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Neogene tectonic evolution of the southern and eastern Carpathians constrained by paleomagnetism

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Abstract

The Neogene geodynamic evolution of the southeastern Carpatho–Pannonian system is constrained by the timing and magnitude of vertical-axis tectonic rotations derived from paleomagnetic analysis. We report results from 13 paleomagnetic localities (139 sites, 993 samples) of Middle Miocene to Pliocene sediments of the eastern Carpathians region, the southern Carpathians region and the actively deforming "Bend Area" between these two regions. Absolute age control of the sampled sediments is provided by previous magnetostratigraphic analysis. Our results indicate: (1) systematic ~30° clockwise rotations occurred in the southern Carpathians after ~13 Ma; (2) tectonic rotation had ceased in the investigated eastern and southern Carpathians regions after ~9 Ma except in the Bend Area where recent clockwise rotations took place after ~5 Ma. This pattern of rotations implies a concentration of tectonic activity during the Middle to Late Miocene collision of the Carpathian arc with the European platform, followed by relative tectonic quiescence through the Pliocene except in the Bend Area subject to late-stage slab pull.

Keywords: paleomagnetism; geodynamics; Carpathians; Neogene

1. Introduction

Using paleomagnetism to record tectonic rotations has proven an indispensable tool for quantifying and following in time the evolution of geodynamic processes in the Calabrian, Hellenic, Gibraltar and the Carpathians arcs [1–3] (Fig. 1). Among these arcs, the Carpathian orogenic system displays the most dramatically pronounced arcuate shape with previous paleomagnetic work suggesting over ~90° opposite rotations on either limb of the arc [4–6]. Understanding the relation between the observed rotations and geodynamic processes at work during formation of the Carpathians requires further paleomagnetic investigation with precise timing in the scarcely explored

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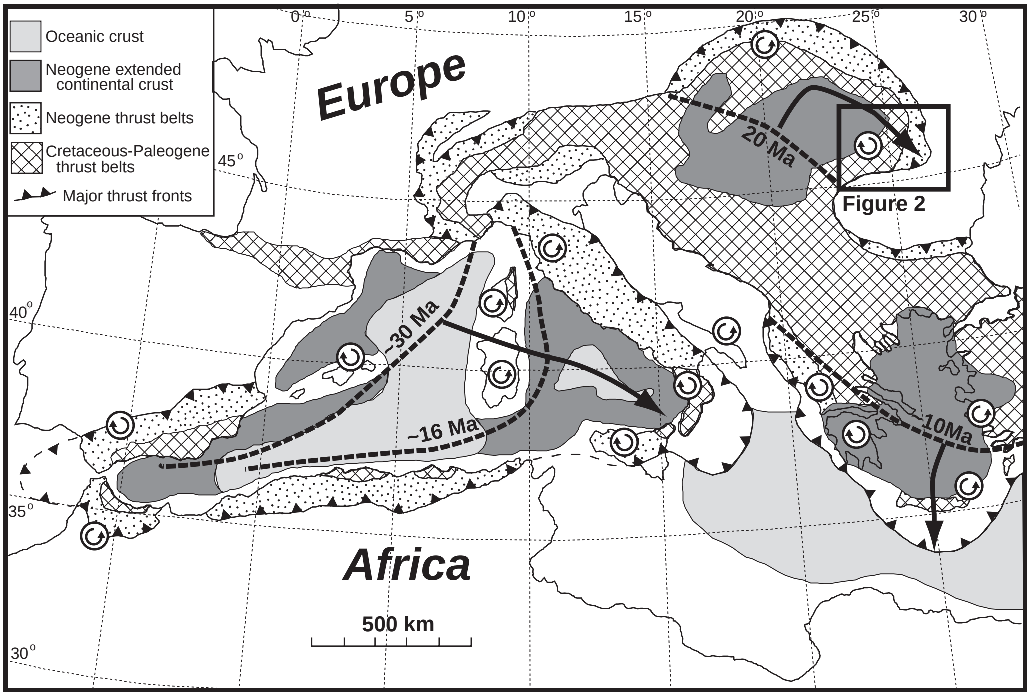

Fig. 1. Tectonic map of the Mediterranean region showing the evolution of arc migration and associated vertical-axis rotations (arrows within circles) recorded by paleomagnetic studies (modified from [1,9]).

southern and eastern parts of the orogen. In this study we report tectonic rotations evaluated from a large paleomagnetic dataset on Miocene to Pliocene rocks with unprecedented magnetostratigraphic age control, covering the areas referred to as the southern Carpathians, the Bend Area and the eastern Carpathians (Fig. 2).

2. Geologic background

Migration of the Carpathian arc driven by slab roll back was followed by collision and accretion of the arc to the European margin along the European platform during Middle to Late Miocene time [4,7,8]. Collision was possibly associated with slab detachment propagating along the eastern Carpathians and allowing further slab roll back towards the Bend Area at the southeastern corner of the Carpathians. Ongoing slab detachment is evidenced in this region by intermediate depth seismicity and tomographic studies [9,10]. A wealth of geologic data is available on the southeastern part of the orogen. Structural geology studies indicate (1) Early to Middle Miocene E–W contraction, followed by (2) Middle to Late Miocene right–lateral oblique convergence in the southern Carpathians and frontal convergence in the eastern Carpathians; (3) Pliocene local contractions restricted to the Bend Area [7,11–16]. Magmatic geochemistry and geochronology, indicate Middle to Late Miocene (~15–8 Ma) continental subduction signature associated with collision followed by Late Miocene to Pliocene (~10–1 Ma) slab detachment [17–19]. Fission track thermochronologic work reveals that strong exhumation associated with continental collision took place between 14 an 9 Ma in the southern and eastern Carpathians then concentrated to the Bend Area from ~5 to 0 Ma [20]. These results coincide with basin analysis and modeling studies indicating accelerated subsidence during the Early to Middle Miocene time followed by a climax of subsidence with deposition of syntectonic strata between ~12 and 10 Ma [21–23]. Seismologic studies yield crustal thicknesses that reveal important preexisting rheological boundaries separated by major faults in the foreland such as the Trotus, the Capidava–Ovidiu, the Peceneaga–Camena

