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PALAEOMAGNETIC RESULTS FROM THE FOLD-AND-THRUST BELT OF THE WESTERN CARPATHIANS: AN OVERVIEW

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Abstract

The Western Carpathians are separated into an Outer and Inner Carpathians (both comprising several nappe systems) by the extremely narrow and highly deformed Pieniny Klippen Belt. The main phase of deformation and thrusting took place during the Late Cretaceous in the Inner Carpathians, at the end of Cretaceous-Palaeocene in the Pieniny Klippen Belt and in the Miocene in the Outer Carpathians. In this paper a huge amount of palaeomagnetic results of different qualities available from several nappe stacks and from overstep sequences were reviewed and interpreted in terms of tectonics. The data suggest that all three main units participated in two phases of CCW rotation starting at 18.5Ma, i.e. the Outer Carpathian nappes in front of the already consolidated Alp–Carpathian–Pannonian block became accreted to the block. Late Cretaceous nappe transport, Neogene uplift of 'core mountains' and possibly oroclinal bending of pre-Oligocene age can account for important differences in pre-Cenozoic palaeomagnetic declinations. Most of them exhibit less or no CCW rotation suggested by the overstep sequences implying pre-Cenozoic CW rotations of variable angles.

Introduction

The Western Carpathians (Fig. 1 inset) are the northernmost segment of the European Alpides. To the north, they are thrusted over the southern margin of the European Platform (Fig. 1 and 2). To the south, the Western Carpathians s.l. contact the Tisza unit along the Mid-Hungarian Line (Fig. 2) a Cenozoic strike-slip fault zone (for review see Fodor 2006). The Western Carpathians are usually subdivided into the Inner Carpathians which formed during the Mesozoic and, the Outer Carpathians formed during the Cenozoic. The two units are separated by the Pieniny Klippen Belt (PKB), a narrow arcuate structure which was formed during two deformational stages, in the Latest Cretaceous-Palaeocene and in the Miocene, respectively. Some authors (e.g. Plašienka 1995) suggest to subdivide the Inner Carpathians into a Central and an Internal Carpathians which are separated by the Meliata suture (Fig. 2 and 3). The Western Carpathians, north of the Pieniny Klippen Belt (Fig. 1) are composed exclusively of non-metamorphosed rocks showing thin-skinned tectonics, whereas the Inner Carpathians are thick-skin orogens (Picha *et al.* 2005), composed of basement fragments and sedimentary cover.

The deformation in the Western Carpathians took place between the Late Jurassic and the Miocene, getting younger outwards (Plašienka *et al.* 1997). The main tectonic features of the Carpathians have been formed largely due to the convergence of the European and African plates and, more specifically as a result of successive closures of three branches of the Tethys oceanic realm resulting in three successive subductions (Froitzheim *et al.* 2008). The final stage of thrusting in the Western Carpathians was partly concomitant with a lateral, northeast directed material escape from the Eastern Alps into the Carpathian–Pannonian realm (Nemčok *et al.* 1998 and references therein).

Products of volcanism related to the youngest Cenozoic subduction cut and cover the Inner Carpathians, the Pieniny Klippen Belt and the inner part of the Outer Carpathians (Fig. 1a). Intramontane basins are filled with Neogene sediments in the Outer Carpathians whereas Upper Cretaceous, Palaeogene and Neogene sediments occur in the Inner Carpathians.

Palaeomagnetic investigations in the Western Carpathians s.s. started in the 1960s. The first rocks studied were the Lower Permian red shales in the Central Western Carpathians of Slovakia (Kotásek & Krs 1965) and Neogene andesites in Poland (Birkenmajer & Nairn 1968). Pioneering studies of Mesozoic sedimentary rocks (Pieniny Klippen Belt, Upper Cretaceous red marls) were published by Bazhenov *et al.* (1980). In the early phase of palaeomagnetic research most of the results were obtained in the former Czechoslovakia (for summary see Krs *et al.* 1982, 1996).

The Mesozoic sequences in the Central West Carpathians (the Tatra Mts and Slovakian 'core mountains') were first studied by Kądziałko-Hofmokl & Kruczyk (1987) and Kruczyk *et al.* (1992). The first publications were followed by several papers by Grabowski (1995, 1997, 2000, 2005; Grabowski *et al.* 2009, 2010) and by a recent one by Szaniawski *et al.* (2012). The Triassic sediments of the Silica Nappe, the innermost unit of the Central Carpathians, extending also to the Internal Western Carpathians, were investigated by Márton *et al.* (1988), Márton *et al.* (1991), Kruczyk *et al.* (1998) and Channell *et al.* (2003). So far the Variscan granitoids of the 'core mountains' were not studied palaeomagnetically, except that of the High Tatra Mts (Grabowski & Gawęda 1999).

More recently, increased interest in the palaeomagnetism of the Pieniny Klippen Belt resulted in several papers. Systematic palaeomagnetic studies were reported from the Neogene andesites and Upper Cretaceous red marls by Márton *et al.* (2004, 2013), while Grabowski *et al.* (2008) and Jelenska *et al.* (2011) investigated the Jurassic rocks in the Polish and the Slovak sectors of the Pieniny Klippen Belt.

The systematic studies of Cenozoic basins (overstep sequences) in northern Hungary, Slovakia and Poland were carried out by Márton *et al.* (e. g. 1992, 1996, 1999, 2000, 2007 *a*, 2007 *b*), Márton & Márton (1996) and Túnyi & Márton (1996), Márton & Pécskay (1998), Póka *et al.* 2002, Túnyi *et al.* 2004, Karátson *et al.* (2007), Extensive database of palaeomagnetic results from the geographically distributed Tertiary sedimentary rocks of the Outer Carpathian nappes (Magura and Silesian) were presented by Márton *et al.* (2009 *a*). A few Mesozoic results were also reported from the Outer West Carpathians. They represent geographically limited areas in the Lower Cretaceous teschenitic rocks in the western part of Silesian Nappe (Krs *et al.* 1982, Grabowski *et al.* 2006), in sediments from the western part of the Silesian Nappe and from the Dukla Nappe (Krs *et al.* 1982), and in red pelagic marls from the eastern sector of Sub-Silesian Nappe (Szaniawski *et al.* 2013).

Short geological description of the different units of the Western Carpathians

Carpathian Foredeep

The Foredeep of the Western Carpathians is part of an elongated basin extending from Vienna Forest to the Iron Gates on the Danube (Fig. 1, inset). Near Vienna it joins the North Alpine Foreland Basin. The Carpathian Foredeep is filled by Miocene, mostly clastic sediments, up to 3.5 km thick and, contains a single intercalation of evaporate (Oszczypko *et al.* 2005) The sediments of the Foredeep basin overly discordantly the southern fringe of European Platform. The contact, where exposed, is sedimentary (Márton *et al.* 2011 and references therein). In the innermost part of the Foredeep, the Miocene strata are incorporated into the imbricated frontal zone of the Outer Carpathians or form separate tectonic units, composed of northward thrusted slices (Oszczypko *et al.* 2005, Picha *et al.* 2005). Outwards, the Miocene strata become sub-horizontal except close to map-scale faults (Márton *et al.* 2011 and references therein). In Eastern Poland, numerous NE-SW and NW-SE trending normal and strike-slip faults, cut the Miocene fill, whereas, strike-slip faults parallel to the Carpathian front are common in the innermost part of the Carpahian Foredeep in the western part (Márton *et al.* 2011 and references therein).

Outer Western Carpathians

The Outer Western Carpathians are north-verging, north-convex thrust-and-fold belt thrusted over the Miocene sediments of the Carpathian Foredeep in the north and separated from the Inner Carpathians by the Pieniny Klippen Belt in the south. They comprise the Skole, Subsilesian-Zdanice, Silesian, Dukla and Magura rootless nappes (Fig. 1), composed largely of Lower Cretaceous to Lower Miocene flysch, locally over 10 km thick (Slaczka *et al.* 2005).

The nappe pile started to form during the Eocene (Świerczewska & Tokarski 1998; Nemčok *et al.* 2006). Later on, the deformation progressed from the hinterland toward the foreland. The regular sequential succession of the forelandward-verging structures is locally disturbed by out-of-sequence thrust sheets.

In traditional view, the age of the termination of the nappe stacking was getting younger eastward (Márton *et al.* 2009 *a*, and references therein), from about 14.5 Ma (end of Langhian, according to Mediterranean and mid –Badenian, according to Central Paratethyan stages, for correlation of the Mediterranean and Central Paratethyan stages, see Rögl, 1996) at the westernmost part, until about 12 Ma (Serravalian, according to Mediterranean and Sarmatian, according to Central Paratethyan stages) at the easternmost part. It was recently discovered, however, that younger than 11.5 Ma (Tortonian, according to Mediterranean and Sarmatian-Pannonian boundary, according to Central Paratethyan stages) old strata are overthrusted by the Outer Carpathian nappes in the western segment (Wójcik & Jugowiec 1998) which implies that the final episode of thrusting affecting possibly the whole Outer Carpathians, must have occurred after 11.5 Ma.

The nappe stacking took place in two successive stages during which tectonic transport was directed (in present co-ordinates) towards the NW and towards the NE, respectively (Aleksandrowski 1985). During the second stage, the first stage folds were partly refolded and overprinted by folds of second generation (Aleksandrowski 1985), whereas, some of the NE-striking thrusts of the first shortening event were reactivated as sinistral strike-slip faults (Fodor *et al.* 1995, Decker *et al.* 1997).

The thrusting in the Outer Carpathians was followed by regional collapse resulting in the formation of intermontane depressions filled by Neogene and Quaternary sediments (Zuchiewicz *et al.* 2002; Zattin *et al.* 2011). Some of the faults and thrusts formed during the nappe stacking and subsequent collapse were reactivated during Quaternary time (Tokarski *et al.* 2007).

