with the magnetic polarities time-scale (Lourens *et al.*, 2004), it became obvious that those early paleomagnetic measurements could not provide the additional information necessary for documenting in detail the time-evolution of the volcanic activity. It consequently resulted that the concerned topic had to be addressed in the framework of new and more elaborate studies.

The main objective of the present paleomagnetic investigation was to acquire geomagnetic field determinations for volcanic rocks with ages younger than 7 Ma in the East Carpathians and to constrain the main time-intervals of volcanic activity by correlating the geographical distribution of the magnetic polarities with the available K-Ar age measurements (Pécskay *et al.*, 1995, Seghedi *et al.*, 2004) in order to refine the model of the temporal evolution of the volcanism. Details about the paleomagnetic work are presented in several other papers (Panaiotu *et al.*, 2012; Vişan, 2013; Vişan *et al.*, in preparation).

The investigated area covers the Harghita Mountains and the southern part of the Gurghiu Mountains, all of which belong to the East Carpathians. The Harghita Mountains are further divided into North Harghita and South Harghita, based on certain geological and geophysical specificities.

2. AGE OF THE VOLCANISM

The CGH volcanic chain is the youngest section of the Neogene magmatic arc of the East Carpathians. It has developed as a result of an eruptive activity that over the time interval 11 - <0.05 Ma progressively migrated from the NE to the SW (Pécskay *et al.*, 1995). Ensuing to the prevalently calc-alkaline volcanic activity, strato-volcanic edifices were built; displaying a generally concentric, yet at the same time asymmetric forms, generating a chain of adjoining and partly superimposed volcanoes (strato-volcanoes), surrounded by volcaniclastic deposits and/or isolated monogenetic domes or polygenetic dome-complexes (Szákacs, Seghedi, 1995; Lexa *et al.*, 2010).

Along the direction of the volcanism migration, the magmatic edifices height and volume progressively decrease, the lowest limits in this respect being reached in the South Harghita Mountains. This situation outlines a gradual decline of the volcanic activity, in terms of both available magma volumes and eruption rates (Szákacs, Seghedi, 1995; Lexa *et al.*, 2010).

Along-arc magma generation was related to progressive break-off of the subducted slab and asthenosphere uprise (Mason *et al.*, 1998; Seghedi *et al.*, 1998; Seghedi, Downes, 2011). The volcanism evolution has been controlled by the faults and fractures location along a trans-tensional corridor of NNW-SSE strike, which was positioned at the eastern boundary of the Dacia continental plate, the volcanic centers being concentrated along the western margin of that corridor. Such a fault-zone has been able to provide the pathways which favored the eruption of the magma that was generated in the upper mantle and in the lower crust (Fielitz, Seghedi, 2005; Seghedi, Downes, 2011).

The basement which directly underlies the igneous rocks of the CGH volcanic chain in the east consists of metamorphic rocks of Precambrian–Cambrian age, which belong both to the Tisza-Dacia microplate and European Plate. Those crystalline formations, displaying various degrees of metamorphism, belong to the East Carpathians Crystalline-Mesozoic zone, being included in three major litho-stratigraphic units, namely Bretila, Rebra and Negrişoara (Kräutner, Bindea, 2002). During their ascent to the surface, the magmas crossed this continental crust and have probably assimilated a certain amount of crustal material (Mason *et al.*, 1996). The external (eastward) part of the East Carpathians consists of flysch-type sedimentary deposits (belonging to the External Flysch units), which are 6–7 km thick and were inferred to be similar to the sediments which have been consumed during the subduction process.

The Gurghiu Mountains form the central part of the CGH volcanic chain. According to K-Ar age determinations, the Gurghiu Mountains volcanic activity developed between 9.4 and 5.4 Ma (Seghedi *et al.*, 2004; Fig. 1). The magmatic activity migrated from North to South and has lasted, in each volcanic center, for about 1 Ma, except for the Fâncel–Lăpuşna caldera, where the volcanic activity persisted a longer time-period, about 2.5 Ma (Seghedi *et al.*, 2004). As a result of the volcanic activity, the following volcanic centers developed: Jirca (9.2–-7.0 Ma), Fâncel–Lăpuşna (9.4–6.0 Ma), Bacta (7.5–7.0 Ma), Seaca–Tătarca (7.3–5.4 Ma), Borzont (6.8 Ma), Şumuleu (6.8–6.2 Ma) and Ciumani–Fierăstraie (7.1–6.3 Ma) (Seghedi *et al.*, 2004).