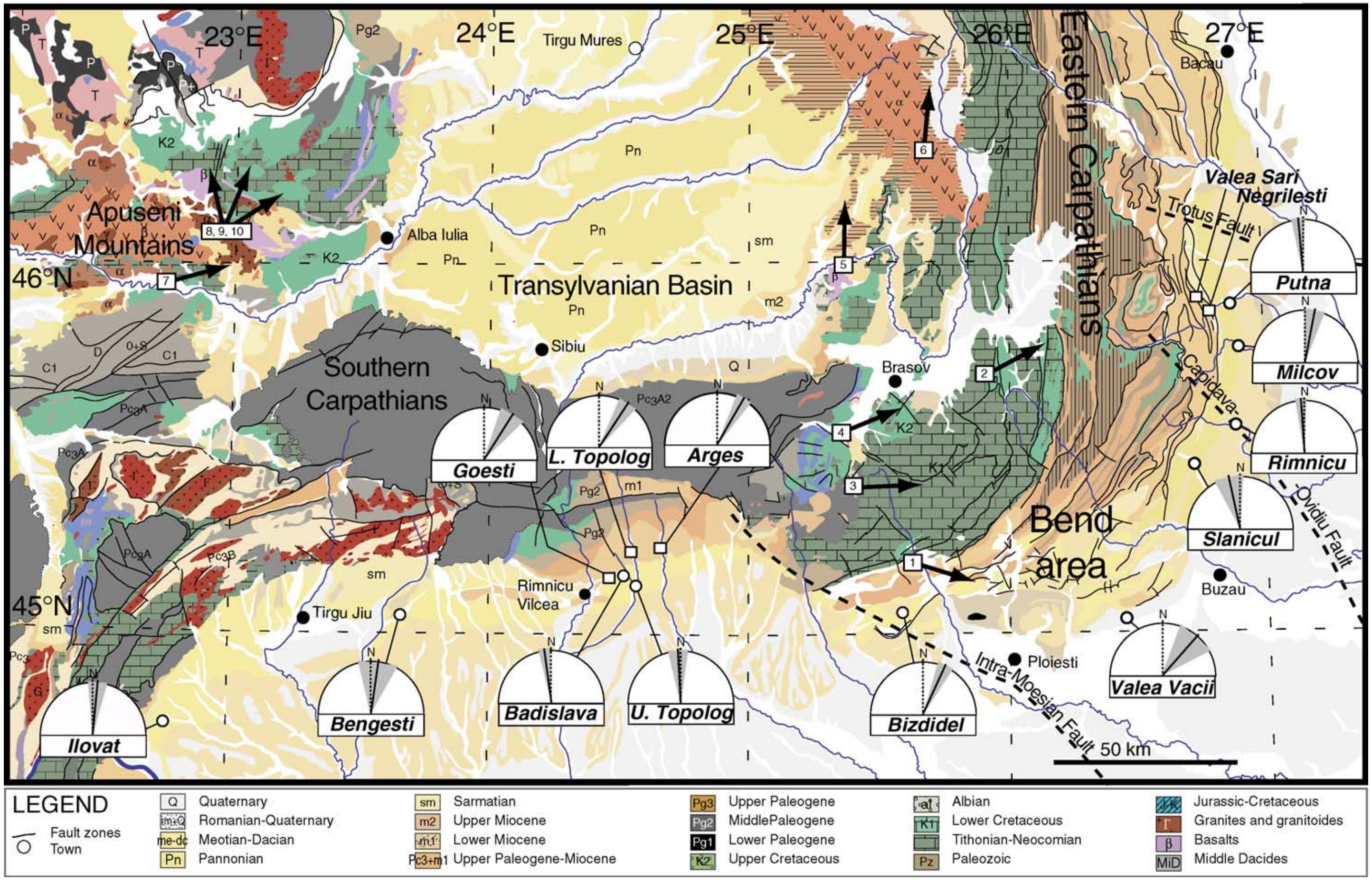

Fig. 2. Geologic map of the paleomagnetic sampling area in the southeastern Carpatho–Pannonian system. Paleomagnetic sampling localities are indicated by white circles (Late Miocene to Pliocene) or white squares (Middle Miocene). Vertical-axis tectonic rotations inferred from paleomagnetic results are indicated with respect to north with 95% confidence (grey cones) within half circles. Black arrows indicate results from previous studies where number in box indicates reference numbered in Table 1 (given locations for these studies is an average of several results spread over a larger area).

and the Intra-Moesian faults [24]. These pre-existing lithospheric heterogeneities in the lower plate may have controlled the locus of deposition and deformation [12,22,25,26].

Previous paleomagnetic studies have provided quantitative constraints on tectonic rotations relevant to reconstructing the evolution of the Carpathian arc (e.g. [4,11,27,28]). Two distinctive tectonic domains separated by the mid-Hungarian line [29] have been defined: the northwestern Carpatho–Pannonian domain with systematic counterclockwise rotations and the southeastern Carpatho–Pannonian domain with systematic clockwise rotations. However, an overwhelming majority of paleomagnetic studies have been conducted in the northwestern part of the orogen. In contrast, the rotation pattern of the southeastern part relies on a few localized studies (e.g. [30]). In the latter region, the Late Tertiary Carpathians thrust belt and associated foredeep are devoid of paleomagnetic data with the exception preliminary analysis of limited dataset [31]. As a result, the sense of rotation remains virtually unknown in most of the eastern and southern Carpathians. In addition, the absence of absolute age control on the stratigraphy does not allow precise estimation of the timing of observed rotations. In a concerted effort to resolve uncertainties related to the lack of paleomagnetic data stated above, we have undertaken a comparatively large paleomagnetic sampling for magnetostratigraphic and for tectonic rotation analysis distributed over Miocene to Pliocene sedimentary rocks from the southern and eastern Carpathians (Fig. 2). In this paper we present tectonic analysis of these combined paleomagnetic datasets.