In plate tectonic terms, the Outer Carpathians are a Tertiary accretionary complex with the backstop located at the Pieniny Klippen Belt. The accretionary complex was related to the southward subduction of the oceanic or suboceanic crust, intervening between the continental crust of the European plate and the continental crust of the Inner Carpathians and their subsequent collision (e.g. Tomek & Hall 1993). This process resulted in considerable shortening. The minimum amount of the shortening was calculated by traditional methods as 60–100 km (Książkiewicz 1977; Oszczypko & Ślączka 1985) and, by restoration of balanced cross-sections as 160 km (Picha *et al.* 2005) to 507 km (Gągała *et al.* 2012).

Most of the palaeogeographic reconstructions show the pre-folding shapes of the Magura and Silesian basins as north convex, similar to the present-day shapes of the Magura and Silesian Nappes (Książkiewicz 1960; Nemčok *et al.* 2000 and references therein; Oszczypko & Oszczypko-Cloves 2006 and references therein). However, in some reconstructions (e.g. Picha *et al.* 2005) both basins are depicted as rectilinear until late Oligocene times. However, no argumets on the shapes of the basins have been presented in any of the above papers. According to Mastella & Konon (2002) the present-day shape of the Silesian Nappe results from tectonic bending and Nemčok *et al.* (2006) suggest that the Magura Nappe radically changed its shape since late Oligocene.

Numerous small-scale andesite intrusions of Miocene age cut the inner part of the Magura Nappe (Birkenmajer & Pécskay 2000 and references therein; Picha *et al.* 2005 and references therein). Furthermore, numerous small-scale Lower Creaceous hypabyssal intrusions and lava flows of alkaline lamprophyres (Teschenite Association Rocks) occur in the western part of the Silesian Nappe (Lucinska-Anczkiewicz *et al.* 2002; Grabowski *et al.* 2003).

Pieniny Klippen Belt (PKB)

The PKB (Figs.1-3) is a narrow, steeply dipping zone of extreme shortening and wrenching (Birkenmajer 1986). It mainly involves Jurassic and Cretaceous sediments with extremely variable lithology and intricate internal structures. Numerous lithostratigraphic and tectonic units of distant provenances were recognized in the Pieniny Klippen Belt, suffering excessive shortening and dispersal within this restricted zone. In general, two types of rock units are distinguished in the belt. The "klippen" which are rigid blocks of Jurassic – Lower Cretaceous limestones. They are embedded in an incompetent matrix, the "klippen mantle", composed of Upper Cretaceous to Palaeogene marlstones, claystones and flysch (Birkenmajer 1986; Plašienka 2012 *a*). The structure results from two successive deformation stages, a Late Cretaceous – Palaeogene one when the nappe stack was formed and a Miocene deformation stage, when it was strongly modified and almost entirely disintegrated by left lateral strike-slip movements, sub-parallel to the PKB trend (Birkenmajer, 1986; Plašienka, 2012 *a*). The two deformation stages resulted in the "block-in-matrix" structure of the PKB. Despite the complicated tectonic history, the rocks of the PKB show very little, if any macroscopically observable, ductile strain.

Inner Western Carpathians

The Inner Western Carpathians are built up of numerous horst blocks (core mountains) separated by intramontane basins and embayments of the Pannonian Basin System. They comprise several stacks of nappes composed of metamorphic and plutonic Palaeozoic basement and of non or moderately metamorphosed Permian to Cretaceous sedimentary cover (Fig. 2). All nappe stacks are north-verging in the Central Western Carpathians. South of the inferred Meliata suture, in the Internal Western Carpathians, the nappes verge to the south The Central Carpathians comprise six nappe-stacks. These are (from S-N): Silicic, Gemeric, Hronic, Veporic, Fatric and Tatric nappe stack. Thick-skinned stacks which comprise both basement and cover are the Tatric, Veporic and Gemeric stacks. Detached cover nappe stacks are the Fatric, Hronic and Silicic stacks, containing Late Palaeozoic to Mesozoic sedimentary rocks with rare volcanics (Froitzheim *et al.* 2008 and references therein). The Central Carpathians show a distinct progradation of Mesozoic shortening and collision events from the south towards the north (in present day coordinates) from Late Jurassic to Late Cretaceous times (Plašienka *et al.* 1997, Picha *et al.* 2005 and references therein; Froitzheim *et al.* 2008) related to successive closures of the Meliata and Vahic oceans (Plasienka *et al.* 1997).

Slivers of oceanic sediments and dismembered ophiolites occur in the in the Meliata suture. South of this suture non-metamorphosed or slightly metamorphosed Palaeozoic and Mesozoic sediments are found in the south- verging Silica Nappe as well as in the different nappe units of the Bükk belt. In the Transdanubian belt the thick Permian - Cretaceous cover complex of a quite simple structure forms the basement, which is a huge SW-NE trending synform (Plašienka *et al.* 1997).

Overstep sequences

The basement units are discordantly covered by Upper Cretaceous and younger sediments and volcanic rocks filling intramontane depressions and embayements of the Pannonian basin system (Frotzheim *et al.* 2008 and references therein). Except for the Upper Cretaceous Gosau facies, the sediments filling the intramontane basins and the Pannonian basin system are unfolded or deformed by open folds.

Permian and Mesozoic palaeomagnetic results

Database for all Palaeozoic and Mesozoic results is presented in the Table 1. Most (but not all) palaeodeclinations are located on the geological maps in Figs 3 and 4. Some data were omitted in the areas where lot of results are available (this concerns especially the area of Tatra Mts. and Silica unit).

Križna unit (Fatricum)

The most numerous pre-Cenozoic data come from the Križna Nappe of Tatra Mts in Poland. The first palaeomagnetic results were presented by Kądziałko-Hofmokl & Kruczyk (1987). The characteristic direction, obtained from Bathonian to Kimmeridgian radiolarian and nodular limestones (1 in the Table 1) did not differ significantly between particular stages, with mean value of pre-folding component close to the expected Eurasian reference direction for the middle - late Jurassic. The shortcomings of the above paper were, that they did not discuss either the problem of remagnetization or the effect of tectonic correction. In the early 1980s the phenomena of remagnetization was not as well known (see McCabe & Elmore 1989) as today. The almost exclusively normal polarity of magnetization (except one site) was in accordance with the concept of 'Jurassic Quiet Zone' – a long normal interval embracing Callovian – Lower Kimmeridgian (Tominaga *et al.* 2008 and references therein). A discovery of frequent magnetic reversals in the Late Jurassic (see Opdyke & Channell 1996; Gradstein *et al.* 2012 for review) caused that the interpretation of data of Kądziałko-Hofmokl & Kruczyk (1987) became not straightforward. The above mentioned Oxfordian radiolarian limestones, were re-studied by Grabowski (1995) (2 in the Table 1). It appeared that clustering of characteristic magnetizations, identical as those of Kądziałko-Hofmokl & Kruczyk (1987) is indeed better after tectonic correction, but their primary origin was questioned: it appeared that other components with higher unblocking temperatures and mixed polarity are better candidates for primary magnetizations. The age of remagnetization was interpreted as Late Cretaceous, since it was definitely older than the final emplacement of the Križna Nappe over the High-Tatric (Tatricum) substratum (Grabowski 1995). In fact, Križna Nappe in the Tatra Mts forms a complicated structure consisting of several imbricated units (duplexes), which behaved quite independently during the late Cretaceous thrusting.

Soon it appeared that the remagnetization is ubiquitous also in the Middle Triassic to Lower Cretaceous rocks of the Križna Nappe (3 and 4 in the Table 1, Fig. 4). Data collected from many localities situated in several duplex structures proved that the remagnetization was acquired during early phases of thrusting (Grabowski 2000). It must have occurred during the Cretaceous Quiet Zone, before the Coniacian (termination of thrusting in the Central Western Carpathians). Nevertheless, primary magnetization was documented in the calpionellid-bearing upper Tithonian – Berriasian limestones (5 in the Table 1, Fig. 3 and 4) of the Križna Nappe by Grabowski (2005) and the rocks yielded valuable magnetostratigraphic results (Grabowski & Pszczółkowski 2006). The calculated Lower to Middle Berriasian palaeopole is indeed located close to the coeval Eurasian data (Galbrun 1985), implying a net post-Berriasian clockwise rotation by amount of 15-20°.

The Jurassic pelagic carbonates of the Križna Nappe were also studied by Kruczyk *et al.* (1992) in several geographically distributed localities in Slovakia: Mala Fatra, Nizke Tatra Mts, Belanske Tatra Mts, Magura Spišska and Choč Mts (6, 9, 10, 11, and 12 in the Table 1, Fig. 3 and 4). The characteristic remanences, of exclusively normal polarity were interpreted as of pre-folding age, with fan-like pattern of palaeodeclinations, coinciding with tectonic vergencies of the studied nappe fragments. The results were interpreted as support of the oroclinal bending model of the Central West Carpathians (Burtman 1988). However the age of bending and tectonic rotations were not constrained in the paper, and the age of magnetization was not clearly discussed. It was subsequently suggested (Grabowski & Nemčok 1999) that these data also might represent the Cretaceous remagnetizations acquired in the "Cretaceous Quiet Zone". The evidences were: 1. exclusively normal polarity of magnetization from rocks belonging to different parts of the Jurassic and 2. unblocking temperatures 350-450°C which are typical for undoubtedly remagnetized carbonates in the Tatra Mts (Grabowski 2000). Additional argument for syntectonic nature of the components is quite a large scatter of "pre-folding" inclinations: from 44 to 63°. This problem was pointed out also by Kruczyk *et al.* (1992). In fact, an inclination only test (Enkin & Watson 1996, not performed in the source paper) applied for these data gives negative results. It could be easily explained assuming syntectonic (syn-thrusting) age of magnetization. Despite the suspicion of remagnetization, the data of Kruczyk *et al.* (1992) yielded useful constraints for the rotation pattern in the Križna Nappe. They were confirmed by subsequent studies of Pruner *et al.* (1998) in the area of Mala Fatra (7 and 8 in the Table 1, Fig. 4), where slight CCW rotations of the Jurassic rocks were documented.

