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The contact zone between the ALCAPA and Tisza-Dacia mega-tectonic units of Northern Romania in the light of new paleomagnetic data

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Key words: rotation, paleomagnetism, Tisza-Dacia, Carpathians, Transcarpathian depression, Northern Romania

ABSTRACT

Paleomagnetic analyses were carried out on samples from 19 localities within two different mega-tectonic units in Northern Romania: Tisza-Dacia (11 localities) and ALCAPA (8 localities). The samples cover a range of different lithologies: (1) Late Cretaceous red-coloured marl to marly limestone, (2) Eo-Oligocene flysch sediments, and (3) mid-Miocene (Langhian) tuffite (Dej tuff and related sediments). The Late Cretaceous and mid-Miocene specimens carry secondary paleomagnetic signals exhibiting a counter clockwise deflection of the paleo-declinations by some 30°, while the Eo-Oligocene localities indicate an overall clockwise deflected (between some 45° and >90°) paleo-declination with respect to present-day north. Clockwise rotation postdates the age of sedimentation (Lower Oligocene), as well as (at least partially) thrusting of the Pienides onto the Tisza-Dacia mega-tectonic unit, which occurred between 20.5 and 18.5 Ma. Clockwise rotation predates post-12 Ma counter clockwise rotations inferred for the mid-Miocene localities.

Surprisingly, the clockwise rotations of the first rotational stage not only affected the (par-) autochthonous sedimentary cover of the Tisza-Dacia mega-tectonic unit, but also the allochthonous flysch nappes of the Pienides, i.e. the eastern tip of the ALCAPA mega-tectonic unit. Well-documented opposed rotation of the remainder of ALCAPA necessitates a detachment of this eastern tip of ALCAPA after 18.5 Ma. The most likely location for this detachment zone is along the margins of the Transcarpathian depression. During a second (post-12 Ma) stage, counter clockwise rotations of up to 30° affected the entire working area. Regarding timing and magnitude, these second stage rotations are similar to rotations documented for the East Slovak basin, but different from those reported from the South Apuseni Mountains and the Central and Inner West Carpathians located west of the East Slovak basin.

ZUSAMMENFASSUNG

An insgesamt 19 Lokalitäten in Nord-Rumänien wurden paleomagnetische Analysen in zwei grosstektonischen Einheiten durchgeführt: 11 Lokalitäten liegen im Tisza-Dacia Block, 8 sind Teil der ALCAPA-Einheit. Die untersuchten Proben umfassen folgende Lithologien: (1) Oberkretazische rote Kalkmergel, (2) Eo-Oligozäne Flysche und (3) Tuffite (Dej-Tuff und assoziierte Sedimente) des Mitteren Miozäns (Langhian). Die Proben aus der Oberkreide und dem Mittleren Miozän zeigen eine sekundäre Magnetisierung, deren Paläo-Deklination um ca. 30° gegen den Uhrzeigersinn rotiert ist. Die Paläo-Deklinationen der Eo- Oligozänen Proben hingegen weisen Abweichungen zu gegenwärtig Nord mit dem Uhrzeigersinn (45° und >90°) auf.

Die Rotation der Eo-Oligozänen Proben fand nach der Sedimentation der jüngsten Proben (unteres Oligozän), und zumindest teilweise nach dem Deckenschub der Pieniden (20.5–18.5 Ma) auf den Tisza-Dacia Block statt. Diese Rotation mit dem Uhrzeigersinn geht der durch die mittel- Miozänen Proben dokumentierten gegenläufigen Rotation (ab 12 Ma) voraus.

Die Rotationen der früheren Phase wurden nicht nur in den Sedimenten aus der (par-) autochthonen Bedeckung von Tisza-Dacia, sondern auch in den überschobenen Pieniden nachgewiesen. Dieses Ergebnis ist auf den ersten Blick überraschend, da sie Teil von ALCAPA sind, der Rest von ALCAPA zu dieser Zeit aber in einem gegenläufigen Sinn, also gegen den Uhrzeigersinn, rotierte. Diese gegenläufigen Rotationen erfordern also eine tektonische Ablösung der östlichsten Spitze von ALCAPA vom Rest dieser grosstektonischen Einheit. Der wahrscheinlichste Ort für eine solche Ablösung befindet sich an den Rändern der Transkarpathischen Depression. Die zweite Rotationsphase, ca. 30° gegen den Uhrzeigersinn nach 12 Ma, ist auch aus dem Ost-Slovakischen Becken bekannt. Sowohl die Internen West-Karpathen westlich des Ost-Slovakischen Beckens, als auch das südliche Apuseni Gebirge, zeigen nach 12 Ma ein vom Arbeitsgebiet abweichendes Rotationsverhalten.

Introduction

Opposed rotations of the two mega-tectonic units building the Carpathians, termed ALCAPA and Tisza-Dacia (Fig.1), are well established by paleomagnetic studies (e.g. Márton & Márton 1978, 1996; Márton & Fodor 1995, 2003; Panaiotu 1998, 1999; Márton 2000) and represent a central issue in the reconstruction of the Tertiary kinematics of these highly mobile units. In several tectonic reconstructions ALCAPA and Tisza-Dacia are treated as two distinct ”microplates” or ”blocks” (e.g. Fodor et al. 1999, Csontos & Vörös 2004), although both

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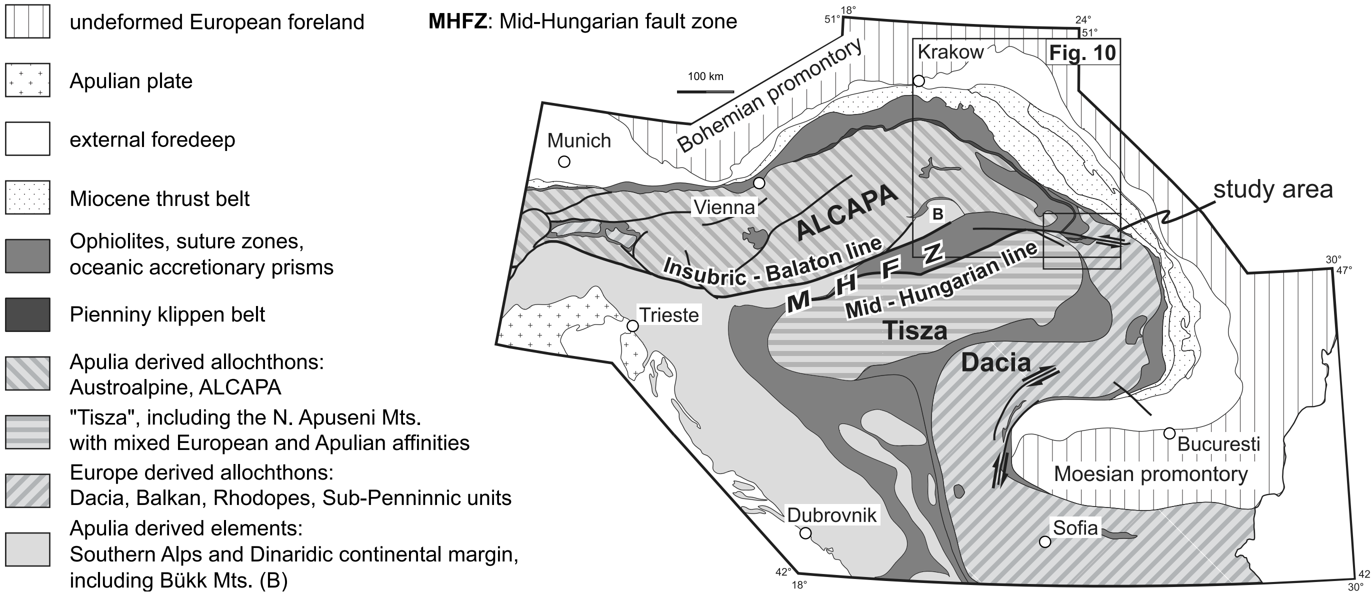

Fig. 1. Major tectonic units of the Alps, Carpathians and Dinarides (simplified after a yet unpublished compilation by S. Schmid, B. Fügenschuh, K. Ustaszewski, M. Tischler and L. Maţenco). The boxes mark the outlines of Fig. 10 and the study area, respectively.

mega-tectonic units were internally deformed. This is particularly true for their contact zone, the Mid-Hungarian fault zone, which continues into Northern Romania (Csontos & Nagymarosy 1998, Fodor et al. 1999, Györfi et al. 1999, Tischler et al. 2007).

The invasion of the ALCAPA and Tisza-Dacia mega-tectonic units into the Carpathian embayment is thought to be driven by retreat of the European lithospheric slab (e.g. Royden 1988, Wortel & Spakman 2000) and is coupled to ”lateral extrusion” in the Eastern Alps (Ratschbacher 1991 a, b; Sperner et al. 2002).

Final emplacement of these mega-tectonic units was accompanied by substantial strike-slip movements, extension and/or block rotations (Fodor et al. 1999, Márton 2000, Csontos et al. 2002, Márton & Fodor 2003, Horváth et al. 2006). Corner effects at the Bohemian (Sperner et al. 2002) and Moesian (Ratschbacher et al. 1993, Schmid et al. 1998, Fügenschuh & Schmid 2005) promontories (Fig. 1) are considered as important causes for the opposed rotations of continental units during their Neogene emplacement into the Carpathian embayment.