3. Paleomagnetic sampling, analysis and results

3.1. Age and setting of sampled formations

Paleomagnetic sampling was performed in fine sediments and occasional intercalated tuffites deposited in fan-delta to distal deltaic environment. We apply the term paleomagnetic locality to an area (usually with dimensions <10 km) from which paleomagnetic sites were collected within one stratigraphic section [32]. Magnetostratigraphic sampling (2–3 cores per sedimentary horizon sampled at typical 5-m stratigraphic interval over a sedimentary section) was performed in Late Miocene to Pliocene foredeep sediments of the southern Carpathians (paleomagnetic localities Ilovat, Bengesti, Badislava and Upper Topolog), the Bend Area (paleomagnetic localities Slanicu, Bizdidel and Valea Vacii) and the eastern Carpathians (paleomagnetic localities Putna, Milcov and Rimnicu). Additional paleomagnetic sampling for analysis of tectonic rotations (8 cores per sedimentary horizon sampled at typical 10–50-m stratigraphic interval over a sedimentary section) has been performed within Middle Miocene foredeep sediments in the eastern Carpathians (paleomagnetic localities Valea Sari and Negrilesti) and the southern Carpathians (paleomagnetic localities Arges, Lower Topolog, Goesti). Straightforward structural control of typical monotonously dipping strata results from regional structural analysis and bedding attitude measured at each sampled stratigraphic horizon.

The magnetostratigraphic work has yielded age control of the eastern Paratethys formations locally referred to as the Romanian (4.1–2.5 Ma), Dacian (4.8–4.1 Ma), Pontian (5.8–4.8 Ma), Meotian (~9–5.8) and down to the top of the Sarmatian (9 Ma) (see [33–35] for magnetostratigraphic correlations to the geomagnetic polarity time scale (GPTS) [36]). Regional correlation of these formations along the Carpathians is usually straightforward due to distinctive lithological characteristics. Age calibration indicates synchronous deposition over the southeastern Carpatho–Pannonian region of Upper Meotian to Romanian formations [33]. However, diachronous deposition of Sarmatian formations along the eastern and southern Carpathians is illustrated by hiatus and facies variation from thick distal units to proximal transgressive conglomeratic deposits [21,37,38]. Consequently, a tectonic event related to continental collision associated with thrusting and enhanced subsidence has been associated to the onset of deposition of the Sarmatian sediments estimated at ~13 Ma [8,12,20,23,25,39,40]. To understand the tectonic rotation pattern related to this tectonic event, additional paleomagnetic sampling for tectonic analysis has been performed in Middle Miocene sedimentary formations (locally referred to as "Helvetian" [38] to "Tortonian" [37] formations but not to be mistaken with the Miocene stage bearing the same name) deposited directly before (below) the Sarmatian (~13–9 Ma) syntectonic strata.

3.2. Paleomagnetic analysis and results

After initial measurement of natural remanent magnetization (NRM), samples were thermally demagnetized at small temperature steps (5–50 °C) up to 680 °C. Based on thermal demagnetization behavior combined with a set of rock magnetic experiments (Curie balance measurement, magnetic susceptibility, hysteresis loops and first-order reversal curves), two categories of characteristic remanent magnetization (ChRM) are clearly distinguished with typical magnetic properties of either iron oxides or iron sulfides [33,34]. After removal of frequent secondary overprint usually below 150 °C, most iron oxide demagnetizations reveal a linear decay of the NRM up to 600 °C interpreted as a magnetite-type magnetic behavior, sometimes up to 670 °C where the combined presence of hematite is confirmed by higher magnetic coercivity and red color of the sediments. Iron sulfide demagnetizations display linear decay of the natural remanent magnetization (NRM) to 320–340 °C followed by a drastic magnetic susceptibility increase interpreted to result from iron sulfide oxidation. Iron oxide properties with the presence of hematite is recognized at the Middle Miocene Arges and Lower Topolog paleomagnetic localities where we preferably sampled thin reddish claystone horizons periodically interlayered within thick massive grey sandstones (Fig. 3a,b). Magnetite-type iron oxide behavior is characteristic of the Goesti paleomagnetic locality sampled within successions of white tuffites and interlayered greenish blue siltstones (Fig. 3c). The presence of iron sulfide is suggested by the paleomagnetic behavior of the grayish siltstone to brownish sandstones samples of the Valea Sari and Negrilesti paleomagnetic localities (Fig. 3d,e). For the other paleomagnetic localities sampled for magnetostratigraphy, further magnetic property analyses were earlier presented in the following references [33,34].

To determine sample ChRM directions, results from at least four successive temperature steps were analyzed by principal component analysis [41]. Samples yielding maximum angular deviation (MAD) >15° were rejected from further analysis. Site-mean directions were calculated from stratigraphic levels yielding at least four sample ChRM directions using Fisher statistics [42]. When compiling magnetostratigraphic sections for tectonic analysis, ChRM direc-