Further evidence for Mesozoic remagnetizations in the Križna Nappe was obtained from the high resolution study of Strážovce section (Tithonian – Neocomian) in the Strážov Mts (Grabowski *et al.* 2009). The statistically well defined secondary magnetization (13 in the Table 1) of normal polarity must have been acquired during thrusting episodes in the late Cretaceous. The most plausible tectonic corrections indicate that the rocks must have been magnetized when they dipped opposite to the thrusting direction, forming a hinterland-dipping duplex. The interpretation is concordant with the internal structure of the Križna Nappe, consisting of imbricated units of duplex-type structure (Prokešova *et al.* 2012). Primary component of double polarity (14 in the Table 1, Fig. 3 and 4,), which was possible to extract from some stratigraphic horizons indicates slight CCW rotation of similar magnitude as in the Mala Fatra Mts (Kruczyk *et al.* 1992).

Successful magnetostratigraphic study of the Tithonian – Berriasian limestones was performed by Grabowski *et al.* (2010) in the Križna Nappe of the Male Karpaty Mts, in the SW termination of the Carpathian arc (15 in the Table 1, Fig. 3). The palaeodeclinations of 300^{o} account for the largest counterclockwise rotation of Križna Nappe fragment studied so far. The studied sequence was apparently not affected by the syn-thrusting remagnetization of Late Cretaceous age.

Tatricum

Palaeomagnetic data from the Tatric units are less numerous than from the Križna unit. Firstly, the Tatric rocks represent mostly a shallow water development and are not as suitable palaeomagnetic material as for example Jurassic – Cretaceous pelagic carbonates of the Križna unit. Secondly, during the Alpine orogeny the Tatricum was deeply buried under the overriding Fatric and Hronic units which resulted even in anchimetamorphic conditions in some Central Western Carpathian massifs (e.g. Plašienka 1995). Most of the published palaeomagnetic data were obtained in the High Tatra Mts: 1. the Lower Carboniferous granitoids of the High Tatra Mts (Grabowski & Gawęda 1999, 16 in the Table 1, Fig. 3 and 4); 2. The Lower Triassic sandstones of the autochthonous sedimentary cover of the Tatricum (Szaniawski *et al.* 2012, 17 in the Table 1, Fig. 4); 3. Jurassic – Lower Cretaceous limestones (Grabowski 1997) overlying the autochthonous Triassic (18 in the Table 1, Fig. 4,) or included in the overthrusted units (19 in the Table 1). The granitoids and the Mesozoic autochthonous cover rocks reveal consistent N to NE palaeodeclinations similar to the palaeodeclinations of the Križna Nappe. According to Szaniawski *et al.* (2012) the Lower Triassic hematite bearing sandstones preserved the primary magnetization while the Jurassic – Cretaceous limestones were remagnetized in the Late Cretaceous during the Cretaceous Normal Superchron (Grabowski 1997). One Upper Jurassic locality situated in an allochthonous position (19 in the Table 1) indicates significant CCW rotation in relation to the autochthon. Two localities (20 in the Table 1, Fig. 4) bear evidence of peculiar reversed polarity remagnetizations, residing most probably in pyrrhotite (maximum unblocking temperatures berween 300 and 350^{o}C) which might be interpreted as Cenozoic, acquired before the Neogene tilting event, connected to the uplift of the High Tatra Mts (Grabowski 1997).

Two results are available from the Mesozoic cover of Tatricum outside of the High Tatra Mts, in the Mala and Velka Fatra (Pruner *et al.* 1998, 21 and 22 in the Table 1, Fig. 3 and 4). Detailed geological setting and tectonic correction is not discussed in the source paper. Mixed polarity in both localities might point to primary magnetization. Slight CCW rotated declinations seem to mirror the trend of rotations described from the Križna Nappe of the Mala Fatra (Table 1, items 6-9) and Strážov Mts (Table 1, item 14).

Choč (Hronicum) and Manin units

Several geographically distributed localities were studied from the Permian melaphires and red sediments of the Choč Nappe in 1960s and 1970s (23-27 in the Table 1, Fig. 3 and 4) and the results summarized in a review by Krs *et al.* (1982). The palaeomagnetic vectors were obtained with the technique typical for that time, i.e. the magnetization exhibiting high stability on thermal or AF demagnetization was isolated and statistically evaluated on locality level. Although the within locality scatter is fairly high, the statistical parameters in most cases satisfy the minimum criteria for acceptable palaeomagnetic direction. Field tests for constraining the age of the magnetizations are lacking, but the shallow inclinations are in harmony with expected ones for the Permian. Originally, these results were interpreted in terms of large CW rotations.

The only Mesozoic palaeomagnetic data from the Choč Nappe come from a single locality of Reifling limestones (Middle Triassic), from the Western Tatra Mts in Poland (Grabowski 2000, 28 in the Table 1, Fig. 4). The rock was remagnetized in the Late Cretaceous, the palaeodeclination indicates large clockwise rotation (almost 80°) in relation to the Tatric autochthon and the Križna Nappe. However, as the remagnetization is of syn-thrusting age and the exact structural position during the acquisition of the secondary magnetization is not known (it might have dipped even 30-40° to the south – see Grabowski 2000) the amount of vertical axis rotation can not be precisely estimated. The remagnetization might have been synchronous with resetting of the K-Ar ages, indicating 90Ma, of the Middle Triassic tuffites in the same locality (Środon *et al.* 2006).

Two results from the Manin unit (Pruner *et al.* 1998, 29-30 in the Table 1, Fig. 3 and 4) indicate slight CCW rotation, similarly to the Mesozoic palaeodeclinations from Mala Fatra and Strážov Mts. Mixed polarity might indicate primary magnetization in the Butkov locality (30 in the Table 1), however directions before tectonic corrections and fold test results are not presented.

Gemericum

There is a single Permian palaeomagnetic direction from this unit (Krs *et al.* 1982, 31 in the Table 1 and Fig. 3 and 4). To this, the same is applicable as for the Permian palomagnetic directions from the Choč Nappe.

Silica unit

Primary magnetization was documented in the Triassic of Aggtelek Mts (Silica Nappe s.s.) and Rudabanya Mts (Bodva Nappe) in the Northern Hungary (Márton *et al.* 1988, 32-34 and 41 in the Table 1 and Fig. 4). Palaeomagnetic record in the Slovakian part of the Silica unit is more complex. Independent studies of Middle to Upper Triassic rocks indicate the presence of remagnetization. Its age is interpreted as syn-tectonic in the Late Cretaceous (Márton *et al.* 1991, 35 in the Table 1 and Fig. 3 and 4) or post-tectonic, acquired in the Oligocene – Miocene (Kruczyk *et al.* 1998, 36-37 in the Table 1 and Fig. 4). Channell *et al.* (2003), in their magnetostratigraphic study in Silická Brezová locality, documented a post-folding secondary component (38 in the Table 1). However they were able to isolate also primary component (39 in the Table 1). Both primary and secondary components in Slovakia account for a ca. 40-50° CCW rotation. The rotation in the southern part of Silica unit seems slightly larger (65-90°) in relation to present day north. The two palaeomagnetic data from the northern periphery of Silica unit (north of Gemeric unit) also indicate net 45° CCW rotation (Márton *et al.* 1991, 40 in the Table 1, Fig. 3 and 4). However differential rotations occur between the particular tectonic sub-units (Muran and Stratena Nappes).

Pieniny Klippen Belt

The three sites of Callovian – Tithonian limestones from the Czorsztyn unit in the central (Polish segment) of the Pieniny Klippen Belt (Grabowski *et al.* 2008) reveal a slight rotation in the CCW sense (42 in the Table 1 and Fig. 3 and 4). The mixed polarity magnetization was interpreted as primary. The palaeodeclinations measured in the middle – Upper Jurassic limestones of the western Slovak sector of the Pieniny Klippen Belt (Jeleńska *et al.* 2011) are badly scattered - the authors did not present any model explaining this observation and therefore the results are not included in Table 1. The palaeodeclination from the Tithonian – Berriasian of the western Slovak sector of the Pieniny Klippen Belt reveal very large CCW rotation (almost 120°). As the studied strata are overturned and refolded, it can not be excluded that additional tectonic correction for the plunge of the fold axis should be applied (Houša *et al.* 1996, 44 in the Table 1, Fig. 3 and 4).

Recently a systematic palaeomagnetic study of the Upper Cretaceous red marls was carried out along the strike of the Pieniny Klippen Belt from Western Slovakia through Poland to Eastern Slovakia (Márton *et al.* 2013). Remanences of pre-folding age were documented for 11 localities pointing to net CCW rotation of ca. 50° in relation to the present day north (45 in the Table 1, Fig. 3 and 4). Differences in palaeodeclinations between particular localities might be interpreted in favour of the secondary bending of the Pieniny Klippen Belt before the Oligocene.