The volcanic activity in the North Harghita Mountains (6.3–3.9 Ma) was partly synchronous with that in the southern part of the Gurghiu Mountains (Szákacs, Seghedi, 1995; Fig. 1).

The Răchitiş, Ostoroş and Ivo–Cocoizas volcanic centers erupted simultaneously, by the time of the Pontian/Dacian transition (6-5.5 Ma), being partly superimposed on the Gurghiu eruptions. For each volcanic center, lavas and intrusions range in a very narrow age-interval (usually ±1 Ma), this circumstance suggesting a fast southward migration of the magmatic activity. A new stage of the magmatic activity developed between 5.5–5 Ma, culminating with the generation of the North Harghita largest volcanic edifice, Vârghiş (Szákacs, Seghedi, 1995).

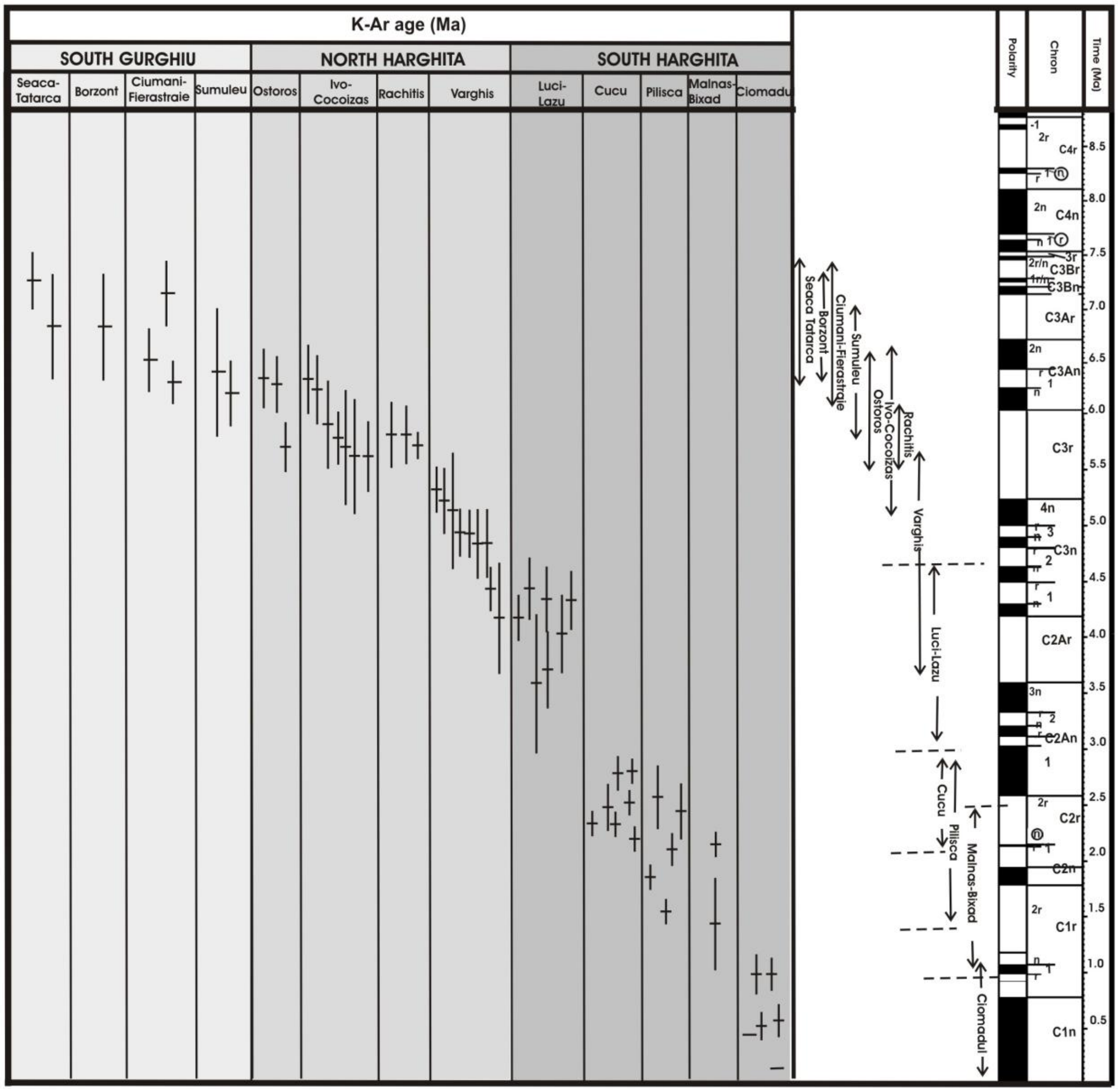

Fig. 1 – The magnetic polarities time-scale (after Lourens *et al.*, 2004) correlated with the K-Ar ages (error bars also indicated) determined for the investigated volcanic rocks (after Peltz *et al.*, 1987; Pécskay *et al.*, 1995; Seghedi *et al.*, 2004).

The South Harghita Mountains correspond to the youngest section of the CGH volcanic chain of the East Carpathians (Fig. 1). The main volcanic structures in the South Harghita

Mountains from N–S are: the Luci–Lazu composite volcano and Şumuleu–Ciuc volcanic dome structures (4.3 (5.1?) –3.6 Ma), the Cucu volcanic structure (2.8–2.2 Ma), the Pilişca volcanic structure (2.5–1.5 Ma), the Malnaş and Bixad intrusive domes (2.2–1.4 Ma), the Balvanyos extrusive domes (0.9–1.0 Ma) and the Ciomadul volcanic structure (0.6–0.2 Ma).

The volcanic activity that took place until 3.9 Ma ago in the Gurghiu, North Harghita and South Harghita Mountains can be designated as a „normal" calc-alkaline one. About 3 Ma ago, the magmas composition became adakite-like calc-alkaline type, a composition that persisted until about 0.03 Ma (Seghedi *et al.*, 2011). The K-alkalic volcanism has developed at Bixad/Malnaş, close to the South Harghita chain southernmost prolongation. The Na-alkalic volcanism (1.5–0.6 Ma) manifested 40 km to the West, in the Perşani Mountains (Downes *et al.*, 1995; Panaiotu *et al.*, 2004, 2013) in association with complex or individual eruption centers located parallel to a system of normal faults striking ~ NNE-SSW and which displayed the same orientation as the main normal faults in the Braşov Basin. The most recent volcanism, of Pliocene (2.8 – 1.6 Ma) and Quaternary (1 – 0.03 Ma) age as being concentrated at the SE margin of the CGH chain, can be connected to the final phases of the Carpathians collision process that are currently developing (Popa *et al.*, 2011).