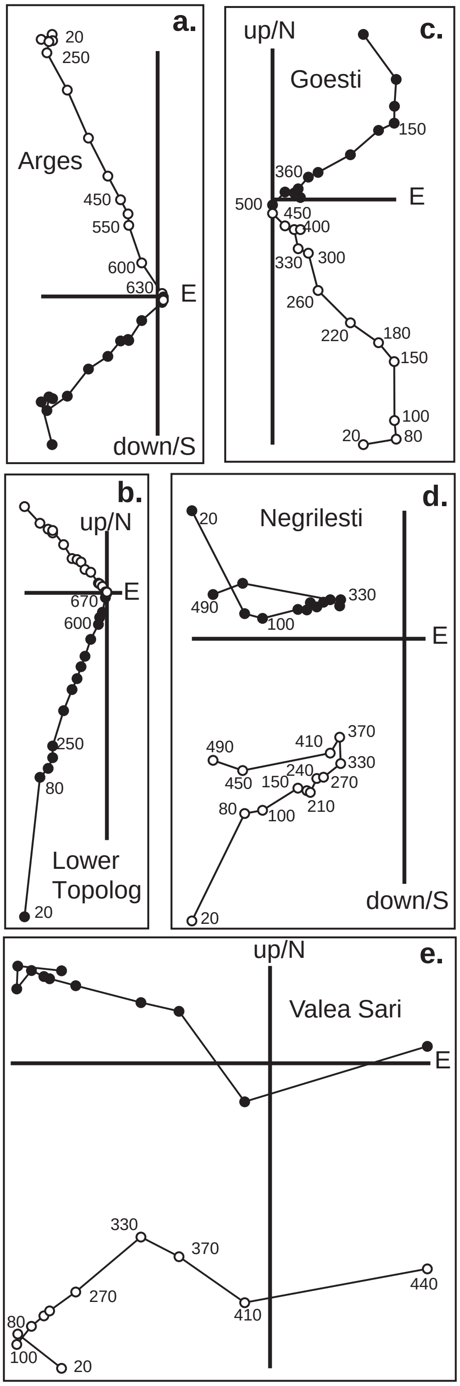

Fig. 3. Vector end point orthogonal diagrams of typical demagnetization behavior during thermal treatment. Black (white) points are projection on the vertical (horizontal) plane. Temperature indicated in degrees Celcius for key demagnetization steps.

tions were processed using principal component analysis with restrictions stated above and site-mean directions were calculated with four to 11 ChRM directions from successive magnetostratigraphic levels (=sedimentary horizon) yielding the same paleomagnetic polarity and similar bedding attitude. Sample ChRM directions more than two angular standard deviations from the initial site-mean direction were rejected prior to final site-mean calculation (Table MMC1 and MMC2). Site-mean directions with $\alpha_{95} > 25^\circ$ were rejected. Locality-mean directions were calculated by applying Fisher statistics [42] to the set of normal-polarity site-mean directions and antipodes of reversed-polarity site-mean directions from each locality (discarding site means more than two angular standard deviations from the preliminary mean).

To assess primary origin of the ChRM, field tests (parametric fold and reversals tests at 95% confidence level [43]) were performed on regional datasets by combining site-mean directions from several paleomagnetic localities within a general area and age window (Fig. 4; Table MMC1 and MMC2). In the eastern Carpathians, combined site mean directions from the Late Miocene to Pliocene Putna, Milcov and Rimnicu paleomagnetic localities have positive fold and reversals test indicating primary magnetization (Fig. 4a). However, the Middle Miocene Valea Sari and Negrilesti paleomagnetic localities have divergent tilt-corrected directions that cluster towards the present day field direction before tectonic tilt correction indicating post-tectonic remagnetization (Fig. 4b). These two paleomagnetic localities were thus discarded for further tectonic analysis. In the Bend Area, combined Bizdidel and Valea Vacii paleomagnetic localities pass fold and reversals test indicating primary magnetization (Fig. 4c). The combined Slanicu, Bizdidel and Valea Vacii pass the inclination only fold test [44] sustaining primary magnetization for Slanicu. In the southern Carpathians, combined

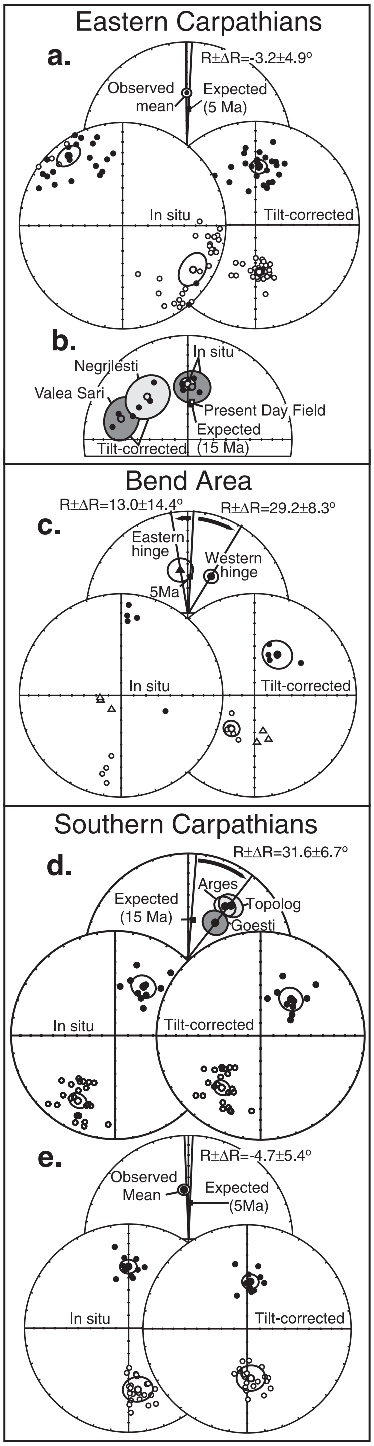

Fig. 4. Observed directions from the combined paleomagnetic localities of Middle Miocene (b and d) and Late Miocene to Pliocene (a, c and e) age for the three investigated regions. Stereographic projections in lower (black symbols) and upper hemisphere (open symbols) compare site-mean directions of normal and reverse polarities in situ and after tilt correction. Top diagrams show the overall observed mean directions with 95% confidence circle compared to the expected direction (black square) to assess rotation.

directions from the Late Miocene to Pliocene Ilovat, Bengesti, Badislava and Upper Topolog paleomagnetic localities, have inconclusive fold test (due to insufficient bedding attitude variations) and positive reversals test attesting primary magnetization (Fig. 4d). Similarly, the combined Middle Miocene Goesti, Arges and Lower Topolog paleomagnetic localities have inconclusive fold test but positive reversals test indicating primary origin of the magnetization.