Some palaeomagnetic directions in the Mesozoic rocks of the Pieniny Klippen Belt are Cenozoic overprints. It concerns two Upper Cretaceous localities in the western and eastern Slovak sector, respectively (Márton *et al.* 2013), with negative within locality fold test and ca. 75° CCW rotated declinations (46a and 46b in the Table 1, Fig. 3). They correspond quite well with the Oligocene-Early Miocene declinations which are characteristic of the Inner Carpathian Palaeogene. Another evidence of Neogene remagnetization was found in Middle – Upper Jurassic rocks in the central segment of the Pieniny Klippen Belt (Grabowski *et al.* 2008, 43 in the Table 1, Fig. 3 and 4). Although fold test was not conclusive, their direction before tectonic correction (component C of Grabowski *et al.* 2008) reveal similar amount of

CCW rotation as the above directions of postfolding age (Márton *et al.* 2013). It should be noted that all these overprints are of reversed polarity, similarly to the primary magnetization of the Neogene andesites in the Pieniny Klippen Belt (Márton *et al.* 2004, 6 in the Table 2, Fig. 4).

Outer Western Carpathians

Palaeomagnetic results were obtained from the Lower Senonian siliciclastics of the Biele Karpaty (Magura Nappe, Krs *et al.* 1993, 47 in the Table 1, and Fig. 3). Double polarity of the characteristic direction, which is based on hematite, suggests primary origin of magnetization. However tectonic correction is not discussed in detail. The palaeodeclination suggests ca. 40° CCW rotation.

Most Mesozoic data from the Outer Western Carpathians come from the siliciclastic and volcanic rocks of the Silesian Nappe in the NE Moravia (Krs *et al.* 1982, 1996, 48-51 in the Table 1, Fig. 3). All of them reveal significant CCW rotated declinations, in accordance with the result from Biele Karpaty. The quality of these results is moderate since clustering parameter k seldom exceeds 10, characteristic magnetizations are given only in situ, without any tectonic correction and there is no discussion about possible remagnetization. For example, stereograms from the teschenitic rocks (Krs & Smid 1979) clearly indicate the presence of rotated and non-rotated palaeodeclinations which suggests that some intrusions might carry a secondary magnetization of normal polarity. Inclination-only test, performed for the teschenite localities in Poland (Grabowski *et al.* 2006, 52-53 in the Table 1, Fig. 3) was not fully positive, indicating that either the rocks were remagnetized during folding and thrusting, or magnetization, although primary, is not synchronous. Indeed radiometric dating of teschenitic rocks gave quite broad spectra of ages, between 149 and 122 Ma (from the J/K up to Barremian/Aptian boundary). In two localities (52a and b in the Table 1, Fig. 3), where positive contact and within locality fold tests were performed, almost no rotation is observed. The other localities (53 in the Table 1, Fig. 3) reveal a CCW rotation of magnitude comparable to that in the Czech part of the Silesian Nappe.

Recently, a result from the Upper Cretaceous red marls of the eastern part of Sub-Silesian Nappe (Szaniawski *et al.* 2013, 54 in the Table 1) was published. The authors claim that although significantly affected by inclination shallowing, their result accounts for lack of significant rotation in relation to the reference Cretaceous palaeomeridian.

Cenozoic palaeomagnetic results

In the Outer Western and in the Central Carpathians the Cenozoic is represented by flysch of Palaeogene and subordinately Lower Miocene age. In the former area the flysch occurs in rootless nappes, while in the latter it forms the autochthonous cover of the basement units.

From the Silesian Nappe of the Outer Western Carpathians mostly Krosno beds (and mostly claystone members) of Oligocene (in the east also Lower Miocene) age were collected from 24 localities, concentrated in the western, central and eastern segments of the nappe, respectively. Using standard laboratory procedure, tectonically interpretable results were obtained for most localities (Fig. 5, light arrows plotted on the Silesian Nappe). In the western and central segments the characteristic magnetizations are of prefolding age (Table 2, items 1a and 1b), In the eastern segment five localities have primary (Table 2, 1c), five post-folding (Table 2, item 1d) remanences, both groups exhibiting CCW rotations of similar angle. The overall mean palaeomagnetic directions from the central and eastern segments show about 60° CCW rotation, while the palaeodeclination for the western segment is about 80°.

From the Dukla Nappe the earlier published palaeomagnetic results (Table 2, item 3) are poorly documented. Judging from the original paper (Korab *et al.* 1981) the results of blanket thermal demagnetization at 350°C, suggesting moderate CCW rotation were interpreted in terms of tectonics. It is quite possible that this temperature was not high enough to remove completely the possibly present overprint in the red sediments, so the result should be considered as indication for rotation, but the angle remained uncertain. Table 2, item 2 summarizes the recently obtained and so far unpublished results by Márton and Tokarski, which suggests synfolding magnetization of the grey clastic sediments exhibiting CCW rotations (Fig. 5, light arrows in the Dukla Nappe).

From the Magura Nappe of the Outer Western Carpathians, Upper Eocene and Oligocene flysch (fine grained sandstones, siltstones and marls) was studied at 34 geographically distributed localities of which 13 yielded statistically acceptable palaeomagnetic results (Table 2, item 4, Fig. 5, light arrows plotted on the Magura Nappe). On restoring the strata to the horizontal, the statistical parameters of the overall-mean direction became worse, i.e. the remanence is of postfolding/tilting age. Nevertheless, the locality mean directions are fairly consistent before tectonic correction and indicate about 60° CCW rotation with respect to the present N (Márton *et al.* 2009 *a*).

From the Central Carpathian Palaeogene basin samples were taken form two sub-basins, the Podhale, north of the Tatra Mts and the Levoča, east of it. From the sampled 18 localities 10 could be evaluated from tectonic point of view (Fig. 5, light arrows without numbers in the Central Carpathian Palaeogene Basin). They indicate about 60° CCW rotation (Table 2, item 7) with positive fold/tilt test (Márton *et al.* 1999, 2009 *b*). It was also documented that the palaeomagnetic directions are current independent, i.e. the generally E-W oriented sedimentary transport could not bias the palaeomagentic directions from that of the ambient Earth magnetic field (Márton *et al.* 2009 *b*). Previously published palaeomagnetic directions interpreted as of pre-tilting age for one locality from the eastern part of the Levoča basin (Fig. 5, Table 2, item 11, Túnyi *et al.* 1996) and from the contact between the Levoča and East Slovak basins (Fig. 5, Table 2, item 12, Márton *et al.* 2000) and one Upper Cretaceous locality with documented secondary remanence (Fig. 5, Table 2, item 46b, Márton et al, 2013) all exhibited large CCW rotations. Such statement can be also made of the area west of the Central Carpathian Palaeogene basin (Fig. 5, Table 2, items 8, 9 and 10, Túnyi *et al.* 1996), interpreted as primary remanences, and the posttilting remanence at the western end of the Pieniny Klippen Belt, measured on Upper Cretaceous red marls, (Fig. 5, Table 2, item 46a, Márton *et al.* 2013).

In the Inner Carpathian area there is another large Palaeogene basin (Fig. 1) from which not only Palaeogene palaeomagnetic results are available, but also younger ones. Three sedimentary Palaeogene localities near the river Danube (Fig. 5, Table 2, items 13-15, Túnyi *et al.* 1996) and three from the southern margin of the Bükk Mts (Márton & Márton 1996) indicate large CCW rotation. Similar values were obtained from Upper Eocene andesites and thermally altered contact sediments from the Mátra Mts (Fig. 5, Table 2, item 16), 11 Lower Miocene ignimbrite sites from the Bükk Mts (Fig. 4, Table 2, item 20) as well as from sediments (Fig. 5, Table 2, item 18) and ignimbrites (Fig. 5, Table 2, item 19) of the Nógrád–Novohrad basin of Northern Hungary (Márton and Márton, 1996) and Southern Slovakia (Márton *et al.* 1996). The mentioned sediments and volcanic rocks are in autochthonous position above Internal Carpathian basement units (Fig. 1 and 2). At several places, they are covered by Mid-Miocene volcanics and sediments which exhibit only about 30° CCW rotation (Fig. 5, 21-23, 25-28), while the Upper Miocene rocks are characterized by slight CW or no rotation with respect to the present North (Table 2, items 24 a-f). As the volcanic horizons are well dated with K/Ar, and most sediments with biostratigraphic method, the age of the rotations are fairly well-constrained in the area of the Inner Carpathian Palaeogene basin. The significance of this age control for the Cenozoic displacements will be discussed later.

The East Slovak basin is separated from the rest of the Pannonian basin by a volcanic chain of the Tokaj-Slanec Mts. In this area, including the Vihorlatské Mts, CCW rotated palaeomagnetic directions characterize most of the magmatic rocks (Table 2, items 31-33) suggesting that here the rotation was younger than in the Central and Internal Carpathian Palaeogene basins.

Discussion and tectonic interpretations of the palaeomagnetic results

Cenozoic results

The Cenozoic palaeomagnetic results from the Western Carpathians represent overstep sequences for the Inner Carpathians, while in the Outer Carpathians the studied Palaeogene sediments were folded and thrusted until the Miocene. Despite of the different tectonic settings, there is a remarkable consistency within and between the two areas in palaeomagnetic declinations measured on Palaeogene rocks, indicating large CCW rotation (Fig. 6). As documented in the original papers, the results were obtained using modern laboratory procedures and evaluation. Before tilt corrections, the directions of the characteristic remanences were typically far from that of the present Earth's magnetic field at the sampling areas, proving long term stability. According to between locality fold/tilt tests and reversal tests (where applicable) the characteristic remanences are primary or of syn-folding age. In the latter case, the acquisition time is quite close to the time of deposition. The Magura Nappe (Table 2, item 4) and a population of localities in the eastern segment of the Silesian Nappe (Table 2, item 4d) are notable exceptions. However, the magnetizations of post-folding age are regionally consistent in both areas, therefore valuable in tectonic interpretation. The results summarized in Table 2 and shown in Fig. 7a-c, suggest that during the Miocene, the Inner Carpathians (an already consolidated block) accreted the sediments of the Outer Carpathians. Relative rotations within and between nappes seem to be within the resolution of the palaeomagnetic data. Some differences in declinations within the central segment of the Silesian Nappe and in the Dukla Nappe can be attributed to post-folding uplift, larger average rotation in the western segment in the Silesian Nappe than elsewhere to strike-slip displacements, also postdating the folding (Márton *et al.* 2009 *a*).