Converging movements partly also accommodated such rotations; they led to the juxtaposition, and finally the thrusting of ALCAPA onto Tisza-Dacia, as is documented by subsurface and outcrop data (e.g. Csontos & Nagymarosy 1998, Györfi et al. 1999, Tischler et al. 2007) along the Mid-Hungarian fault zone. The Mid-Hungarian fault zone shows a polyphase history, allowing for repeatedly occurring differential movements between the invading mega-tectonic units (e.g. Csontos & Nagymarosy 1998, Fodor et al. 1998, 1999). Most of the contact zone between the ALCAPA and Tisza-Dacia mega-tectonic units is covered by the Neogene fill of the Pannonian basin, but it is exposed in the Maramures area (Northern Romania).

In this paper two independent methods and studies are combined to better understand the tectonic evolution of the region, namely outcrop-scale structural studies (Huismans et al. 1997, Györfi et al. 1999, Tischler et al. 2007) and paleomagnetic investigations. The latter became possible since the recent regional tectonic study by Tischler et al. (2007) provided suitable outcrops for paleomagnetic sampling, in a generally badly exposed area with friable lithologies. The analysis of structural and paleomagnetic data sets was performed separately and was only combined in a last step. Paleomagnetically registered rotations were robust and extended beyond the study area. This leads us to propose a working hypothesis for the structural and rotational history of the area for the last 30 Ma.

Geological setting

The study area, located in northern Romania, at the northern margin of the Transylvanian basin, is in an internal position with respect to the main Carpathian chain. The crystalline basement and Mesozoic cover units, which crop out in the study area (Fig. 2), belong to the Tisza unit (Biharia unit) and the Dacia-unit (Infra- Sub- and Bucovinian nappes). Both units form a single Tisza-Dacia mega-tectonic unit since Early Tertiary times. These basement units have a poly-phase deformation history; their internal structure was formed during middle to latest Cretaceous times (Săndulescu et al. 1981). During Late Cretaceous and Paleocene times, a common

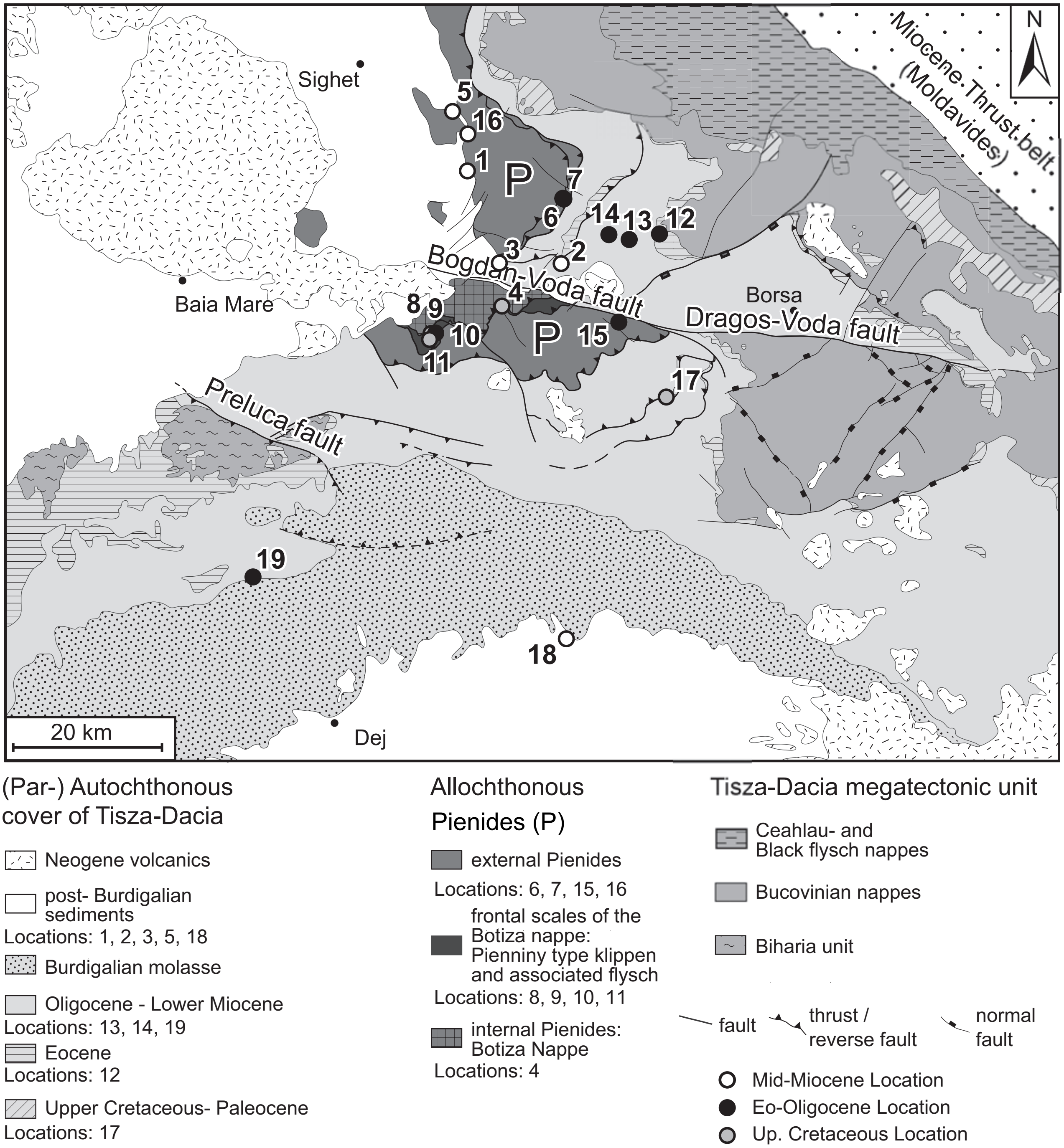

Fig. 2. Tectonic map of the study area, based on published geological maps (1:50.000 & 1: 200.000) of the Geological Survey of Romania, Dicea et al. (1980), Săndulescu (1980), Săndulescu et al. (1981), Aroldi (2001) and Tischler et al. (in press). Sampling localities are indicated.

sedimentary cover (”autochthonous cover” of Fig. 2) was deposited onto both Tisza and Dacia units, thus sealing all earlier tectonic contacts (Săndulescu 1994).

Eocene strata again un-conformably overlay these Late Cretaceous and Paleocene sediments. In the northern part of the study area a westward deepening of the depositional environment is documented (local carbonate platforms and conglomerates in the east, marly littoral-neritic facies in the west; Dicea et al. 1980, Săndulescu et al. 1981). In the southern part of the study area, continental to shallow marine environments prevail during the Eocene (Popescu 1984, De Broucker et al. 1998).

Table 1. List of sampling localities. X/Y coordinates are given in Lat/Long WGS84.

Nr	X	Y	Tectonic unit	age	lithology
1	24.0715	47.8040	Dej tuff	Langhian	tuff
2	24.2418	47.6984	Dej tuff	Langhian	tuff
3	24.1337	47.6965	Dej tuff	Langhian	tuff
4	24.1409	47.6456	Botiza nappe	Sennonian (Turonian?)	marly limestone
5	24.0414	47.8737	Dej tuff	Langhian	tuff/marl
6	24.2425	47.7750	Leordina nappe	Ypresian-Low.rupelian	marl
7	24.2407	47.7758	Leordina nappe	Oligocene	marl
8	24.0274	47.6019	Botiza frontal scales	Cenomanian-Sennonian	marly limestone
9	24.0292	47.6011	Botiza frontal scales	Eocene	marl
10	24.0357	47.6026	Botiza frontal scales	Eocene	marl
11	24.0254	47.5947	Botiza frontal scales	Cenomanian-Sennonian	marly limestone
12	24.4124	47.7375	Autochtonous	Priabonian	marl
13	24.3596	47.7297	Autochtonous	Low. Rupelian	menilithic marl
14	24.3238	47.7347	Autochtonous	Low. Rupelian	marl
15	24.3466	47.7347	Wildflysch nappe	Lutetian - Priabonian	marly silt
16	24.0699	47.8477	Petrova nappe	Lutetian - Priabonian	marly silt
17	24.4338	47.5447	Autochtonous	Turonian - Priabonian	marly limestone
18	24.2742	47.2545	Dej tuff	Langhian	tuff/marl
19	23.7255	47.3135	Autochtonous	Low. Oligocene	marl

Following a regional drowning event at around the Eocene/Oligocene boundary terrigenous siliciclastics have been deposited in a E-W to SE-NW oriented basin (De Broucker et al. 1998). A SE-ward thinning clastic wedge of Burdigalian age ("Burdigalian molasse", Fig. 2), deposited in an ENE-WSW trending basin, is documented at the northern border of the Transylvanian basin (Ciulavu et al. 2002).