To assess flattening and rotation following the methods of [45] and [46], mean observed directions for each paleomagnetic locality were compared to the appropriate reference paleomagnetic pole for Europe [47] calculated from 10 Ma window (Table 1). Observed paleomagnetic inclinations are always too shallow with flattening ranging from 5° to 25°. Because the anomalies recorded at various localities are not systematic in time and space as would be expected for external processes such as tectonic related northward transport, modification of the geocentric axial dipole field or erroneous reference pole, we interpret shallow inclinations to result from processes intrinsic to each locality such as inclination shallowing during deposition and compaction. To test this assertion, we perform the Elongation–Inclination (E–I) correction method developed in [48]. Because this method requires at least 100 independent recording of the paleosecular variations, we apply it to 366 sample ChRM directions from different stratigraphic levels of the combined Putna and Rimnicu paleomagnetic localities for the eastern Carpathians and 114 sample ChRM directions from different levels of the combined Upper Topolog and Badislava paleomagnetic localities for the southern Carpathians. In both cases, the inclination is corrected to within statistical error of the expected reference inclination strongly supporting a rock magnetic origin for the observed flattening of inclination (Fig. 5). Vertical-axis tectonic rotations can be inferred from observed divergence from the expected declination (Fig. 4; Table 1). In the eastern Carpathians, at all three paleomagnetic localities within Sarmatian and younger formations (~9–2.5 Ma; see [34] for calibration to GPTS) no significant rotations are recorded (Fig. 2; Table 1). The two paleomagnetic localities in older sediments did not yield interpretable results due to remagnetization. In the southern Carpathians, the four investigated paleomagnetic localities in Pontian and younger formations (6.2–3.0 Ma; see [33,35] for calibration to GPTS) yield no significant rotation. However, the three paleomagnetic localities sampled just below Sarmatian strata (before ~13 Ma) yield systematic ~30° clockwise rotations. Finally, in the Bend Area, both paleomagnetic localities sampled west of the hinge of the bend in Meotian to Pontian formations (6.6–5.4 Ma) indicate clockwise rotations (29.2 ± 8.3) while northeast of the hinge Dacian to Romanian formations (4.7–3.5 Ma) indicate counterclockwise rotation (-13.0 ± 14.4). From this data, we can draw the following straightforward first order conclusions regarding tectonic rotations: 1) no significant rotation has affected the investigated eastern Carpathians region since at least 9 Ma; 2) in the southern Carpathians, ~30° clockwise rotations are recorded by sediments directly below the Sarmatian formation (~13–9 Ma) but not recorded by sediments younger than 6.2 Ma. This indicates that a regional tectonic event occurred in this time frame most probably during deposition of the syntectonic Sarmatian strata (~13–9 Ma); 3) while tectonic rotation had ceased in all other investigated areas, rotations affected the Bend Area during Pliocene time until at least 3.5 Ma. To understand the tectonic significance of these results, we discuss in the following their possible relationship with the tectonic context arising from previous paleomagnetic and other geologic datasets.

4. Geodynamic implications and discussion

The systematic 30° clockwise tectonic rotation recorded in the southern Carpathians implies that a regional tectonic event occurred within ~13–6.2 Ma. Our results are consistent with various geological constraints arising from basin analysis, geochemistry and thermochronology recording important tectonic activity during ~15–8 Ma [17,19,20,22,25]. In agreement with those studies, we interpreted this Middle to Late Miocene tectonic event to result from continental collision of the Carpathian arc with the European margin. The large amount of structural data available for the study area offers the possibility to investigate possible mechanisms responsible for the Middle to Late Miocene 30° clockwise rotation observed in the southern Carpathians. As shown in previous palinspastic restorations of cross sections, insufficient orogen parallel extension precludes pure oroclinal bending to