An interesting aspect of the palaeomagnetic data set is that overall mean palaeomagnetic declinations of the vectors, both of pre and postfolding ages (Table 2, items 1-4, Fig. 7a-c), are practically coincident. It follows that the internal deformation of the nappes must have taken place between the two acquisition times. In the Silesian and Dukla Nappes, where AMS lineations are well defined, there is a good correlation between them and the strikes of the sampled beds (Fig. 8), i.e. the magnetic fabric was imprinted during the compressional regime which prevailed during folding and thrusting of the nappes. Thus, the order of the events which were important from palaeomagnetic and tectonic aspects are the following. (1) Acquisition of the remanent magnetizations of prefolding age, before the Miocene, (2) internal deformation of the nappes, during which remanences of syn-folding age and the AMS lineations were acquired, (3) co-ordinated rotation of the nappes together with the Inner Carpathian block.

The co-ordinated rotation of the Outer and Inner Western Carpathians must have taken place during two time periods, between 18.5-17.5 and between 16.0 -14.5 Ma. The time constraints are coming from the Internal Carpathian (North Hungarian-South Slovakian) Palaeogene basin, where a large number of well dated localities/sites in sedimentary and igneous rocks yielded good palaeomagnetic results (Table 2, and Fig. 7d and e). Here, older than 18.5 Ma sediments and igneous rocks exhibit about 60° CCW rotation, those between 17.5 and 16.0 Ma about 30°, while younger than 14.5 Ma are characterized by declinations which are close to what is expected in a stable European framework. This means that the final thrusting of the Outer Western Carpathians around 11.5 Ma postdates the process of the docking of the Outer Carpathian nappes by CCW rotation to the southern margin of the European plate.

By the time the rotations were over in the Internal Carpathian Palaeogene basin, CCW rotation was still in progress in the East Slovak basin (Fig. 7e). The tectonic implication of this results, which is corroborated by those from the Maramures area in Romania (Márton *et al.* 2007 *c*) is still to be explored.

Mesozoic and Palaeozoic results

Interpretation of the Mesozoic palaeomagnetic data from the Western Carpathian area poses more problems than Cenozoic. As can be seen from the Fig. 3 and 4, senses and amounts of rotations are varied, even within the same tectonic units. Regional syn-tectonic remagnetizations were documented in several tectonic units (like Silica, Križna and Choč). An additional problem is related to the complexity of the tectonic correction: Mesozoic rocks were deformed during nappe thrusting in the late Cretaceous and the geometry of these Eo-Alpine structures was definitely modified during the Neogene uplifts of the "core mountains". In order to reconstruct the position of Mesozoic nappe stacks between Late Cretaceous and Neogene a tectonic correction for the overlying Palaeogene rocks is applied which in the Tatra Mts amounts to 10° (azimuth)/30° (tilt around horizontal axis) (see e.g. Grabowski 1997; Grabowski *et al.* 2009; Szaniawski *et al.* 2012). In fact all secondary magnetizations of inferred syn-thrusting age are of limited value for regional palaeotectonic interpretations, although they appeared to be useful in local tectonic reconstructions (e.g. position of beds during intermediate stages of thrusting – see e.g. Grabowski 2000; Grabowski *et al.* 2009).

Areas with consistent and partly consistent sense and magnitude of rotations observed on Cenozoic and older rocks

Consistent CCW rotated palaeodeclinations in both primary and secondary palaeomagnetic components are observed within the Triassic rocks of the Silica unit. The observations are in good agreement with the results from the surrounding Cenozoic basins and indicate that the rotations observed within the Mesozoic rocks of the Silica unit are predominantly of Cenozoic age. The Silica units must have rotated together with the ALCAPA superunit and no significant rotation of Silica took place between the Triassic and Miocene.

Coincidence between the Mesozoic and Cenozoic palaeodeclinations is observed in the Male Karpaty Mts. The detected CCW rotations of the Križna unit and the Palaeogene cover are identical and therefore must be interpreted as Neogene. The same sense of rotation with somewhat larger angle can be inferred for the Permian volcanics of the Choč Nappe, although the almost equatorial inclination permits also alternative interpretation of large CW rotation of the Choč Nappe in the Male Karpaty.

Participation of the Pieniny Klippen Belt in the Miocene CCW rotation of the Alp-Carpathian-Pannonian superunit is well constrained (Márton *et al.* 2004, 2013), since the overall-mean primary magnetizatons of the Upper Cretaceous pelagic marls exhibit similar rotation than the oldest group of Cenozoic rocks from the Inner Western Carpathians (Fig. 7a). Thus it might be accepted that PKB units have not rotated significantly between the late Cretaceous (Albian?) and Miocene, except some small scale disturbances that might be attributed to weak oroclinal bending (Márton *et al.* 2013). The pre-Late Cretaceous data set from the same belt clearly disagrees with the late Cretaceous data. Callovian – Kimmeridgian results from the central part of the Pieniny Klippen Belt (Grabowski *et al.* 2008) exhibit only weak CCW rotations. The data might be interpreted in favour of a local(?) CW rotation of the central part of the belt, between the Late Jurassic and Late Cretaceous. However bearing in mind intensive tectonic reworking of the Pieniny Klippen Belt (e.g. Birkenmajer 1986; Ratschbacher *et al.* 1993; Nemčok & Nemčok 1994; Plašienka 2012 *a*) it can not be excluded that different palaeodeclination trends observed result rather from local tectonic rotations and/or disharmonic tectonic deformations of hard blocks of Upper Jurassic Czorsztyn limestones and relatively more competent Upper Cretaceous marls.

Mesozoic (Krs *et al.* 1982, 1993, 1996) and Cenozoic (Márton *et al.* 2009 *a*) results from the western part of the Outer Western Carpathians indicate generally consistent CCW rotations of both Magura and Silesian Nappes which must have occurred after the Oligocene. Non-rotated Mesozoic palaeodeclinations were reported east of 19°E from two localities of the Lower Cretaceous teschenitic rocks of the Silesian Nappe (Grabowski *et al.* 2006) and the Upper Cretaceous marls of Sub-Silesian Nappe (Szaniawski *et al.* 2013). At present state of investigations it is too early for their robust tectonic interpretation. The apparent lack of rotations in the Mesozoic of the central part of the Silesian unit (Grabowski *et al.* 2006) needs confirmation from well bedded sedimentary rocks – secondary nature of magnetization can not be excluded: although both fold and contact tests were positive, a very steep palaeoinclination observed (between 60 and 70°, which corresponds to a latitude ca. 48°N) is hardly acceptable for the Early Cretaceous in the area. Characteristic directions of Szaniawski *et al.* (2013) although they pass the fold test, need some additional assumption for a proper interpretation, since the inclination is far too shallow for the Late Cretceous and results from more geographically distributed localities are needed to verify the regional significance.

Areas with non-consistent sense and magnitude of rotations observed on Cenozoic and older rocks

The best documented contrast between Palaeogene and Mesozoic palaeodeclinations occurs in the area of the High Tatra Mts. A difference between palaeodeclinations from the Central Carpathian Palaeogene Basin (Márton *et al.* 1999; 2009 *b*) and the Tatric and Fatric sequences (e.g. Kądziałko-Hofmokl & Kruczyk 1987; Grabowski 2005) amounts to 90°. The logical consequence of those observations is that the area must have rotated clockwise by amount of ca. 90° between the Late Cretaceous (Turonian?) and Oligocene (Grabowski & Nemčok 1999; Grabowski 2005). The nature and geographical extent of the areas involved in the rotation remains unclear. Paralellisation of this rotation with that which affected the Northern Calcareous Alps between the Barremian and Danian (Mauritsch & Márton 1995; Grabowski 2005) is also hypothetical since palaeomagnetic interpretations in the Northern Calcareous Alps have been substantially modified (Pueyo *et al.* 2007). It is noteworthy that the results from the Tatra Mts were obtained from all major tectonic units: Tatricum (both basement rocks and sedimentary cover), Fatricum and Hronicum. All primary and most secondary Mesozoic directions reveal NNE to E rotated trend of palaeomagnetic declinations. The Neogene uplift most probably did not affect significantly the primary Mesozoic palaeodeclinations (Grabowski 2005; Szaniawski *et al.* 2012) since the bedding azimuth of the studied Mesozoic beds is very close to those of the Palaeogene cover (see also Piotrowski 1978).

Most palaeomagnetic results from the Mesozoic rocks between the High Tatra and Male Karpaty Mts were obtained from the Križna Nappe. It must be kept in mind that a part of these directions (Kruczyk *et al.* 1992) most probably represent syn-tectonic remagnetizations and a real structural context of their acquisition is not clear. It seems however, that a trend of increasing CCW rotations is observed along the strike of the orogen (Grabowski *et al.* 2010). It is supported by the sporadic results from Tatric and Manin units (Pruner *et al.* 1998). As a whole, the data might be interpreted as an effect of oroclinal bending (Kruczyk *et al.* 1992) or radial thrusting. In this case difference between Palaeogene and Mesozoic palaeodeclinations would have decreased SW from the High Tatra Mts. An alternative explanation would be, that the rotations within the Križna Nappe might be related to the different tilting azimuths of different massifs during the Neogene (Szaniawski *et al.* 2012). Indeed massifs uplifted around a roughly E-W oriented axis (like Tatra, Nizke Tatry or Choč Mts) reveal no rotation or slight CW rotation, those uplifted around SW-NE axes –

CCW rotations (Mala Fatra, Strážovske Vrchy and Male Karpaty) while a single locality in the Spišska Magura, located just at the prominent Neogene strike-slip fault (Sperner *et al.* 2002) – extreme CW rotation. Definite verifications of either models is not possible now and would need further integrated palaeomagnetic and field studies.