Coevally with the deposition of this clastic wedge, flysch nappes ("Pienides", Fig. 2) have been thrust onto the autochthonous cover of the Tisza-Dacia mega-tectonic unit, leading to imbrication of this autochthonous cover in the Lower Burdigalian (20.5–18.5 Ma; De Broucker et al. 1998, Györfi et al. 1999, Tischler et al. 2007). The various units of the Pienides (Săndulescu 1984, 1994; Săndulescu et al. 1993) consist of Eocene and Oligocene flysch units and can be divided, from internal to external, into: Botiza nappe, Pieniny type klippen including associated flysch, and external nappes (Petrova, Wildflysch and Leordina nappes). The Pienides represent the eastern continuation of the Pieniny Klippen Belt and the Magura unit of the Western Carpathians (Săndulescu 1980). Hence they are considered as parts of ALCAPA by most authors (e.g. Balla 1984, Csontos 1995, Kováć et al. 1994, Fodor et al. 1999, Tischler et al. 2007). Their emplacement onto the autochthonous cover of the Tisza-Dacia mega-tectonic unit is thought to represent the last increment of thrusting of the frontal part of ALCAPA onto Tisza-Dacia (see also Györfi et al. 1999). The direction of emplacement (SE-directed in present coordinates) is roughly perpendicular to the long axis of the wedge of the Burdigalian molasse (Fig. 2). This supports the interpretation of the wedge-shaped Burdigalian deposits in terms of a foreland basin fill related to the emplacement of the Pienides, as was previously suggested by De Broucker et al. (1998), Györfi et al. (1999) and Ciulavu (1999). During Miocene times the ALCAPA and Tisza-Dacia mega-tectonic units were docked to the European foreland, generating the Miocene thrust belt (Fig. 2).

Above a second regional unconformity dacitic tuffs (Dej Tuff) of Langhian (Badenian) age (post-16 Ma; this and all later conversions into an absolute time scale are after Gradstein et al. 2004) were deposited onto both the Tisza-Dacia mega-tectonic unit and the Pienides, already thrust onto Tisza-Dacia. The source area of the volcanic activity is thought to be located NW of the study area (Szakács et al. 2000). Andesitic volcanic activity between 14–9 Ma (Pécskay et al. 1994) led to the formation of the volcanic body near Baia Mare (Fig. 2), which obscures the western continuation of the Pienides.

Starting in mid-Miocene times, two stages of strike slip dominated brittle deformation indicate ongoing deformation after the amalgamation of Tisza-Dacia with ALCAPA (Tischler et al. 2007). A first transpressional stage (16–12 Ma) is dominated by SW-NE compression; active map scale features are the Preluca fault and the Bogdan-Voda fault. This transpressional stage is followed by transtension (SW-NE compression, with dominant NW – SE extension, 12–10 Ma), representing the main phase of left lateral movement along the so-called Bogdan- Dragos-Voda fault system. These deformations are most probably connected to left lateral transtension along the Mid-Hungarian fault zone (e.g. Csontos & Nagymarosy 1998). According to Tischler et al. (2007) substantial opposed-sense rotations across the Bogdan- Dragos-Voda fault system can be excluded for this late stage of the tectonic evolution.

Paleomagnetic sampling

Samples were collected at 19 localities (Table 1 and Fig. 2). They cover a range of lithologies and represent different ages and tectonic units. Great care had to be taken to avoid strata, which had been affected by recent gravitational creep or sliding, which is common in the study area. In addition, the need

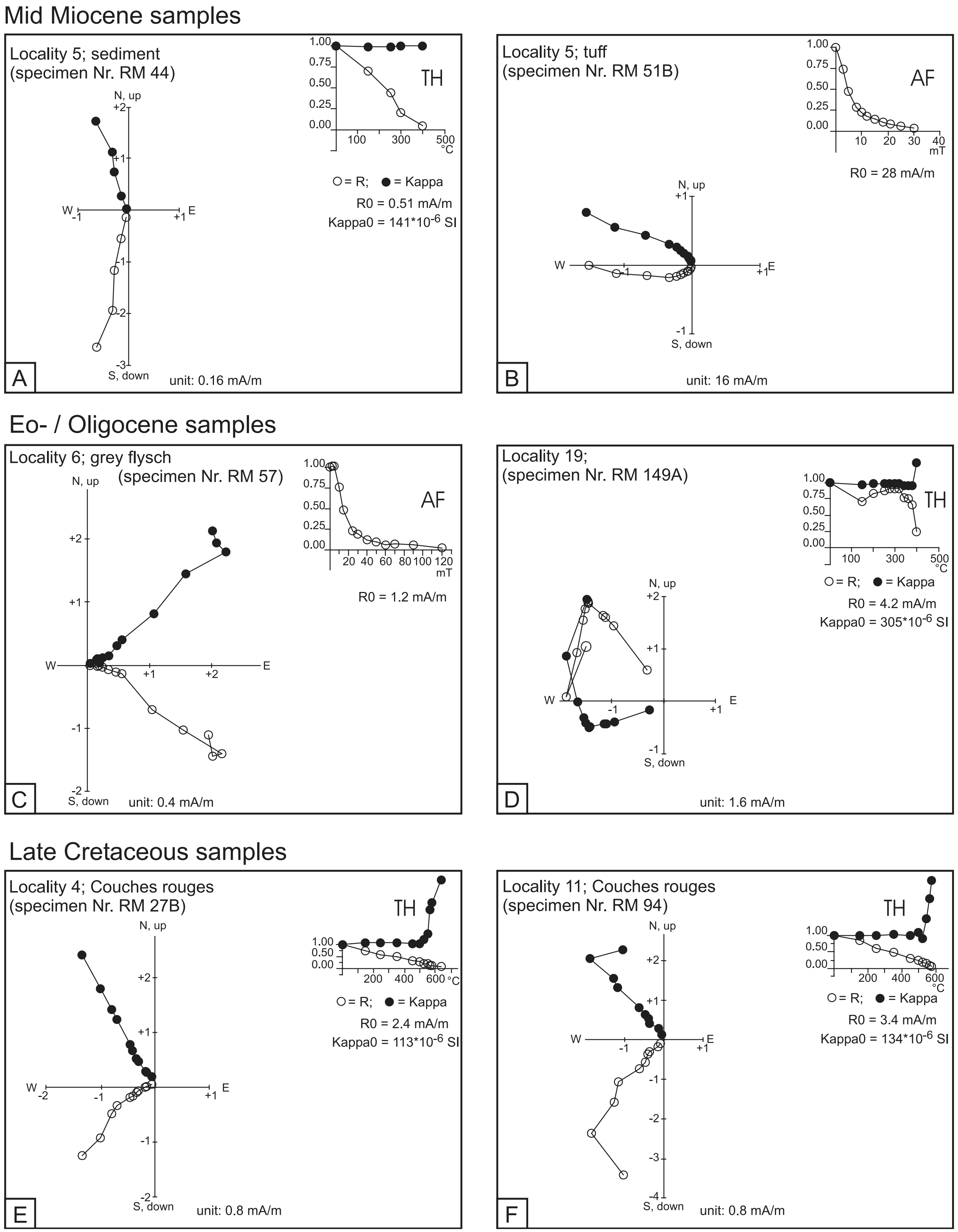

Fig. 3. Maramures area: Zijderveld diagrams and intensity/susceptibility versus temperature (TH) or demagnetizing field (AF) curves. Zijderveld diagrams: full/open circles: projection of the natural remnant magnetization in the horizontal and vertical plane, respectively. Other diagrams: dots: susceptibility; circles: intensity of NRM.

Table 2. Maramures area. Locality mean paleomagnetic directions with statistical parameters. Key: n/no: number of used/collected samples; D°, I° (Dc°, Ic°): declination, inclination before (after) tilt correction; k and α_{95}°: statistical parameters (Fisher 1953). Calculation of directions from least-squares fit of straight line segments after Kirschwink (1980).

Nr	Locality	n/no	D°	I°	k	α_{95}°	D_C°	I_C°	k	α_{95}°	dip
Dej tuffs and accompanying sediments											
1	Tuff *Langhian* RM 1-9	4/9	353	+72	212	6	289	75	212	6	224/18
2	Tuff *Langhian* RM 10-19	4/10	334	+73	151	8	222	78	151	8	181/24
3	Tuff *Langhian* RM 20-26	7/7	204	-30	104	6	166	-61	104	6	236/45
5a	Sediment *Langhian* RM 39-47	5/9	339	+57	32	14	3	+14	32	14	28/51
5b	Tuff *Langhian* RM 48-53	6/6	325	+45	22	14	345	+15	22	14	23/46
18	Dej tuff and ** accompanying sediment *Langhian* RM 131-141 (135-137)	3/11	337	+52	159	10	321	+54	159	10	225/10

	Locality	n/no	D°	I°	k	α_{95}°	D_C°	I_C°	k	α_{95}°	dip
Autochtonous											
12	Slump? *Priabonian* RM 97-101	5/5	237	17	13	22	241	2	13	22	238/27
13	*lower Rupelian*	5/6	330	+26	63	10	324	+8	63	10	280/27
	RM 102-107 *	5/6	328	+10	43	12	329	-8	43	12	
14	*lower Rupelian* RM 108-114	6/7	264	-26	41	11	274	-57	41	11	251/32
19	Marl *Lower Oligocene or* *Upper Eocene* RM 142-153	10/12	256	-49	21	11	276	-43	21	11	157/20
17	red marl *Turonian to Priabonian* RM 123-130	8/8	188	+18	36	9	173	+66	36	6	20/50 average