Table 1

#	Localities/reference	Site location		Observed direction					Reference pole				Rotation	Flattening	Age control			Rock type
		Lat. (° N)	Long. (° E)	I_s (°)	D_s (°)	α_{95} (°)	k	n	Age (Ma)	Lat. (° N)	Long. (° E)	A_{95} (°)	$R \pm DR$ (°)	$F \pm DF$ (°)	Low. (Ma)	Upp. (Ma)	Given age	
	This study																	
	Bend Area Latest Miocene–Pliocene																	
	Bizdizel (BI)	45.06	25.57	56.0	27.0	5.8	90.9	8	5	86.3	172.0	2.6	24.2 ± 8.8	4.9 ± 5.0	6.6	5.4	Meotian–Pontian	Sediments
	Valea Vacii (VA)	45.06	26.43	52.3	44.5	15.1	67.7	3	5	86.3	172.0	2.6	41.7 ± 20.4	8.6 ± 12.2	6.4	5.6	Pontian	Sediments
	Mean of Western hinge	45.06	26.00	55.2	32.0	5.5	69.0	11	5	86.3	172.0	2.6	29.2 ± 8.3	5.7 ± 4.8	6.6	5.4		
	Slanicul (SL) eastern hinge	45.46	26.68	55.2	349.9	10.0	154.1	3	5	86.3	172.0	2.6	−13.0 ± 14.4	6.1 ± 8.2	4.7	3.5	Dacian–Romanian	Sediments
	Southern Carpathians Middle Miocene																	
	Arges (AB)	45.23	24.65	39.4	35.8	7.9	26.1	14	15	84.2	154.9	3.2	29.9 ± 8.9	20.9 ± 6.7	16.4	13.0	Badenian	Sediments
	Lower Topolog (TV)	45.23	24.54	35.8	39.5	9.1	26.2	11	15	84.2	154.9	3.2	33.6 ± 9.6	24.6 ± 7.6	16.4	13.0	Badenian	Sediments
	Goesti (RC)	45.15	24.48	55.3	37.9	9.4	35.6	8	15	84.2	154.9	3.2	32.0 ± 13.8	5.0 ± 7.9	16.4	13.0	Badenian	Tuffites
	Mean	45.20	24.56	42.1	37.5	5.3	23.2	33	15	84.2	154.9	3.2	31.6 ± 6.7	18.3 ± 4.8	16.4	13.0		
	Southern Carpathians Latest Miocene–Pliocene																	
	Ilovat (IL)	44.78	22.77	53.0	7.7	6.6	344.8	3	5	86.3	172.0	2.6	5.2 ± 9.3	7.6 ± 5.6	6.2	6.1	Pontian	Sediments
	Bengesti (BE)	45.06	23.66	50.2	11.2	20.2	38.4	3	5	86.3	172.0	2.6	8.6 ± 26.2	10.6 ± 16.2	5.3	4.8	Dacian	Sediments
	Badislava (BD)	45.17	24.51	50.7	−5.6	4.4	56.7	20	5	86.3	172.0	2.6	−8.3 ± 6.2	10.3 ± 3.9	6.0	4.4	Pontian–Dacian	Sediments
	Upper topolog (TP)	45.14	24.56	55.4	359.1	7.5	65.6	7	5	86.3	172.0	2.6	−3.6 ± 11.0	5.5 ± 6.3	5.0	3.0	Pontian–Romanian	Sediments
	Mean	45.04	23.88	50.9	358.0	3.6	50.4	33	5	86.3	172.0	2.6	−4.6 ± 5.4	9.9 ± 3.4	6.2	3.0		
	Eastern Carpathians Late Miocene–Pliocene																	
	Milcov (MV)	45.79	26.85	39.2	13.3	10.9	72.6	4	5	86.3	172.0	2.6	10.4 ± 11.6	22.4 ± 8.9	9.0	6.0	Sarmatian–Meotian	Sediments
	Rimnicu (RM)	45.56	26.84	50.4	359.2	4.5	34.4	30	5	86.3	172.0	2.6	−3.7 ± 6.3	11.0 ± 4.0	7.0	2.5	Sarmatian–Romanian	Sediments
	Putna (PU)	45.89	26.82	47.9	357.1	5.4	38.9	19	5	86.3	172.0	2.6	−5.8 ± 7.1	13.7 ± 4.7	9.0	5.2	Sarmatian–Pontian	Sediments
	Mean	45.75	26.84	48.0	359.8	3.5	32.6	53	5	86.3	172.0	2.6	−3.2 ± 4.9	12.8 ± 3.2				
	Previous studies																	
	Southern Carpathians																	
1	Bazhenov et al.,1993 [31][a]	45.40	25.40	43.0	112.0	7.6	116.0	3	80	81.0	232.5	6.9	106.9 ± 10.8	13.7 ± 8.0	91.0	65.0	Up. Turonian–Lo. Maastrichtian	Sediments
2	Bazhenov et al. [31][a]	45.70	25.90	26.0	65.0	10.2	24.0	2	75	81.3	188.6	7.2	61.8 ± 11.6	30.8 ± 9.8	83.0	65.0	Campanian–Maastrichtian	Sediments
3	Bazhenov et al. [31][a]	45.20	25.60	48.0	89.0	7.8	27.0	2	70	80.0	213.2	4.8	87.4 ± 10.5	6.7 ± 7.3	74.0	65.0	Maastrichtian	Sediments
4	Panaiotu [6,55]	45.50	25.30	50.8	72.5	12.6	54.1	3	50	81.3	151.9	4.2	63.4 ± 16.7	8.3 ± 10.5	55.0	40.0	Ypresian–Lutetian	Sediments

Transylvania basin																		
5	Panaiotu [57]	46.00	25.40	64.1	3.5	4.3	60.8	19	5	86.3	172.0	2.6	0.7 ± 8.4	− 2.6 ± 3.9	1.2	0.6	0.6–1.2 Ma	Volcanics
	Panaiotu [6][b]	46.80	25.10	62.3	359.3	3.9	42.4	31	10	85.0	155.7	3.1	− 5.9 ± 7.5	− 0.1 ± 3.7	8.5	6.5	6.5–8.5 Ma	Volcanics
6	Panaiotu [6][b]	46.40	25.70	61.2	7.2	3.3	37.0	52	5	86.3	172.0	2.6	4.4 ± 6.2	0.7 ± 3.2	6.5	4.0	4–6.5 Ma	Volcanics
	Panaiotu [6,55]	47.10	23.80	56.7	67.8	8.1	18.6	3	15	84.2	154.9	3.2	61.8 ± 12.4	5.2 ± 6.8	15.0	13.0	Badenian–NN4 (below Dej Tuff)	Sediments
	Panaiotu [6,55]	47.20	23.20	35.9	87.1	9.0	16.8	17	55	81.4	168.3	4.2	80.7 ± 9.9	23.3 ± 7.8	55.0	50.0	Lo. Ypresian	Sediments
	Panaiotu [6,55]	46.70	23.20	38.3	82.3	6.8	128.3	2	45	81.1	150.4	5.3	72.9 ± 8.9	21.7 ± 6.6	50.0	40.0	Lutetian	Sediments
Apuseni Mounts																		
7	Panaiotu [6,55][c]	45.90	22.80	42.2	81.8	5.8	18.4	35	80	81.0	232.5	6.9	76.1 ± 9.4	15.8 ± 6.9	77.0	65.0	Maastrichian	Volcanics
8	Panaiotu, Rosu et al. [6,27,54][d]	46.10	23.00	61.1	63.4	8.3	45.8	8	15	84.2	154.9	3.2	57.6 ± 14.3	0.0 ± 7.0	14.7	13.5	14.7–13.5 Ma	Volcanics
9	Panaiotu, Rosu et al. [6,27,54][d]	46.10	23.00	60.6	28.2	5.8	52.3	13	15	84.2	154.9	3.2	22.4 ± 10.1	0.5 ± 5.1	13.4	12.3	13.4–12.3 Ma	Volcanics
10	Panaiotu, Rosu et al. [6,27,54][d]	46.10	23.00	63.3	350.7	3.6	53.3	30	10	85.0	155.7	3.1	− 14.3 ± 7.3	− 1.8 ± 3.6	12.8	10.3	12.3–10.3 Ma	Volcanics
Eastern Carpathians (North of Fig. 2)																		
	Bazhenov et al. [31][a]	48.20	23.70	29.0	29.0	7.0	41.0	*10*	80	81.0	232.5	6.9	23.3 ± 9.7	30.4 ± 7.4	94.0	65.0	Turonian–Maastrichtian	Sediments
	Bazhenov et al. [31][a]	48.30	23.50	42.0	52.0	5.7	15.0	*43*	80	81.0	232.5	6.9	46.3 ± 9.5	17.5 ± 6.7	94.0	65.0	Turonian–Maastrichtian	Sediments
	Bazhenov et al. [31][a]	48.10	23.90	34.0	18.0	15.6	13.0	*7*	80	81.0	232.5	6.9	12.4 ± 16.8	25.3 ± 13.4	94.0	65.0	Turonian–Maastrichtian	Sediments
	Panaiotu [6][e]	47.60	23.80	63.0	4.9	2.7	22.4	123	10	85.0	155.7	3.1	− 0.3 ± 5.9	− 0.3 ± 3.0	11.0	9.0	9–11 Ma	Volcanics