Palaeozoic and a single Mesozoic result from the central and eastern part of the Choč unit reveal large rotations. The Palaeozoic results should be verified since the results were obtained in the early days of palaeomagnetism and neither details of demagnetization nor the interpretation of characteristic directions were clearly presented. If we accept the reality of CW rotated declinations in the Choč Nappe and correct them for effect of the CCW rotation of entire Alp-Carpathian-Pannonian unit in the Miocene, we have to calculate with a huge CW rotation (ca. 80-130°) of the Choc Nappe before Neogene.

Palaeogene - Neogene(?) remagnetizations of the Mesozoic rocks in the Central Western Carpathians and the Pieniny Klippen Belt

Documentation of secondary magnetizations of the Palaeogene or Neogene age in the Mesozoic rocks is very important, since it creates a link between the Mesozoic and Cenozoic kinematics. It was already mentioned that presence of consistent post-folding remagnetizations of reversed polarity and presumed Neogene age was reported from the western, central and eastern sectors of the Pieniny Klippen Belt (Grabowski *et al.* 2008; Márton *et al.* 2013).

In the rocks of the Križna Nappe no similar directions have been reported so far. However, reversed polarity magnetizations documented in two localities of the Tatricum unit of the Tatra Mts (component C of Grabowski 1997) might be interpreted as overprints acquired just before the Neogene uplift of the Tatra Mts. Having rotated the Tatra Mts back to its pre-Neogene position (see chapter Mesozoic and Palaeozoic results) the reversed overprints attain a declination of 140°, which is again close to the secondary directions from the Pieniny Klippen Belt mentioned above and primary directions from the Pieniny andesites (Marton *et al.* 2004). It seems that a persistent reversed polarity remagnetization which might have been coeval with intrusions of the Pieniny andesites (Birkenmajer & Pécskay 2000), affected also the Mesozoic rocks. Its age might be related with so-called "Mid-Miocene thermal event" which caused resetting of the fission track ages some of the Oligocene rocks in the Podhale Basin (Danišik *et al.* 2012; Anczkiewicz *et al.* 2013).

Mesozoic palaeolatitudes

It is evident from the Table 1 that only a small amount of the available palaeomagnetic data might be suitable for palaeolatitude estimations. All syntectonic remagnetizations must be excluded since their acquisition took place at different stages of thrusting processes in the Late Cretaceous and the position of beds during acquisition of secondary magnetization is not always possible to reconstruct. It must be stressed that data of Kądziałko-Hofmokl & Kruczyk (1987) which for a long time has been referred among the reference Middle – Late Jurassic poles for the European Platform as 'Subtatric nappe sediments, Poland' (see e.g. Besse & Courtillot 1991, 2002, 2003; Van der Voo 1993; Torsvik *et al.* 2012) must also be included to the group of syn-thrusting remagnetizations. It is supported not only by incomplete demagnetization but also by the new results from the coeval rocks from the Pieniny Klippen Belt. Primary palaeoinclinations of the Middle – Upper Jurassic rocks of the Pieniny Klippen Belt (see below) are significantly shallower than those from the Križna unit (Kądziałko-Hofmokl & Kruczyk 1987 – ca. 40°N lat.) and the difference is statistically significant. As it is extremely unlikely that the depositional area of the Križna unit was situated north of the Pieniny Klippen Belt (see e.g. Birkenmajer 1986; Plašienka *et al.* 1997) the secondary nature of the component earlier interpreted as primary, from the Križna Nappe must be accepted.

Despite the need to reject a number of data, the palaeolatitudinal drift history of the Central and Inner West Carpathians together with the Pieniny Klippen Belt, might be roughly constrained (Fig. 9). The Lower Triassic palaeoinclinations obtained from the northern (Szaniawski *et al.* 2012) and southern periphery of the Inner Western Carpathians (Márton *et al.* 1988) are quite concordant and account for the palaeogeographic position of the area at palaeolatitude of ca. 11–13°N. For the rest of the Triassic, results are available from the Silica and Bodva Nappes (Márton *et al.* 1988; Márton *et al.* 1991; Channell *et al.* 2003). They indicate a quick northward drift from ca. 23–25°N in the Middle Triassic up to 34°N in the Late Triassic. No data exist for the Lower Jurassic. Middle and Upper Jurassic results from the Polish sector of the Pieniny Klippen Belt point to ca. 22°N (±5°) latitude in the Callovian – Kimmeridgian (Grabowski *et al.* 2008). The relatively low palaeolatitudes for the Bajocian (21.7°N ±1.5°) and Oxfordian – Kimmeridgian (24.6°N ± 5.6°) were also reported for the western Slovak sector of the belt by Jeleńska *et al.* (2011). These observations might be interpreted in favour of a southward drift of the Western Carpathians between the Late

Triassic and Middle Jurassic. It matches well the model of the southward drift of the Adriatic Plate between the Lower and Middle Jurassic due to an opening of the Liguria – Piedmont ocean (Muttoni *et al.* 2005, 2013) which continued to NE into the Carpathian realm as Vahic – Magura Ocean (e.g. Plašienka 2012b and references therein). It should be noted that southward drift between the Middle Jurassic (Bajocian – Bathonian) and mid-Oxfordian was documented in the easternmost part of the Pieniny Klippen Belt in Ukraine (Lewandowski *et al.* 2005), but its timing was apparently slightly later than in the Western Carpathians.

Abundant data from the Berriasian (Houša *et al.* 1996; Grabowski 2005; Grabowski *et al.* 2009, 2010) are very consistent and indicate a palaeolatitude of ca. 28°N for both the Central Western Carpathians and Pieniny Klippen Belt. The northward drift of both units in the latest Jurassic is again concordant with the similar palaeolatitudinal shift of the Lombardian basin (Muttoni *et al.* 2005) and Ukrainian part of the Pieniny Klippen Belt (Lewandowski *et al.* 2005).

The northward drift apparently continued throughout the Cretaceous, similarly to that of the Adriatic Plate (Márton *et al.* 2010) since the mean Late Cretaceous palaeolatitude of the Pieniny Klippen Belt amounts to 33°N, ± 10° (Márton *et al.* 2013).

The Mesozoic palaeolatitude data for the Outer Western Carpathians are sparse. Very high palaeolatitudes calculated from the Lower Cretaceous teschenitic rocks (ca. 43°N – Krs *et al.* 1982, 1996; Grabowski *et al.* 2006) correspond rather to expected Cenozoic values (Besse & Courtillot 2002, 2003). The mean value for the four studies of the Upper Cretaceous rocks of the Magura and Silesian Nappes (Krs *et al.* 1982, 1996) is ca. 34°N which is not far from the coeval results from the Pieniny Klippen Belt (Márton *et al.* 2013).

Conclusions

The present review focused on the tectonic applications of the palaeomagnetic results from the Western Carpathians which are subdivided into an Outer and an Inner Western Carpathian nappe system, separated by a narrow, tectonically complicated zone, the Pieniny Klippen Belt. The Inner Western Carpathians are further subdivided into a Central and an Internal Carpathians which are in contact along the Meliata suture. The nappes of the Outer Western Carpathians are rootless and were emplaced in the Early Miocene. The overstep sequences here are Miocene sediments occurring in isolated basins. The basement of the Inner

Western Carpathians is built up of several nappe stacks, some thick skinned, consisting basement and cover units, while the others are only cover units. Nappe transport terminated in the Inner Carpathians during Late Cretaceous and the nappes are discordantly covered by latest Cretaceous–Miocene sediments and Neogene igneous rocks. The palaeomagnetic results discussed in this paper represent the above mentioned main units and their analysis lead to the following conclusions:

1. The Internal Western Carpathians are characterized by high diversity of the palaeomagnetic declinations obtained for the basement rocks. The results, interpreted partly as of pre-, partly of syn- and post-folding age suggest important relative rotations during nappe transport, uplift of the 'core mountains' and possibly by oroclinal bending.
2. Overall-mean palaeomagnetic declinations (based on several sites/localities) in the Central Carpathians only slightly depart from the present north in the Tatra Mts, while moderate westerly declinations occur towards the west. Exceptions are the Little Carpathians and the Silica Nappe, where large CCW rotations are documented. Single sites/localities usually indicate large CW or CCW rotations. Checking on their quality (basically applicable to Permian results) and their tectonic significance (local anomalies connected to tectonic lines?) is to be explored in the future.
3. Overstep sequences in the Internal Western Carpathians (namely in the Central and Internal Carpathian Palaeogene basins) exhibit large and fairly consistent CCW rotation up to the age of 18.5 Ma, which is similar in sense and magnitude to the net post-Late Cretaceous rotation of the Pieniny Klippen belt. These observations prove that the named areas formed a single block during the Miocene. The block rotated first in the CCW sense between 18.5 and 17.5 Ma, then during the interval of 16.0-14.5.
4. The above described Miocene CCW rotations must have affected the basement of the Internal Western Carpathians. Consequently, the basement areas exhibiting less CCW rotation than the overstep sequences, must have rotated in the CW sense before the Late Cretaceous.
5. From the Outer Western Carpathians most Cretaceous and all Palaeogene data suggest an overall CCW rotation. The palaeomagnetic control on the Mesozoic situation is quite poor, but the Palaeogene results are geographically distributed and represent the Magura, the Dukla and the Silesian Nappes. They suggest that the Outer Carpathians rotated in co-ordination with the already consolidated Inner Carpathians and the Pieniny KIlippen belt during the Miocene. The folding of the nappes (also manifested

in well defined AMS lineations correlating in direction with the strike of the sampled beds) followed the acquisition of the primary magnetizations of the Palaeogene flysch. As the magnetization of post-folding age is aligned with that of the primary, even the first CCW rotation must have been subsequent to the folding events and the Outer Carpathians attained their present orientation only during the Miocene.