	Locality	n/no	D°	I°	k	α_{95}°	D_C°	I_C°	k	α_{95}°	dip
Botiza nappe and frontal scales of Botiza nappe (Pienniny type klippen and accompanying sediments)											
9	Flysch *Eocene* RM 77-79	3/3	351	30	106	12	350	-3	106	12	344/34
10	Flysch	7/9	294	+27	15	16	295	-13	15	16	312/42
	Eocene * RM 80-88	8/9	298	+14	14	15	296	-26	14	15	
4	red marl *** Senonian *(Turonian?)* RM 27-38	8/12	329	+40	24	12	335	+23	7	23	0/28 125/15
8	red marl *Cenomanian-Senonian* RM 71-76	6/6	321	+51	165	5	321	+21	165	5	300/30
11	red marl *** *Cenomanian-Senonian* RM 89-96	8/8	338	+39	29	10	331	+21	12	17	337/30 243/22

Table 2. Continue

Nr	Locality	n/no	D°	I°	k	α_{95}°	D_C°	I_C°	k	α_{95}°	dip
External Pienides (Petrova nappe)											
6	Flysch *Ypresian - lower Rupelian* RM 54-61	5/8	63	+19	8	23	32	+35	8	23	303/57
7	Flysch *Ypresian - lower Rupelian* RM 62-70,	5/9	269	-3	23	16	249	-41	23	16	311/58
External Pienides (Wildflysch nappe)											
15	Wildflysch *Lutetian-Priabonian* RM 115-120	0/6	Large scatter, bad demagnetisation behaviour								306/8

* directions calculated from end points of demagnetization

** sediments failed

*** negative within locality fold test

for sufficiently fine-grained and visibly unaltered sediments led to the abandonment of some of the localities visited without sampling. Samples were taken using a portable drill; the cores were oriented with a magnetic compass. The number of independently oriented cores at each locality (Table 1) depended on the outcrop conditions in terms of lithology, angle of dip (hence tilt) of the sediments and also on the prospect of obtaining useful paleomagnetic directions. The lithologies included dacite tuffite (”Dej tuff”) and accompanying sediments (e.g. localities 5 and 8) as well as dark grey (silty) marls and red marls (Couches rouges). The age of the sampled rocks ranges from latest Cretaceous to Langhian (Badenian).

Standard-size specimens were cut from a total of 153 samples drilled at these 19 sites. They were subsequently subjected to paleomagnetic and magnetic susceptibility anisotropy measurements at the Paleomagnetic Laboratory of the Eötvös Loránd Geophysical Institute of Hungary.

Laboratory measurements and results

The natural remnant magnetization (NRM) of each specimen was at first measured by using JR-4 and JR-5a spinner magnetometers. This was followed by the measurement of the anisotropy of magnetic susceptibility (on KLY-2). Sister specimens of selected samples were subsequently stepwise demagnetized, by the alternating field (AF) or the thermal method. After each step the remaining NRM was re-measured (also susceptibility in cases where the thermal method was applied). As the NRM was rarely single component, most samples had to be demagnetized in several, sometimes in a large number of steps (Fig. 3).

Demagnetization graphs (examples are shown in Fig. 3) were analysed for linear segments (representing components of the NRM; Kirschvink 1980), and the directions of these segments were used for estimating the mean paleomagnetic directions with statistical parameters (Table 2).

After removing a small viscous component, NRM sometimes consisted of a single component (Fig. 3A, 3F); sometimes two components could be separated (Fig. 3B, 3C, 3D, 3E). Occasionally, the direction of the natural remnant magnetization for some samples moved along a great circle without reaching a stable end point (i.e. the components constraining the great circle were not clearly separable). In such cases (localities 10 and 13, see Table 2) the mean paleomagnetic directions for a given locality were determined in three different ways. One was based on linear segments, the second was calculated from the last meaningful demagnetization steps, and the third was based on the combination of stable vectors and remagnetization circles (McFadden 1990). As Table 2 documents, the three methods provided the same directions (within the error limit). Unstable behaviour, and consequently failure to determine a mean paleomagnetic direction, only concerned locality 15, and partly locality 18 (Lower Langhian = lower Badenian sediments). However, one or more samples from other localities had to be rejected for reasons of instability.

From a statistical point of view, the results compiled in Table 2 are of different quality. Parameters, k and alpha are excellent for localities 1, 2, 3, 8 and 17 (k high and alpha small; Table 2); regarding localities 4, 5, 7, 9, 10, 11, 13, 14, 18 and 19 they are good or acceptable. For localities 6 and 12 the statistical parameters are poor (k lower than 10 or alpha more than 16°; Van der Voo 1993). Nevertheless, the tectonic information contained in the result for locality 6 is important. When used in combination with the paleomagnetic direction for locality 7 it provides interesting information about the Pienides. Results for localities 16 and 15 are not tabulated, because too few samples are available and because of the instability of NRM.

Magnetic mineralogy experiments (Lowrie 1990) revealed that the mid-Miocene samples and the Eocene–Oligocene sediments contain magnetite (Fig. 4 a–c). In the Senonian red marls (Fig. 4d) the magnetic mineral is hard and hematite

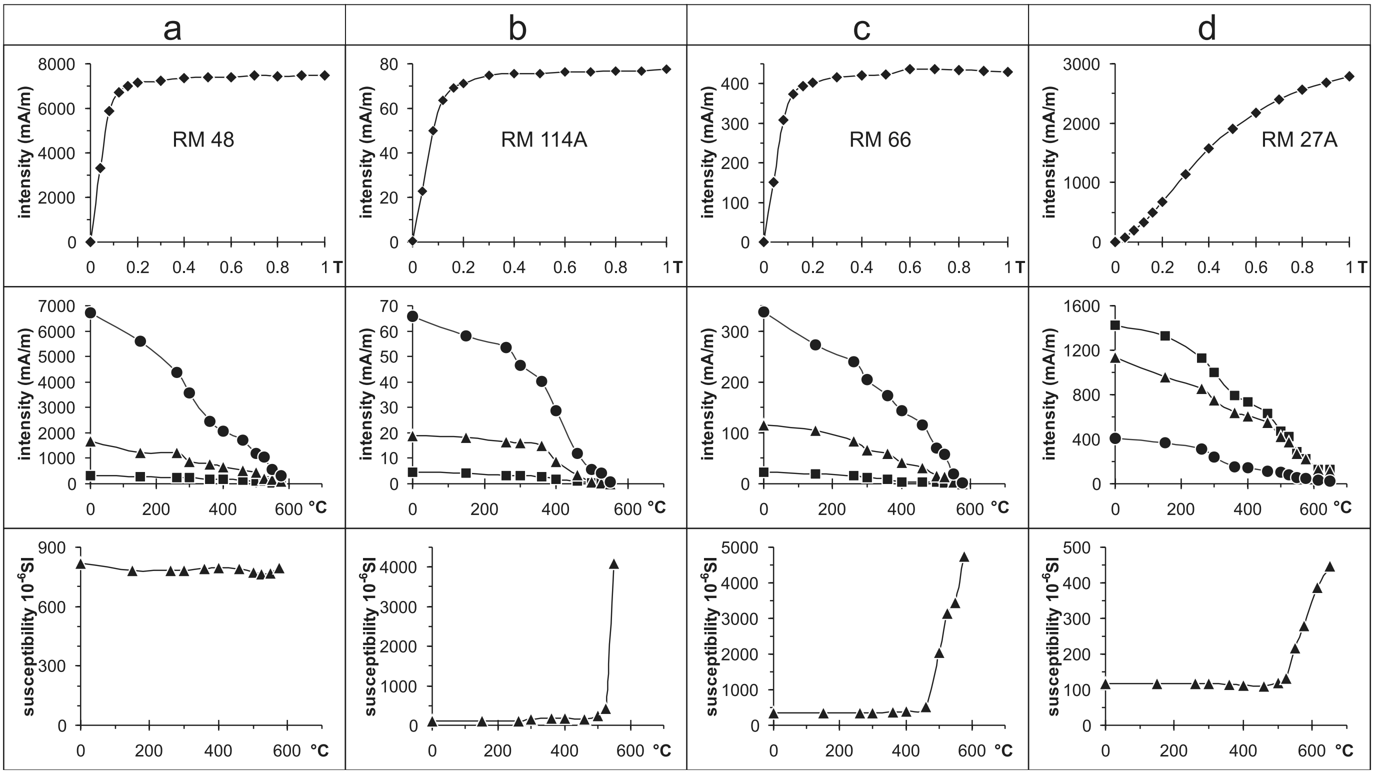

Fig. 4. Magnetic minerals, identified by acquisition of isothermal remnant magnetization (IRM, top row), stepwise thermal demagnetization of 3-component IRM (Lowrie 1990), acquired successively in fields of 1.0T (squares), 0.36T (triangles) and 0.12T (circles), respectively, and by the behaviour of the magnetic susceptibility on heating.