The fact that over a short time-interval – during the Pliocene–Quaternary – there were simultaneously generated various melt compositions, is an indication that rapid changes occurred in the collisional tectonic regime (Seghedi *et al.*, 2011; Panaiotu *et al.*, 2013).

3. PALEOMAGNETIC POLARITIES

For the entire investigated area, the magnetic polarities distribution (as summarized in Table 1) is illustrated in Figure 2. For the Gurghiu Mountains, out of a total of 39 sampling sites, 27 sampling sites were identified as having normal polarity, 6 reverse polarity and 3 transitional directions, while the remaining 3 sampling sites displayed unstable or dispersed magnetizations. Considered in terms of repartition by volcanic structures, in Seaca Tătarca volcano there was identified one sampling site with normal polarity and another site with transitional polarity. In the Borzonţ volcanic structure there were identified 3 sampling sites with normal polarity; in the Şumuleu volcanic structure there are 5 sampling sites with reverse polarity and 3 with normal polarity; in the Ciumani-Fierăstraie structure there were identified 20 sampling sites with normal polarity, 2 with transitional polarity and one with reverse polarity.

Over the entire area of the North Harghita Mountains, 89 sampling sites were analysed. There were identified 56 sites with reverse polarity, 18 sites with normal polarity and 7 sites with transitional directions, the remaining 8 sites showing unstable or dispersed demagnetizations. In terms of repartition to volcanic structures, in Vârghiş volcano there were identified 16 sampling sites with normal polarity, 32 sampling sites with reverse polarity and 5 sampling sites with transitional directions. In the Ivo–Cocoizaş volcanic structure the reverse polarities prevail (13 sampling sites have reverse polarity) and only 2 sampling sites have normal polarity. In the Ostoroş volcanic structure 11 sampling sites have reverse polarity and 2 are transitional.