#: Number of paleomagnetic result as referred in Fig. 2. Locality/reference: name of paleomagnetic sampling locality/reference for previous studies. Site location: latitute and longitude of sampling locality. Observed direction: inclination (I) and declination (D) of mean paleomagnetic direction in stratigraphic coordinates with the radius of 95% confidence circle (α_{95}), the precision parameter (k) and the number of sites used to calculate mean direction (n); n is italicized if number of sample ChRM directions. Reference pole: age, latitude and longitude, and A_{95} (95% confidence) limit of Eurasian paleomagnetic pole [48]. Rotation $R \pm \mathrm{DR}$: vertical axis rotation with 95% confidence limit (positive indicates clockwise rotation). Flattening $F \pm \mathrm{DF}$: flattening of inclination with 95% confidence limit (rotation and flattening are derived from observed direction minus expected direction at locality calculated from reference pole). Age control: lower and upper limits of attributed age of the sampled rocks.

[a] Data based on thermal demagnetizations up to 400 °C analyzed without principal component analysis ("demagcode 2" in IAGA paleomagnetic database).

[b] Supercedes [57].

[c] Supercedes [30].

[d] Supercedes [56].

[e] Supercedes [58].

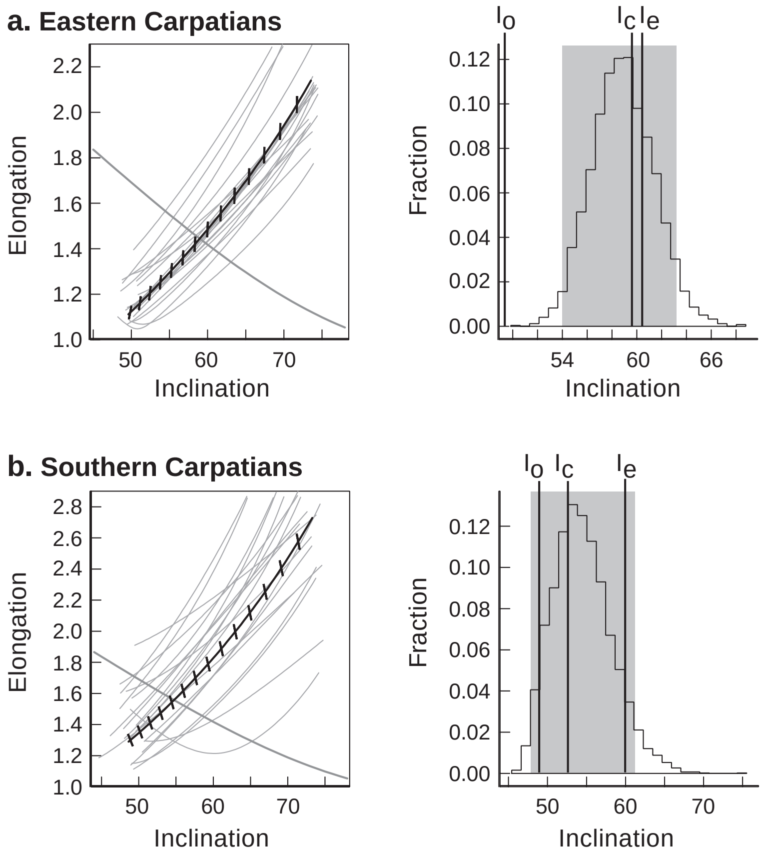

Fig. 5. Correction of inclination error using the method developed in [48]. On the left diagrams, the black curve shows variation of the elongation of the dataset distribution with respect to mean inclination when affected by a flattening factor ranging from 0.35 to 1.00; light gray curves are the same for generated datasets from bootstrat analysis. The corrected inclination is given by the intersection with the dark grey curve (expected elongation from geomagnetic model of [48]). Right diagrams indicate distribution of corrected inclinations with 95% confidence interval (grey area); Io is the mean observed inclination, Ic the mean corrected inclination and Ie the expected inclination from the APWP of Besse and Courtillot [47].

account for the rotation [14]. A more likely mechanism is provided by dextral wrenching occurring during Middle to Late Miocene southeastward collision and convergence of the Carpathian arc as demonstrated by well-documented structural studies [7,12,13]. Large scale dextral strike-slip duplexes have been recognized to accommodate the dextral transpressive convergence along the South Carpathians [16]. Crustal fragments involved in such structures in right lateral setting are generally associated with clockwise rotations [49]. Thus, we propose that crustal blocks have rotated 30° clockwise in domino fashion along the southern margin of the southern Carpathians during the Middle to Late Miocene southeastward collision (Fig. 6a).

Furthermore, the absence of tectonic rotations in the eastern and southern Carpathians after ~9 Ma, implies a change of tectonic regime. This change coincides with the post-Sarmatian cessation of thrusting reported by structural reconstructions [12,50] strongly suggesting a genetic link between vertical-axis rotations and thrusting during the collision. As previously proposed, this cessation of crustal deformation may reflect gridlocking of the Carpathian collisional system [25].