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Figure captions

Fig. 1. The geological build-up of the Western Carpathians. Simplified geological map of the area (modified after Lexa *et al.* 2000) and the location of the cross section ABC. The inset shows the location of the Western Carpathians in the East Alpine–Carpathian-Pannonian system (**a**). The NNW-SSE oriented cross section shows the positions of most of the tectonostratigraphic units of the Westrn Carpathians (**b**).

Note that the sediments of the Central Carpathian Palogene basin were preserved in one larger (surrounding the High Tatra Mts.) and in several smaller outcroping areas, and the Palaeogene rocks of the Internal Carpathian Palogene basin are accessible in outcrops also in the areas covered by Neogene sediments and volcanics.

Fig. 2. Basement map of the Inner Western Carpathians (simplified after Plašienka *et al.* 1997). The map shows the locations of the most important 'core mountains' which are the High Tatra (Tatry), the Low Tatra (N. Tatry), the Little Fatra (M. Fatra), the Innovec and the Little Carpathians (M. Karpaty).

Fig. 3. Structural scheme of the Western Carpathians and adjacent areas (after Lexa *et al.* 2000, slightly modified) with distribution of palaeomagnetic results (palaeodeclinations) obtained from the Palaeozoic and Mesozoic rocks, with age of magnetization indicated. Arrow (palaeodeclination) number corresponds to the entries in the Table 1. Rectangle indicates area presented in the Fig. 4. Some Palaeozoic declinations show two alternative interpretations of vertical axes rotations (clockwise and counter-clockwise).

Fig. 4. Geological sketch of the middle part of the Inner Carpathians (after Lexa *et al.* 2000, slightly modified) with all available palaeomagnetic data indicated.

Arrow (palaeodeclination) number corresponds to the entries in Tables 1 (black numbers) and 2 (grey numbers). Big arrow indicates result based on several sites or detailed magnetostratigraphic study in a single section; small arrow indicate result based on single locality. For lithological key (except items 15a-c) and other explanations, see Fig. 3. 15a – Fatric unit, sediments; 15b – Tatricum, sedimentary cover, 15c – Hronic unit, sediments.

Fig. 5. Palaeomagnetic declinations obtained from Cenozoic rocks and two localities of the Upper Cretacous red marls from the Pieniny Klippen belt with post-folding remanence. Numbers up to 33 refer to Table 2, 46a and 46b to Table 1.

Fig. 6. Palaeomagnetic locality mean directions (providing the entry data for calculating overall-mean paleomagnetic directions tabulated in Table 2) from the dominantly Paleogene sediments (squares) from the Silesian (Table 2, rows 1a-d) and Magura nappes (Table 2, row 4) of the Outer Western Carpathians, from the Central (Table 2, row 7) and Inner Carpathian (Table 2, rows 13-15, 17 and 18) Paleogene basins, from the latest Cretaceous red marls (Table 1, rows 45 and 46) of the Pieniny Klippen belt (dots and circles) and from the igneous rocks of the Pieniny Klippen Belt (Table 2, row 6) and of the Inner Carpathian Paleogene basin (Table 2, rows 16, 19 and 20). Stereographic projections, full/empty symbols are vectors pointing downwards/upwards, representing vectors with positive and negative inclinations, respectively.

Figs 6a (before tilt corrections) and 6b (after tilt corrections) show the paleomagnetic directions interpreted as of pre-folding/tilting age. Note that in the Pieniny Klippen belt overturned strata also occur and these have negative inclinations before and positive after tectonic corrections.

Figs 6c (after tilt corrections) and 6d (before tilt corrections) show the paleomagnetic directions interpreted as of post-folding/tilting age from the PKB (Table 1, rows 46a and 46b), from the Magura nappe (Table 2, row 4) and from the Silesian nappe (Table 2, row 1d).

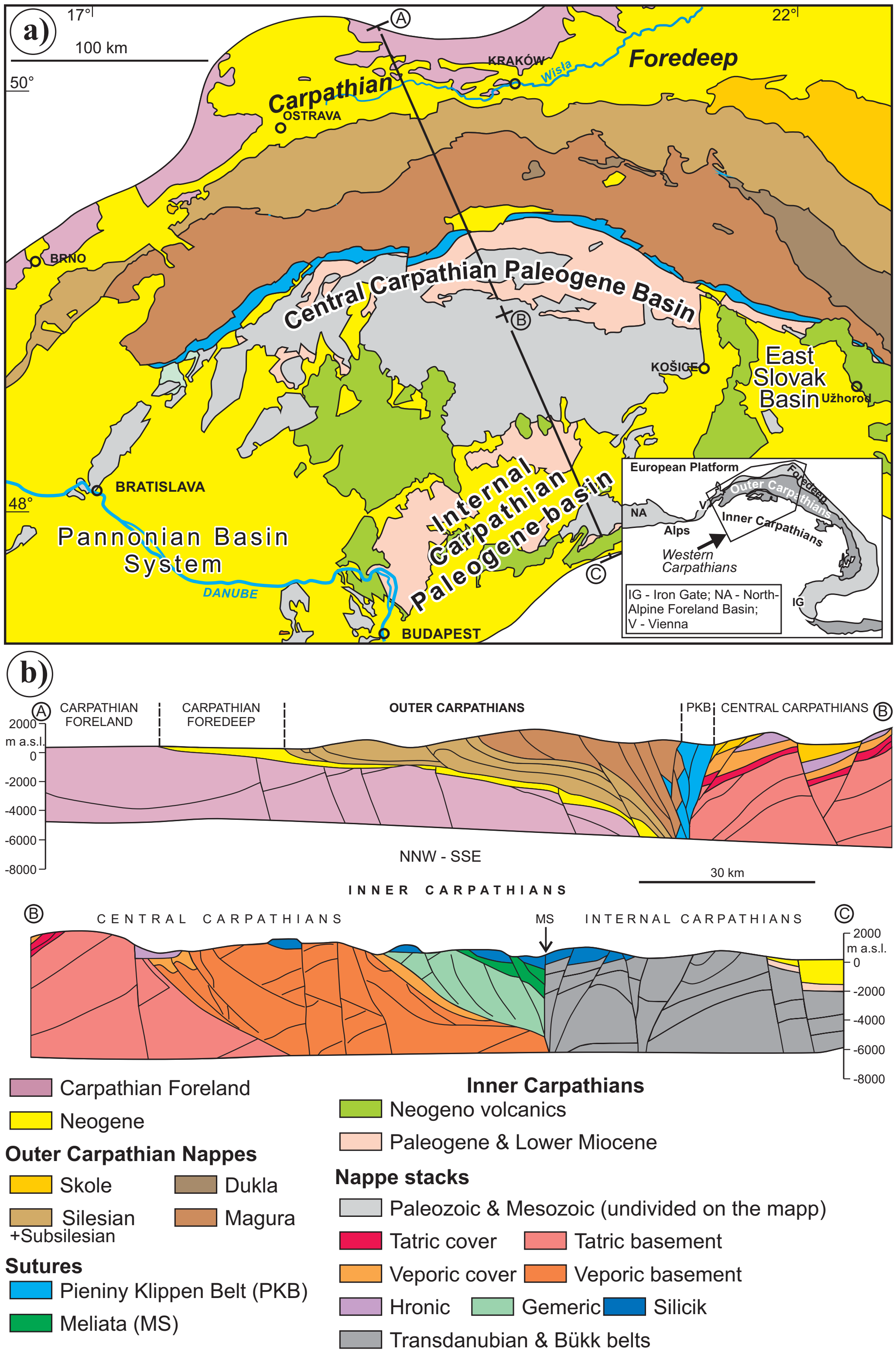
Fig. 7. Palaeomagnetic directions with confidence circles for the Palaeogene rocks of the Outer Carpathian nappes, the Upper Cretaceous red marls and the Miocene andesites of the Pieniny Klippen belt and the overstep sequences of the Internal Carpahians. Stereographic projections, all directions are plotted as of normal polarity. It is documented that the Miocene overall rotations of the Outer Carpahian nappes (Silesian, Dukla and Magura Table 2, items 1 - prefolding, 1d - postfolding, 2 - synfolding, 4 - postfolding respectively), the Pieniny Klippen belt (Upper Cretaceous red marls, Table 1, item 45 - prefolding, Pieniny andesites, Table 2, item 6) and the Podhale-Levoča basin (Table 2, item 7) are the same (**a**), that the Palaeogene sediments (single localities) outside of the Podhale-Levoca basin (Table 2, items 8-12)

also exhibit large CCW rotations (**b**) that the Podhale-Levoča basin rotated in co-ordination with the Internal Carpathian Palogene basin (Table 2, items 16, 18-20) during the Miocene (**c**). The net Miocene rotation is the results of two rotational phases, since younger that 17.7 Ma rocks from the Internal Carpathian Palogene basin (Table 2, items 21-23, 25, 27 and 28) exhibit only moderate CCW rotation (**d**) and by the time the rotations are over there (Table 2, items 24, 28-30), they are still going on (Table 2, items 31 and 32) in the East Slovak basin (**e**).