Table 1

The magnetic polarities distribution of the Gurghiu and Harghita Mountains

Major mountain unit	**Volcanic structure**	**Number of sites**		
		Normal polarity	**Reverse polarity**	**Transitional polarity**
Gurghiu	Seaca Tătarca	1	-	1
	Borzonţ	3	-	-
	Şumuleu	3	5	-
	Ciumani-Fierăstraie	20	1	2
Total	**39**	**27**	**6**	**3**
North Harghita	Vârghiş	16	32	5
	Ivo–Cocoizaş	2	13	-
	Ostoroş	-	11	2
Total	**89**	**18**	**56**	**7**
South Harghita	Luci–Lazu, Şumuleu	14	8	2
	Cucu	15	6	-
	Pilişca	1	10	2
	Malnaş, Bixad	6		1
	Bálványos	1	-	-
	Ciomadul	2	-	-
Total	**68**	**39**	**24**	**5**

Within the South Harghita Mountains, 68 sampling sites have been analyzed. In terms of repartition to volcanic structures, in the Luci–Lazu volcanic structure there have been identified 13 sampling sites with normal polarity, 8 sampling sites with reverse polarity and 3 sampling sites with transitional directions. In the Cucu volcanic structure 15 sampling points have normal polarity and 6 sampling points have reverse polarity. In the Pilişca volcanic structure the reverse polarity sampling points are prevailing (12, out of a total of 13 sampling points). It is worth mentioning that only normal polarities were identified in all our sampling sites within the sub-volcanic domes of Malnaş and Bixad: most corresponding directions display just a small scatter, accordingly suggesting that the two domes have cooled during the same magnetic chron.

The following main periods of volcanic activity – constrained by correlating the magnetic polarities with the K-Ar age determinations available for the volcanism of that region (Seghedi *et al.*, 2004; Pécskay *et al.*, 1995) – resulted (Figs. 1 and 2):