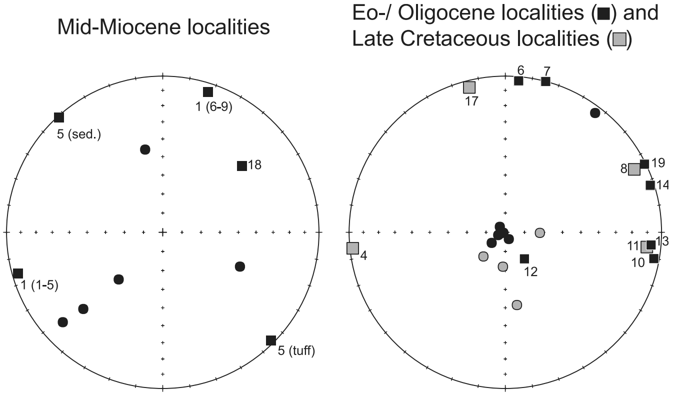

Fig. 5. Directions of magnetic lineations (squares; numbered, according to table 1) and foliation poles (dots) in stereographic projection (tectonic system). Note that all magnetic lineations, except 12, are practically horizontal.

seems to dominate. However, the NRM signal is lost at around 600°C (see Fig. 3E). This suggests that slightly oxidized magnetite, rather than hematite, is the actual carrier of the remnant magnetization.

Measurements of magnetic susceptibility anisotropy showed that the degree of anisotropy (kmax/kmin) is low in mid-Miocene samples (between 0.8 and 2.4%), with the exception of locality 18 (as high as 10%). In the remaining samples, the degree of anisotropy lies between 4 and 9%, except for those taken from locality 15, which show a surprisingly low (average 1.4%) degree of anisotropy. This is probably due to the dominance of secondary magnetic minerals, an interpretation corroborated by the failure to obtain a paleomagnetic direction for this locality.

Magnetic fabric is foliated; foliation poles are close to the bedding poles for sedimentary localities, pointing to a dominantly sedimentary origin of the fabric. Magnetic lineation is subordinate (normally less than 1%), yet lineation directions are usually clustered at a given locality (Fig. 5). There is definitely a small imprint by deformation in case of the sediments that pre-date the Dej tuff, since lineation coincides with the strike of the beds measured in the field. However, a weak lineation suggests weak internal deformation. Consequently, bias of the paleomagnetic vector towards the axis of maximum susceptibility (=”magnetic lineation”) is highly unlikely. Concerning the foliation, shallow paleomagnetic inclinations observed for localities 9,10 and 13 (Table 2) are not coupled with a stronger foliation. Therefore inclination shallowing due to compaction is not likely, either.

Discussion of paleomagnetic results

All sampled strata were tilted, occasionally also folded (localities 4 and 11) at the scale of the outcrop. This allowed for fold tests at localities 4 and 11, and for tilt tests on a regional level, thus helping to decide if the paleomagnetic signals were acquired before or after folding/tilting. A positive fold test, characterised by significantly improved clustering of the paleomagnetic directions after application of tilt corrections, suggests acquisition of magnetization before tilting. A negative fold test, with better directional grouping before applying tilt corrections, suggests acquisition of magnetization after tilting. For the test only strata or localities of similar age within the same tectonic unit should be considered. In figures 6–8 the plots labelled "geographic system" and "tectonic system" show directions before and after tilt corrections ("fold test"), respectively, for the populations of mid-Miocene, Eo-/Oligocene and Late Cretaceous samples.

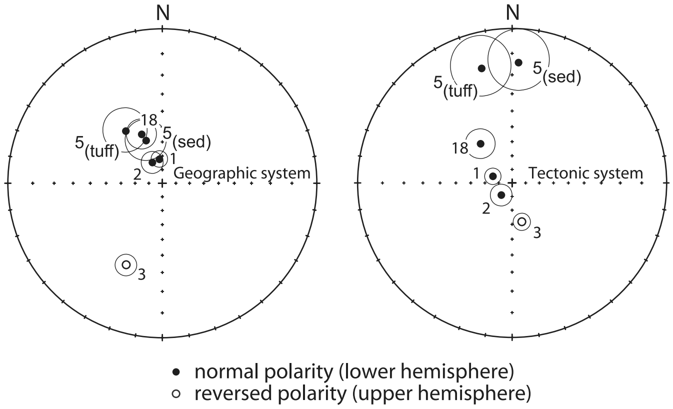

Fig. 6. Mean paleomagnetic directions (with confidence circles) for the mid-Miocene localities. Left: no tilt correction applied; right: tilt correction applied. Tilt test is negative for localities 1, 2, 5 and 18 (Table 3), while the mean direction of locality 3 moves towards the rest (with opposite polarity) of the localities after tilt correction.

Mid-Miocene localities: Dej tuff and related sediments

Paleomagnetic directions with normal polarity prevail among the Dej tuff and related sediments. They yield a negative response to tilt corrections (Fig. 6, Table 3). In our tectonic interpretation we will therefore consider the mean paleomagnetic direction in a geographic co-ordinate system. If we compare the paleomagnetic direction with reversed polarity (locality 3) to this overall mean direction, we can immediately notice that it has a much shallower inclination in geographic coordinates. However, after tilt correction it moves close to the overall mean direction for the normal polarity group (in antipodal position), the latter still in a geographical co-ordinate system. As the improvement in clustering is basically due to a dramatic improvement in the degree of consistency of inclinations, we interpret the paleomagnetic direction for locality 3 to pre-date tilting (Fig. 6). This interpretation implies that number 3 is the only site amongst the Dej tuffs, which preserved the paleomagnetic signal acquired before the tilting event. The overall mean paleomagnetic direction determined this way (Table 3, number 3) departs by some 30° from present-day north in a counterclockwise sense (Fig. 6). It is interesting that locality 18, which is situated south of the Bogdan- Dragos-Voda fault system, also exhibits counter clockwise rotation. This poses a problem in the context of the earlier postulated repeated clockwise rotation of the Tisza-Dacia mega-tectonic unit (Panaiotu 1999); but we have to keep in mind that this result is based on only three samples. Due to the small number of samples, this direction should only be taken into account as an indication, rather than firm evidence, in a tectonic interpretation.

Late Cretaceous localities: red marls

Three out of four Late Cretaceous localities yield good results and are located in allochthonous units (locality 4 at the base of the Botiza nappe; localities 8 and 11 in the Pieniny type klippen and associated flysch). Locality 17 is in the parautochthonous cover of the Tisza-Dacia mega-tectonic unit. At localities

Table 3. Overall mean paleomagnetic directions constraining the Tertiary rotations of the Maramures area. Key as for Table II, and N is the number of localities.

		N	D°	I°	k	α_{95}°	D_C°	I_C°	k	α_{95}°	remark
1	Dej tuffs and accompanying sediments localities: 1, 2, 5a, 5b, 18	5	336	+60	38	13	337	+53	4	41	present paper max: -10%
2	Dej tuffs and accompanying sediments localities: 1, 2, 5a, 5b, 18 and 3	6	348	+57	15	18	339	+54	5	32	present paper max: +20%
3	Dej tuffs and accompanying sediments localities: 1, 2, 5a, 5b, 18 before tilt correction and 3 after tilt correction	6	337	+60	46	10	-	-	-	-	present paper
4	Cenomanian-Senonian red marls localities: 4, 8, 11	3	330	+43	81	14	-	-	-	-	present paper
5	Eo/Oligocene autochthonous localities: 14, 19 and Panaiotu RONAP, DS	4	259	-42	37	15	269	-44	60	12	present paper + Panaiotu 1999 max: +60%
6	Eo/Oligocene localities 6,7	2	256	-11	-	-	230	-40	-	-	present paper

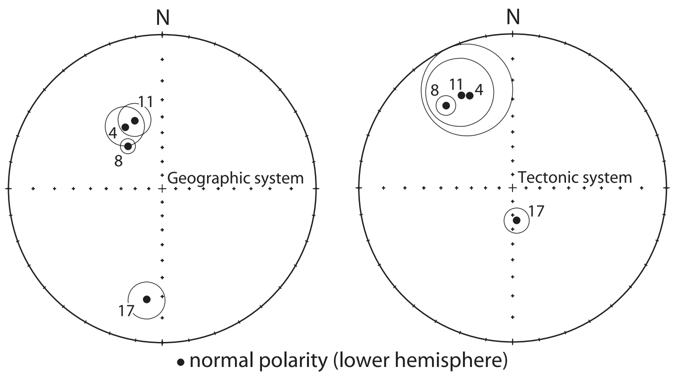

Fig. 7. Mean paleomagnetic directions (with confidence circles) for the Late Cretaceous localities. Note that the data obtained for localities 4 and 11 fail the within-locality fold test (Table 2) and thus indicate remagnetization (probably) during mid-Miocene times.