Finally, Pliocene tectonic rotations occurring exclusively in the Bend Area are in agreement with structural and basin analysis that indicate continuing tectonic activity restricted to the southeastern corner of the Carpathians during Pliocene to present time

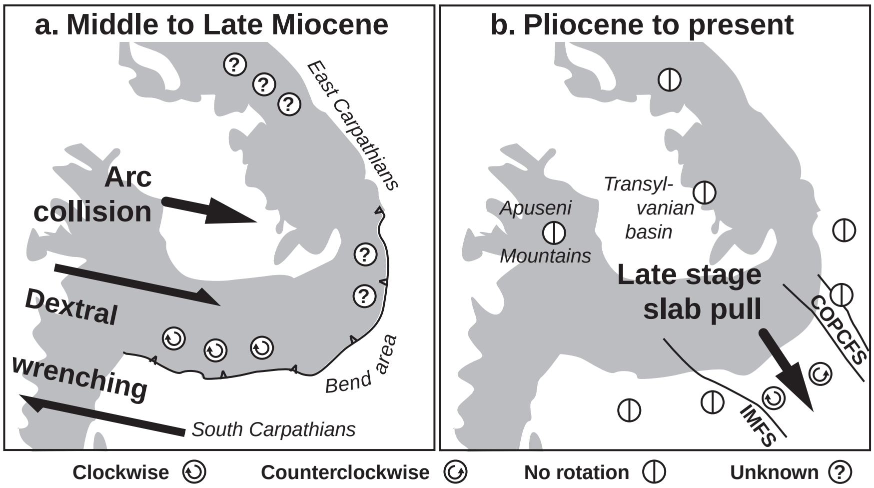

Fig. 6. Tectonic rotations during Neogene geodynamic evolution of the Southeastern Carpatho–Pannonian system. Shaded area is Carpathian orogen, IMFS: Intra-Moesian Fault System, COPCFS: Capidava–Ovidiu/Peceneaga–Camena Fault System.

[26,50]. The cause of this deformation is the topic of an ongoing discussion arguing for horizontal far-field stresses due to lithospheric buckling after collision and/or late-stage slab pull [9,22]. However, most studies agree that Pliocene deformation is strongly influenced by preexisting crustal to lithospheric heterogeneities (e.g. [25]). This is confirmed by our paleomagnetic data showing Pliocene rotations occurring only south of the Capidava–Ovidiu/Peceneaga–Camena Fault System (COPCFS) and northeast of the Intra-Moesian Fault System (IMFS). Consistent with southeastward motion of the Bend Area between these fault systems, the sense of these rotations is clockwise in the southwest (Bizdidel and Valea Vacii localities) and counterclockwise in the northeast (Slanicu locality). A similar pattern of rotations is observed in the late-stage slab pull of the Calabrian arc [51–53] providing a possible process driving southeastward motion of the Bend Area bounded by dextral IMFS and sinistral COPCFS (Fig. 6b). Additional Pliocene paleomagnetic data needs to be acquired in the Bend Area to test this assertion and define with more confidence the locus of deformation and the active lithospheric boundaries during this period.

Our results are in general agreement with previous paleomagnetic results from the southern and eastern Carpathians (Fig. 2 and Table 1). In the southern Carpathians, results from Cretaceous sediments (data based on thermal demagnetizations up to 400 °C analyzed without principal component analysis) indicate rotations of ~60–100° systematically in a clockwise sense at several locations [31]. These preliminary results suggest that the southern Carpathians have been affected by two distinct episodes of clockwise rotation; (1) the Middle to Late Miocene 30° rotation reported in the present study and (2) a possible older 30–70° rotation phase occurring earlier. In the hinterland, important Neogene results from K/Ar dated volcanic complexes of the Apuseni Mountains [54–56] and sediments from the Transylvanian basin [55] indicate systematic 60–80° clockwise rotations for rocks older than ~15 Ma, ~20° for 13.4–12.3 Ma rocks and slightly counterclockwise rotation for rocks younger than 12.3 Ma. Although this pattern was originally interpreted to result from recording of a continuous rotation from 15 to 12 Ma, it does not exclude the possibility that the rotation occurred in two distinct short phases. Further paleomagnetic investigations are needed in the southern Carpathian region to assess correlation between rotations observed in the hinterland and in the foreland and to test whether the total observed rotations results from one or two distinct episodes. Within the eastern Carpathians belt further to the north (not shown on Fig. 2; see Table 1), paleomagnetic data from Neogene volcanics (11 Ma and younger) of the outer Carpathian nappes [55,57,58] show no significant rotations and less reliable results from Cretaceous sediments indicate systematic 10–50° clockwise rotations [31]. The Neogene results are consistent with cessation of crustal rotations after Middle to Late Miocene collision as observed in our eastern Carpathians localities (Putna, Milcov and Rimnicu). However, the existing data is not sufficient to interpret the sense and the timing of possible rotations recorded before and during the Middle to Late Miocene collision. This was the aim of our paleomagnetic sampling from Middle Miocene localities (Negrilesti and Valea Sari) which have unfortunately not yielded primary magnetizations. Further paleomagnetic investigations are therefore required to understand how the Middle to Late Miocene collision has affected the eastern Carpathians.

5. Conclusions

Paleomagnetic results presented in this study have provided the pattern of vertical-axis rotation in the eastern and southern Carpathians. In the southern Carpathians, ~30° of clockwise rotations occurred during Middle to Late Miocene collision of the Carpathian arc. Well-documented structural studies support that clockwise rotations of crustal blocks occurred in domino fashion along the dextral transpressive collisional boundary. In the eastern and southern Carpathians, cessation of tectonic rotations after ~9 Ma coincides with the absence of major thrusting and gridlocking of the collisional system through the Pliocene. Continuing rotations restricted to the Bend Area are occurring in a pattern consistent with late-stage slab pull towards the southeast. This study confirms that, of the various geological tools at hand today, paleomagnetism is a powerful element to resolve the geodynamic evolution of orogenic systems.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2005.04.030.

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