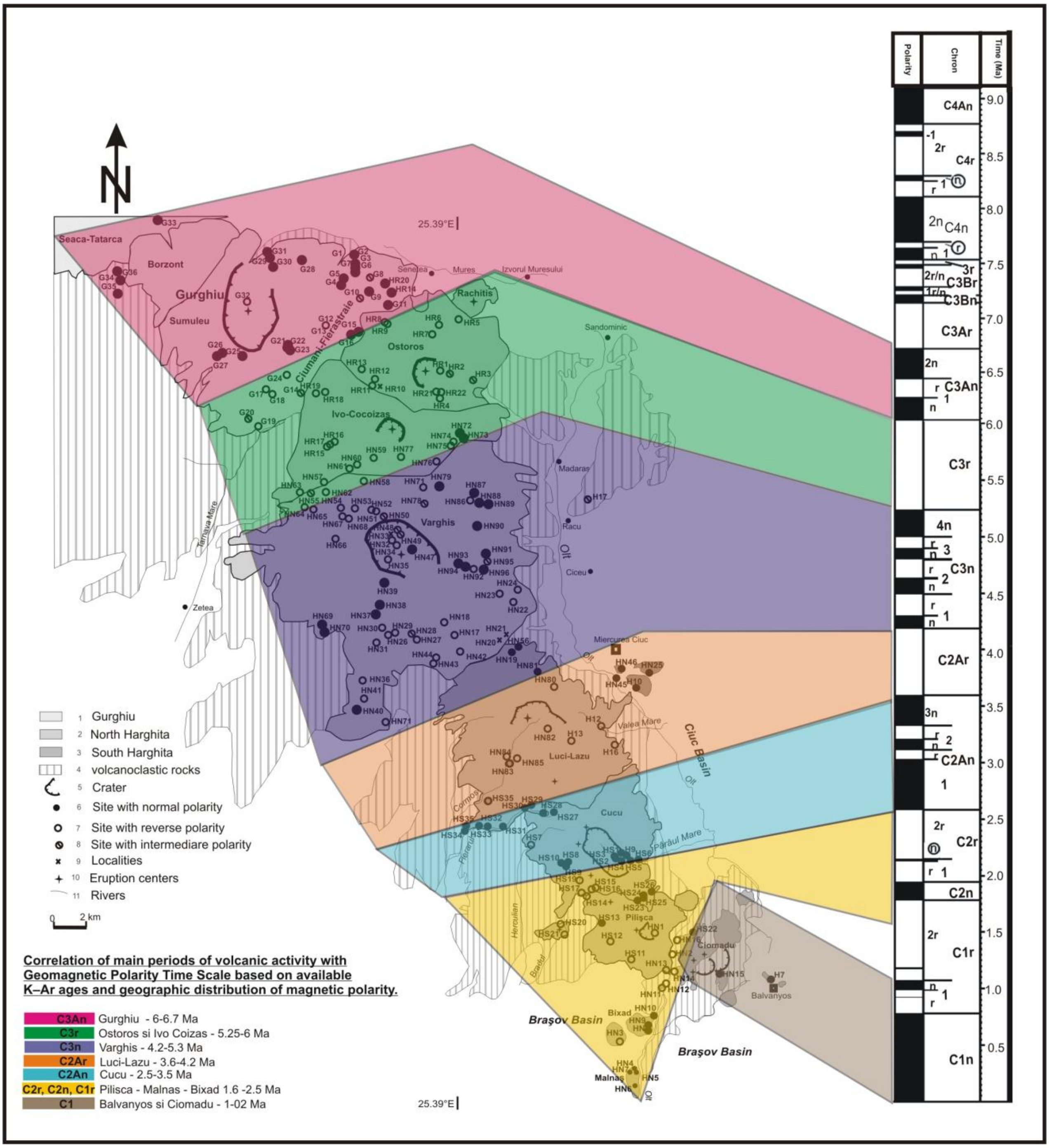

Fig. 2 – Polarities distribution illustrating the correlation of the main volcanic activity periods with the Magnetic Polarities Time Scale, for the entire investigated volcanic domain: the Gurghiu Mountains, the North Harghita Mountains and the South Harghita Mountains. Large circles indicate sampling sites with available both K-Ar age determinations and polarity data (filled circles – normal polarity; empty circles – reverse polarity). The Magnetic Polarities Time Scale is after Lourens *et al.* (2004). K-Ar ages are after Seghedi *et al.* (2004) and Pécskay *et al.* (1995).

– The Borzonţ, Şumuleu and Ciumani-Fierăstraie structures (in the southern section of the Gurghiu Mountains) are included in the C3An chron, with ages in the 6–6.7 Ma range; an exception are the 5 reverse polarity sampling sites identified within the Şumuleu volcanic structure: they might belong to the volcanic eruption stage associated to the Ivo–Cocoizaş and Ostoroş (North Harghita) structures, thus falling into the age interval which correspond to the C3r chron.

– In the Ivo–Cocoizaş and Ostoroş (North Harghita) structures most polarities are reverse, that fact being in agreement with the associated K-Ar ages which correspond to the C3r chron. The two normal polarity sampling sites located close to the eastern border of that volcanic structure could belong to a particular eruption episode that was prolongation of the Vârghiş structure activity, and which approached the 4n subchron of the C3n chron. The corresponding ages range between 5.2–5.6 Ma.

– The Vârghiş (North Harghita) structure is included in the C3n chron and its age ranges between 4.2–5.3 Ma;

– The Luci–Lazu (South Harghita) structure is included in the C2Ar chron, its age ranging between 3.6–-4.2 Ma;

– The Cucu (South Harghita) structure is included in the C2An chron and its age ranges between 2.5–3.5 Ma;

– The Pilişca–Malnaş–Bixad (South Harghita) structures are included in the chrons C2r, C2n, C1r, in the 1.6–2.5 Ma age intervals. It is worth mentioning that only normal polarities were identified in all our sampling sites within the sub-volcanic domes of Malnaş and Bixad suggesting a short cooling time: The Balvanyos and Ciomadul structures are included in C1 chron, in the 1–0.2 Ma age interval.

CONCLUSIONS

A clear zoning pattern is visible in the magnetic polarities distribution for the entire investigated domain: there is either dominance of a certain polarity (as for instance in the Gurghiu volcanic structures, or in the North Harghita Mountains), or a rather equilibrated mix of both polarities (*e.g.*, the volcanic structures Vârghiş or Cucu).

The polarities distribution highlights the fact that in most volcanic structures, the main eruption period lasted for less than 1 Ma; accordingly, the time-interval suggested by the polarities distribution is shorter (~0.8 Ma) than the one inferred from K-Ar age determinations. Overall, the results are consistent with the currently accepted model of a progressive migration of the volcanic activity from North to the South (*e.g.* Pécskay *et al.*, 1995; Seghedi *et al.*, 2004), being at the same time emphasized the clear distinctions existing between the individual time steps of that migration (the corresponding durations being just about 1 Ma, occasionally even less).

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