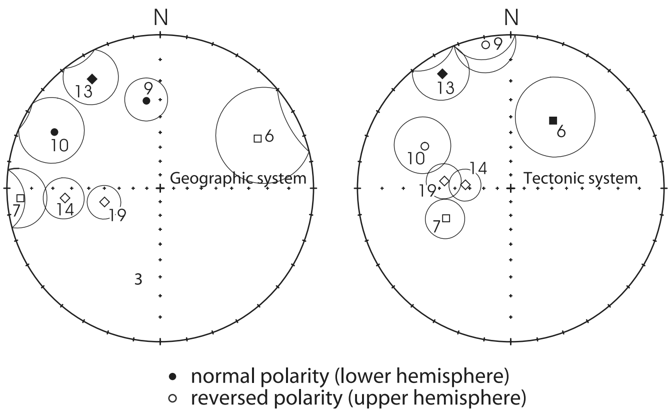

Fig. 8. Mean paleomagnetic directions for the Eo-Oligocene localities (autochthon: diamond; Leordina nappe: squares; Botiza nappe: circles). Note that the fold test improves the grouping for 6 (normal polarity), 7, 14, 19 (reversed polarities), and that the paleomagnetic direction for locality 10 moves closer to the cluster after tilt correction.

4 and 11 samples were drilled from strata with variable tilts. Within-locality fold tests for these localities yielded negative results (Table 2), which indicates re-magnetization. Since the direction of locality 8 groups well with those of 4 and 11 (Fig. 7), it is also considered as remagnetized. The most likely explanation for remagnetization after folding is that the red marls originally contained goethite, which became dehydrated and converted into a hematite-like mineral, perhaps under the influence of Neogene volcanism because their paleomagnetic directions show a remarkable similarity to the paleomagnetic directions obtained for the mid-Miocene localities and depart from paleomagnetic directions expected for Cretaceous (Besse and Courtillot 2002).

Locality 17 has excellent paleomagnetic properties, but appears as an outlier, both when plotted in the geographic as well as in the tectonic co-ordinate system, respectively (Fig. 7). Being collected from the parautochthonous cover of Tisza-Dacia, its unexpected direction is difficult to interpret in terms of tectonics. Quite possibly these strata were also influenced by gravitational movements which were evident nearby but not within the sampled outcrop.

Eo- to Oligocene localities: flysch samples

Seven localities plotted in Figure 8 yielded statistically good or acceptable paleomagnetic directions (see Table 2). Three of them (localities 14, 19 and 13) belong to the autochthonous-parautochthonous cover of the Tisza-Dacia mega-tectonic unit. Localities 14 and 19 in both geographic and tectonic co-ordinate systems indicate about 90° clockwise rotation with respect to present north (and also to expected directions for Eocene-Oligocene, Besse & Courtillot 2002), while inclinations are consistent and moderately steep. Locality 13 yields extremely low inclination values, both before and after tilt correction. We suspect that the apparently good magnetic signal still is a composite one, and must be disregarded in tectonic interpretation.

Localities 6, 7 are from the allochthonous external Pienides (Leordina nappe). The mean directions have very shallow inclinations before tilt correction, while after tilt correction (tectonic system in Fig. 8), the mean directions become roughly antipodal and inclinations become similar to those obtained for localities 14 and 19 from the autochthonous. We consider these directions as original, pre-folding magnetizations, showing marked clockwise rotation.

Localities 9 and 10 are from the internal Botiza nappe. Paleomagnetic directions obtained for them are far apart from each other in both co-ordinate systems; inclinations are too shallow in order to represent Paleogene or younger inclinations. Therefore we do not consider them in our tectonic interpretation.

In summary, out of seven tabulated mean paleomagnetic directions for the Eo-Oligocene, four localities are suitable for an interpretation in terms of regional tectonics: two from the autochthon and two from the Leordina nappe. They have consistent inclinations and all of them exhibit a clockwise deviation of the declination with respect to present-day north. There is, however, a difference in declination between the autochthon and the Leordina nappe, as will be discussed below.

Discussion and tectonic interpretation of the results

Re-magnetization of the Cretaceous localities led to paleomagnetic directions, which are remarkably similar to those obtained for the mid-Miocene localities. Hence, these two data sets will be discussed together to make inferences about post mid-Miocene counter-clockwise rotations. In a second step we discuss clockwise rotations indicated by the data obtained from the Eo- Oligocene formations.

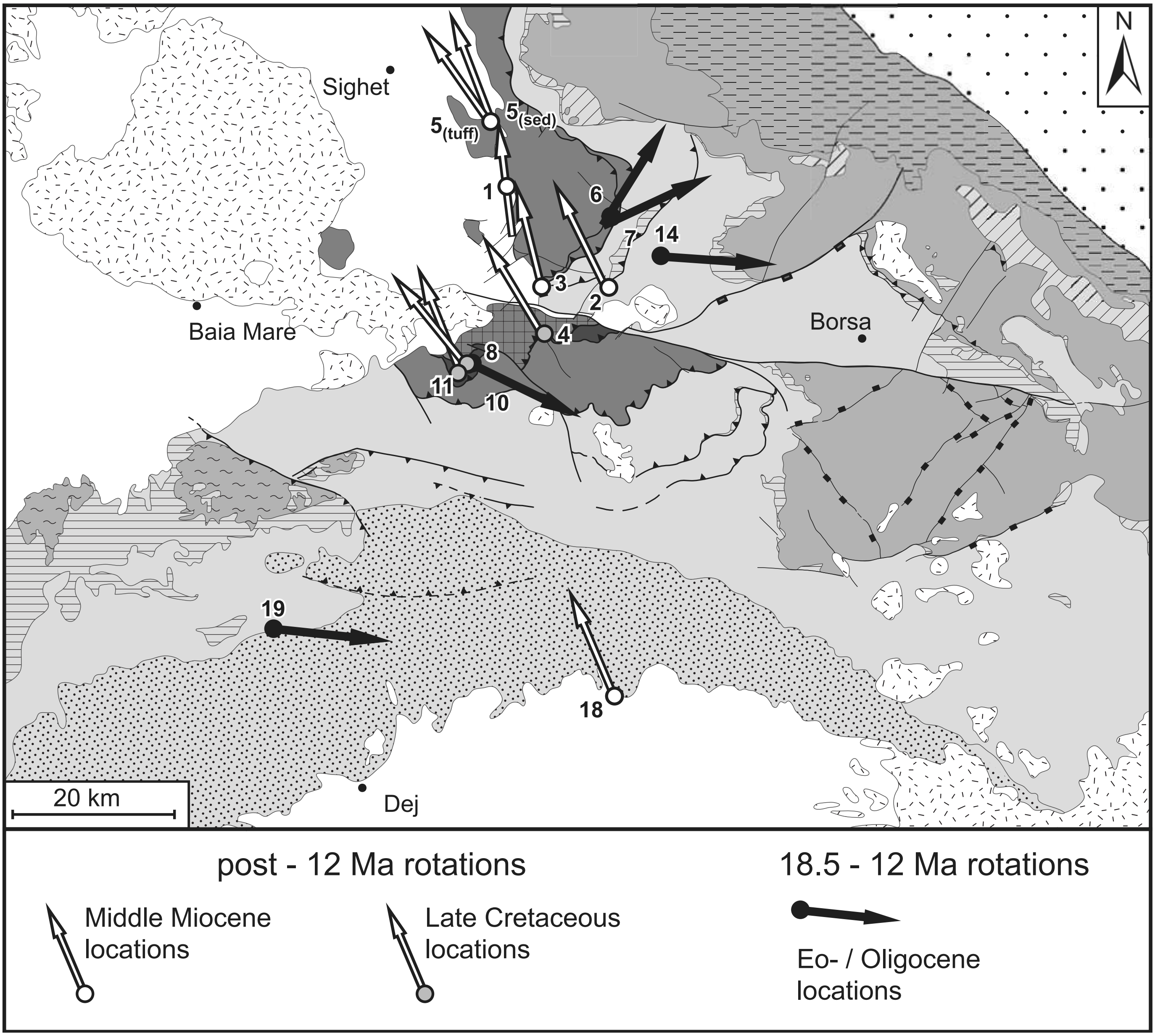

Fig. 9. Paleo-declinations, plotted relative to present-day north on a geological map. The secondary magnetizations of mid-Miocene and Late Cretaceous localities indicate a post-12 Ma (see text) counter clockwise rotation of about 30° (white arrows). The Eo-Oligocene locations show consistent clockwise rotations that pre-date the counter clockwise rotations (black arrows; see discussion in text).

Inferences regarding post-12 Ma counter-clockwise rotations (mid-Miocene and Late Cretaceous localities)

The mid-Miocene localities (with the exception of locality 3) and the Late Cretaceous localities carry secondary paleomagnetic signals departing from the direction of the present-day earth magnetic field in the sampling area (Fig. 9). The deflection indicates counter-clockwise rotations of about 30° (Table 3). This rotation must have taken place later than 12 Ma ago, since the negative fold/tilt tests indicate that their characteristic remnant magnetism was acquired after folding, which ended 12 Ma ago (Tischler et al. 2007). A similar rotation was suggested for the Sarmatian (13–11.6 Ma) members of the volcanic body of Baia Mare (Pătrăscu 1993), while the Late Miocene (Pannonian, post-11.6 Ma) members in the same body remained unaffected by this rotation. Thus, the counter-clockwise rotation observed for the Dej tuff and or the Late Cretaceous localities must have occurred immediately after tilting and magnetization, i.e. about 12 Ma ago. Note that this rotation involved the cover of the Tisza-Dacia mega-tec-

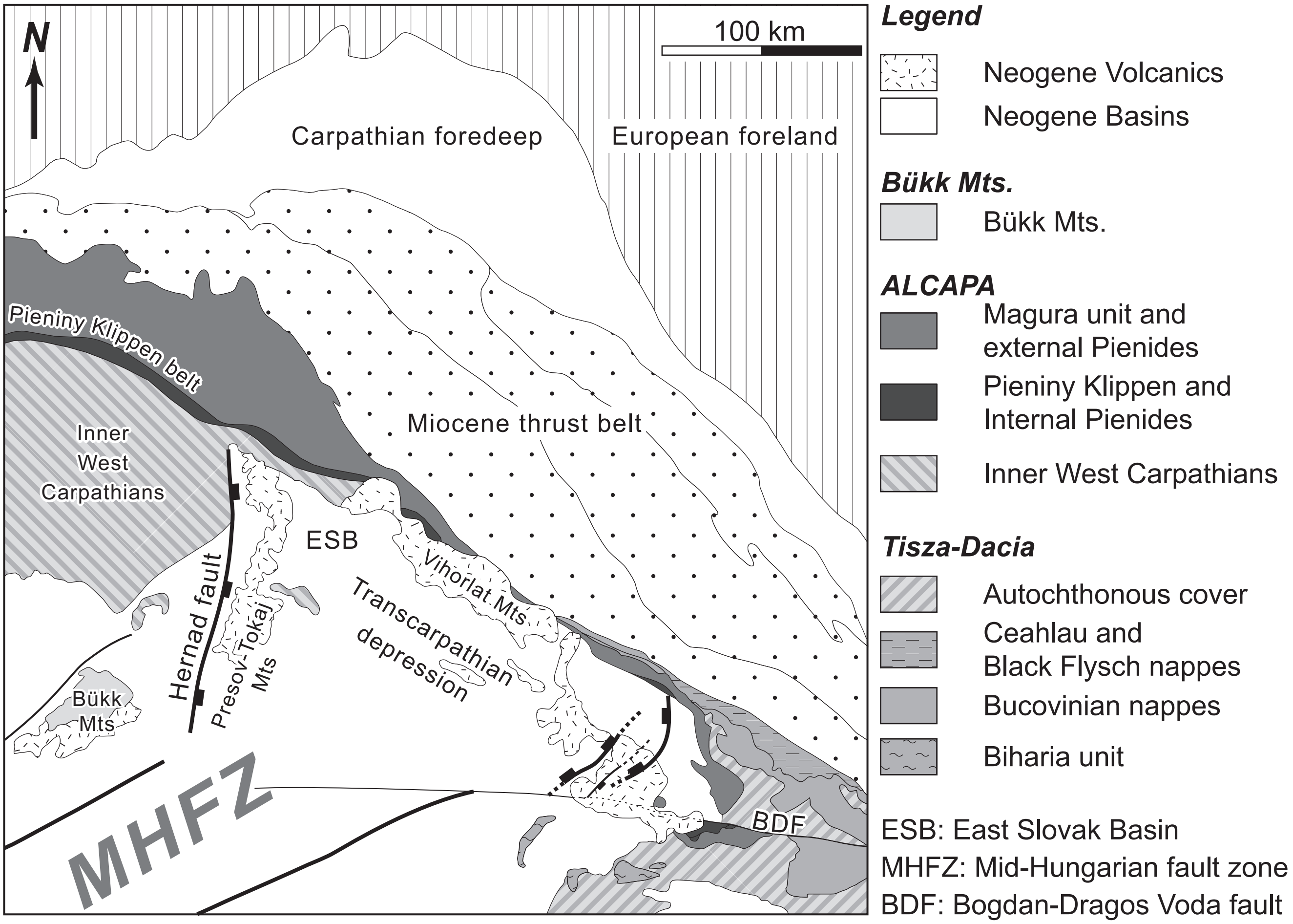

Fig. 10. Geological sketch map of the triple junction between ALCAPA, Tisza-Dacia and the European foreland. Map redrawn after Fig. 1, Kováč et al. (1995) and Săndulescu et al. (1978). The Hernád fault is interpreted as providing the detachment of the counter clockwise rotating domain of ALCAPA (Inner West Carpathians) and the Transcarpathian depression. The fault pattern of the corresponding eastern detachment fault, between the Transcarpathian depression and the clockwise rotating Tisza-Dacia (including the eastern tip of ALCAPA), follows structures taken from the subcrop map of Săndulescu et al. (1993).

tonic unit north, (and possibly south, as our locality 18 suggests) of the Bogdan-Dragos Voda fault (Fig. 9), as well as the Pienides, which were originally part of ALCAPA.

Sense, magnitude and timing of these post-12 Ma rotations in the study area are similar to rotations inferred for the East Slovak Basin (Orlický 1996, Márton et al. 2000), for the Vihorlat Mts (Túnyi et al. 2005) and for the Tokaj area (Márton 2001). Therefore, we think that the East Slovak basin and our working area (Fig. 10) behaved as a single tectonic unit after some 12 Ma ago.

Rotations, however, are different in those parts of the ALCAPA mega-tectonic unit, which are located west of the Hernád-fault (Central W-Carpathians, see Fig. 10), where counter clockwise rotation stopped earlier, at around 14.5 Ma (Márton 2001). This different timing of rotations west and east of the Hernád fault calls for a tectonic separation across this fault.

The onset of the post-12 Ma counterclockwise rotations in the study area coincides with a significant change of the tectonic setting. According to Tischler et al. (2007) sinistral transpression (16–12 Ma) changed to sinistral transtension (12–10 Ma), concentrating along the Bogdan-Dragos Voda fault system. This transition is probably due to soft collision of ALCAPA, including the northern parts of the Tisza-Dacia mega-tectonic unit with the European foreland (Tischler et al. 2007). Convergence continued however further south, i.e. in the East Carpathians (Matenco et al. 2003). The clockwise rotation documented for the 14.2–11 Ma time interval (Panaiotu 1998, 1999), which affected the southern Apuseni Mountains (which are part of Tisza) can also be connected to this event.

Inferences regarding pre-12 Ma clockwise rotations (Eo-/Oligocene localities)

Those four Eo-/Oligocene localities from the study area, which we consider in our tectonic interpretation, exhibit substantial clockwise deflections of paleo-declinations (Fig. 9, Table 3), suggesting clockwise rotations which pre-date the counterclockwise rotations discussed above. Due to the subsequent counter clockwise rotation, the clockwise rotations suggested by the paleo-declinations in Fig. 9, and discussed below, represent an under-estimate by some 30°.

The observed pre-12 Ma clockwise rotations for the autochthon (localities 14 and 19) are in line with earlier paleomagnetic results from the Tisza-Dacia mega-tectonic unit (Panaiotu 1998). However, clockwise rotations are unexpected for the Pienides. These are considered as part of the ALCAPA unit, which is known to have suffered counter-clockwise rotations during the Miocene (e.g. Bükk Mts.: Márton & Fodor 1995; Gemer region: Márton et al. 1988; Inner West Carpathian flysch basin: Márton et al. 1999).

The following is an important starting point for reconstructing the main rotational events in the Maramures area: localities 14 and 19 of the present study from the (para-) autochthonous sedimentary cover of the Tisza-Dacia mega-tectonic unit, when combined with two earlier published results of the same age from the autochthon (Panaiotu 1998), define a rotation for the autochthon which has good statistical parameters (Table 3). The timing of this rotation is not well constrained, except that it must post-date the Eo-Oligocene ages of deposition of the analysed sediments. Compared to this ”reference” direction, localities 6 and 7 from the Pienides (i.e. the easternmost tip of ALCAPA) show less clockwise rotation. This situation suggests that the Pienides and Tisza-Dacia rotated, at least partly, in a different manner and/or at different times.

According to our interpretation Tisza-Dacia started to rotate clockwise before emplacement of the Pienides at around 18.5 Ma. This is supported by independent observations. According to Fügenschuh and Schmid (2005) a substantial clockwise rotation of the Tisza –Dacia mega-tectonic unit predates 18.5 Ma. Also the change in strike of the foredeep (from E-W to SE-NW in Late Oligocene times towards ENE-WSW in Early Miocene times; De Broucker et al. 1998; Györfi et al. 1999) suggests clockwise rotation. Since ongoing clockwise rotation affected the Pienides only after emplacement onto and their mechanical coupling with Tisza-Dacia, a smaller angle of rotation is expected for the Pienides.

An alternative to the above interpretation would be that the smaller clockwise rotation of the Pienides resulted from a previous counter-clockwise rotation of the Pienides by about 45°, predating a 90° clockwise rotation (together with the Tisza-Dacia mega-tectonic unit). This possibility is considered, since the Pienides represent the eastern tip of the ALCAPA mega-tectonic unit, which is characterized by counter clockwise rotated Miocene declinations (e.g. Márton 1987; Balla 1987). Fortunately, a paleomagnetic study (Márton & Márton 1996) followed by integrated paleomagnetic measurements and K/Ar isotope age determination (Márton & Pécskay 1998) provided precise time constraints for the rotations of the area W of the Hernád fault. These studies suggest that no Tertiary rotation occurred before 18.5 Ma. The first counter clockwise rotation took place in the 18.5–17.5 Ma time interval, the second from 16 to 14.5 Ma. As both rotation events post-date thrusting of the Pienides, this second alternative interpretation is far less probable compared to the first one.

Disintegration of the ALCAPA mega-tectonic unit starting at 18.5 Ma ago

Our results, in the context of previously published paleomagnetic data, clearly imply that the ALCAPA mega-tectonic unit started to disintegrate during the Miocene. This process started with the decoupling of its northeastern-most tip (Pienides) from the rest of ALCAPA. The decoupling must have occurred somewhere within the Transcarpathian depression (Fig. 10), which is an intervening area that strongly subsided since the Middle Miocene, due to transtension (i.e. Kováč et al. 1994). A window of lower structural units (Ináčovce Krichevo unit) in the basement of the East Slovak basin (Soták et al. 1993, 1994) has been interpreted as a metamorphic core (Soták et al. 2000).

We therefore propose that the Transcarpathian depression is the site of major extension. This major NW-SE extension can also be seen in some Slovak seismic lines and is evidenced by thick deposits, tilted beds, syn-rift style geometry and fault offsets (Santavy & Vozár 1999) which occurred between 17.5 Ma and 11 Ma ago. Major Neogene extension is evident also in our study area. Immediately NW of the internal Pienides a deep Miocene basin (the SE edge of the Transcarpathian depression) is found, featuring thick Langhian (Badenian) salt deposits. Large amounts of buried Middle-Late Miocene volcanites in the area of the Transcarpathian depression (Fig. 10) also suggest major extension.

Tentative model for the tectonic evolution

Data and considerations discussed in the previous part of this chapter lead to the following model. The easternmost tip of the ALCAPA mega-tectonic unit (Pienides) was emplaced onto the Tisza-Dacia mega-tectonic unit along the Pienide thrust front between 20.5 Ma and 18.5 Ma. Before this thrusting, Tisza-Dacia underwent some 45° out of its bulk clockwise rotation (Fig. 11). After 18.5 Ma both the Pienides and Tisza-Dacia underwent a common clockwise rotation of some 45° (75° if the subsequent counter clockwise rotation is also taken into account), while the rest of the ALCAPA mega-tectonic unit followed a pattern of counter-clockwise rotations (Fig. 11b).

This led to the disintegration of ALCAPA, and the decoupling of its easternmost tip (the Pienides), which was previously fixed to Tisza-Dacia. Differential stretching took place across the N-S to NE-SW trending normal faults within the Transcarpathian depression (Fig. 10). One of these, the Hernád fault, accounts for decoupling and clockwise rotation of the tip of ALCAPA from the bulk of this mega-tectonic unit. Hence major NW-SE rotational stretching within the

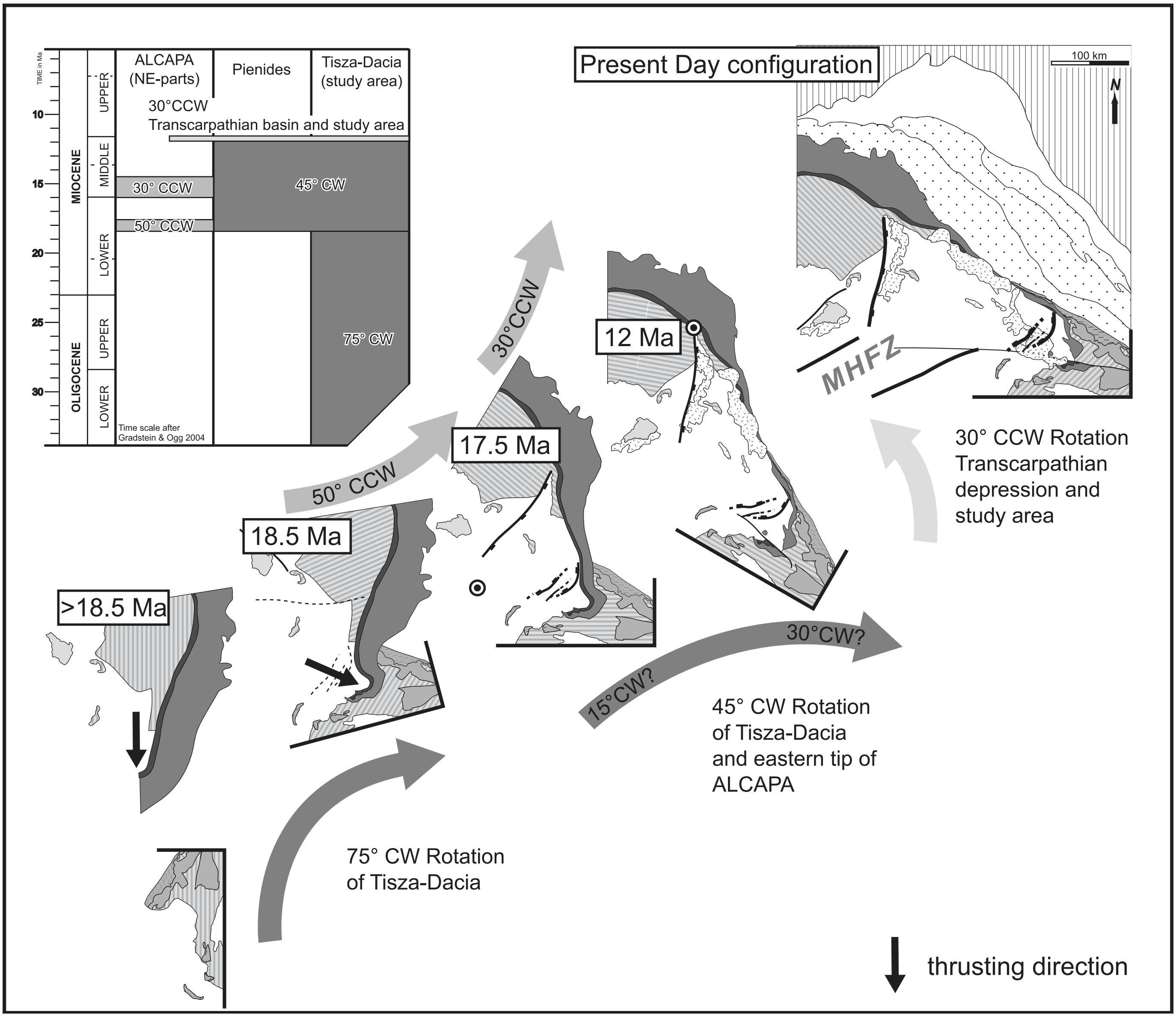

Fig. 11. Sketch of the proposed rotational history of the study area and the NE parts of ALCAPA.

Transcarpathian depression, and the East Slovak basin in particular, was driven by differential rotations of the main body of ALCAPA in respect to the thrust tip of ALCAPA (Fig. 11). The pole for this rotation is suggested to be located somewhere near the southern termination of the Hernád fault. This implies that the northern rim of the Transcarpathian depression should be stretched and bordered by transfer type faults, as is suggested by the thinning and the NW-SE elongation of the belt of external Carpathian Flysch units.

At around 12–11.5 Ma, when transpression along the Bogdan-Dragos Voda fault system changed to transtension (Tischler et al. 2007), a second differential rotation and decoupling from the main body of ALCAPA occurred at or near the Hernád fault. Syn-rift type Sarmatian beds corroborate this interpretation. The observed 30° counter clockwise rotation in the study area, as well as in the Transcarpathian depression, is modelled as ”en block” rotation around a pole at the northern tip of the Hernád fault in Figure 11. An alternative explanation for the observed 30° counter clockwise rotation could be the rotation of smaller, strike slip fault bound blocks in a deformation corridor. Such a rotation would also imply a stretched southern margin, where large subsidence and thick buried Miocene volcanites do occur (Széky-Fux & Pécskay 1991).

Conclusions

During a main rotational stage, i.e. between 18.5–12 Ma, large clockwise rotations of at least 45° did occur in the study area. These affected the (par-) autochthonous sedimentary cover of the Tisza-Dacia mega-tectonic unit, as well as the allochthonous flysch nappes of the Pienides, representing the easternmost tip of the ALCAPA mega-tectonic unit. Since the Pienides originally belonged to ALCAPA, and because the main body of ALCAPA rotated counter clockwise, our new results from the Maramures area necessitate the disintegration of ALCAPA at around 18.5 Ma ago. The site of disintegration has to be looked for within the Transcarpathian depression (East Slovak basin in particular), located in the NE prolongation of the Mid-Hungarian fault zone, where numerous normal faults account for differential stretching (Fig.10). The opening of the Transcarpathian depression was accompanied by the sedimentation of mid-Miocene and younger sediments of great thickness.

During a second stage, immediately after 12 Ma, counter-clockwise rotations of about 30° are documented in the entire working area. These counter-clockwise rotations are similar in timing and magnitude to rotations observed for the East Slovak basin, for the Tokaj Mts and for the Vihorlat Mts., i.e. areas that are part of the Transcarpathian depression. However, counter-clockwise rotations stopped after 14.5 Ma west of the Hernád-fault, i.e. in the W-Carpathians, as well as in the Bükk Mountains. Hence this second decoupling of the Central W-Carpathians from the Transcarpathian depression occurred along the Hernád fault.

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