Fig. 8. Correlation between local tectonic strikes and AMS lineations in the Silesian and Dukla Nappes, due to compressional tectonics.

Fig. 9. Palaeolatitudinal drift of the Inner Carpathians and Pieniny Klippen Belt in the Mesozoic. Numbers corresponds to entries in Table 2. Asterisk (*) denote data from Jeleńska *et al.* (2011) not enclosed into the Table 1.

Fig. 1.



a)
17°
22°
100 km
50°
48°
Carpathian
Foredeep
KRAKÓW
Wisła
OSTRAVA
BRNO
Central Carpathian Paleogene Basin
KOŠICE
East
Slovak
Basin
Užhorod
BRATISLAVA
Pannonian Basin
System
DANUBE
Internal
Carpathian
Paleogene basin
BUDAPEST
European Platform
Foredeep
Outer Carpathians
NA
V
Alps
Inner Carpathians
Western
Carpathians
IG
IG - Iron Gate; NA - North-Alpine Foreland Basin; V - Vienna
b)
CARPATHIAN FORELAND
CARPATHIAN FOREDEEP
OUTER CARPATHIANS
PKB
CENTRAL CARPATHIANS
2000
m a.s.l.
0
-2000
-4000
-6000
-8000
NNW - SSE
30 km
INNER CARPATHIANS
CENTRAL CARPATHIANS
MS
INTERNAL CARPATHIANS
Carpathian Foreland
Neogene
Outer Carpathian Nappes
Skole
Dukla
Silesian +Subsilesian
Magura
Sutures
Pieniny Klippen Belt (PKB)
Meliata (MS)
Inner Carpathians
Neogeno volcanics
Paleogene & Lower Miocene
Nappe stacks
Paleozoic & Mesozoic (undivided on the mapp)
Tatric cover
Tatric basement
Veporic cover
Veporic basement
Hronic
Gemeric
Silicik
Transdanubian & Bükk belts

Fig. 2.

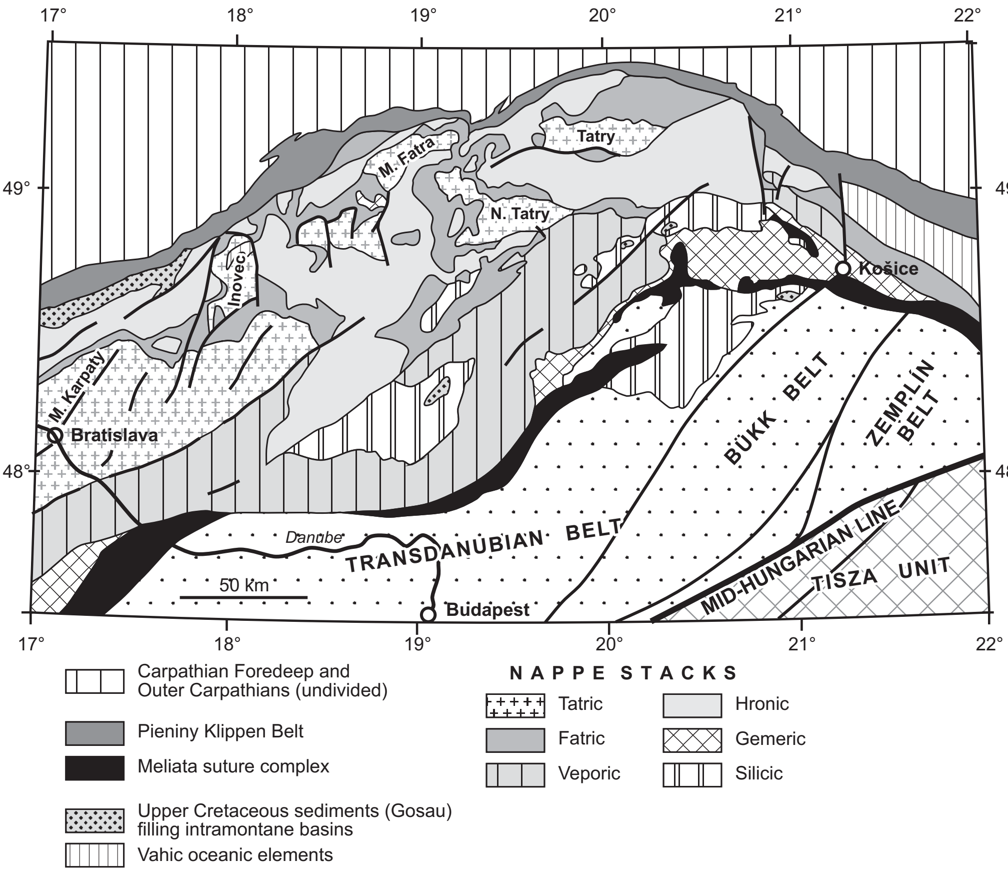

17°
18°
19°
20°
21°
22°
49°
48°
Tatry
M. Fatra
N. Tatry
Inovec
M. Karpaty
Bratislava
Košice
BÜKK BELT
ZEMPLÍN BELT
Danube
TRANSDANUBIAN BELT
MID-HUNGARIAN LINE
TISZA UNIT
50 km
Budapest
Carpathian Foredeep and
Outer Carpathians (undivided)
Pieniny Klippen Belt
Meliata suture complex
Upper Cretaceous sediments (Gosau)
filling intramontane basins
Vahic oceanic elements
NAPPE STACKS
Tatric
Fatric
Veporic
Hronic
Gemeric
Silicic

Fig. 3.

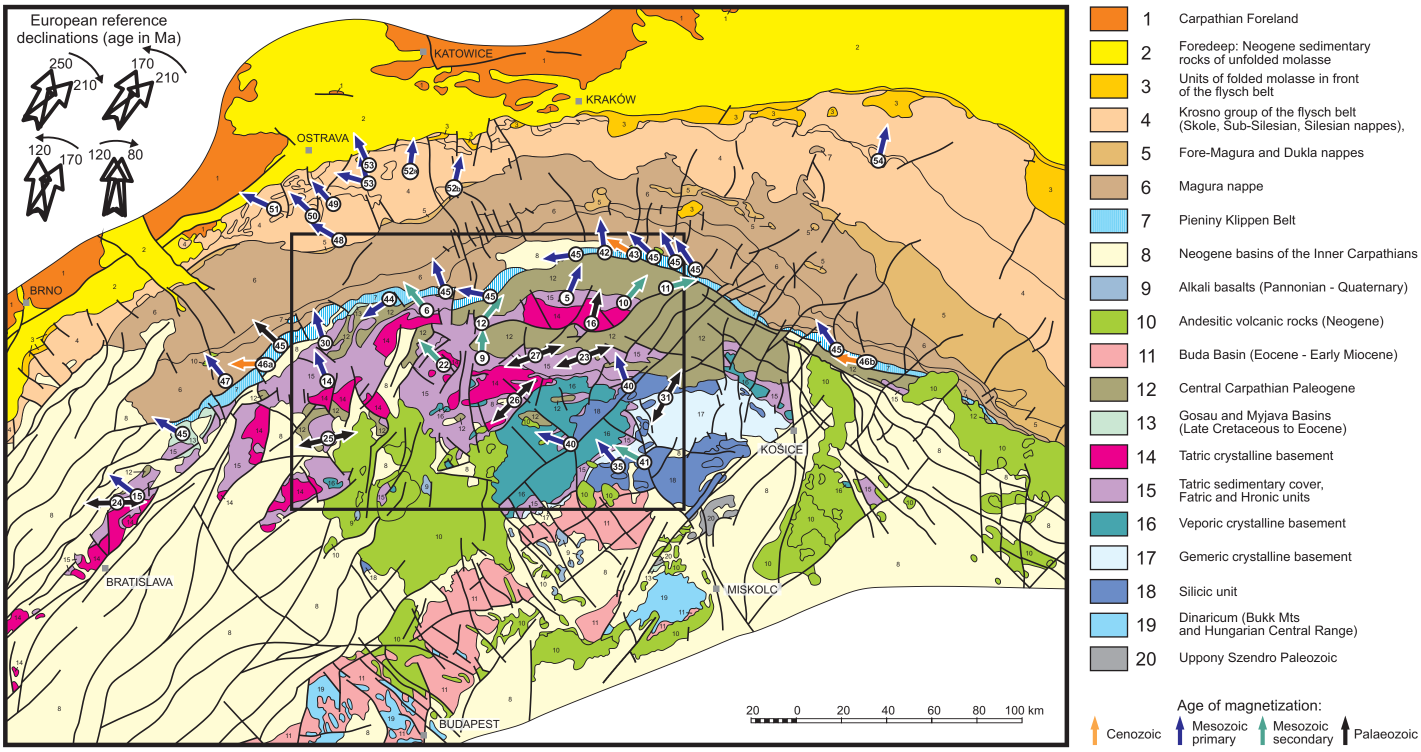

European reference declinations (age in Ma)
250
210
170
210
120
170
120
80
KATOWICE
KRAKÓW
OSTRAVA
BRNO
BRATISLAVA
BUDAPEST
MISKOLC
KOŠICE
20 0 20 40 60 80 100 km
1 Carpathian Foreland
2 Foredeep: Neogene sedimentary rocks of unfolded molasse
3 Units of folded molasse in front of the flysch belt
4 Krosno group of the flysch belt (Skole, Sub-Silesian, Silesian nappes),
5 Fore-Magura and Dukla nappes
6 Magura nappe
7 Pieniny Klippen Belt
8 Neogene basins of the Inner Carpathians
9 Alkali basalts (Pannonian - Quaternary)
10 Andesitic volcanic rocks (Neogene)
11 Buda Basin (Eocene - Early Miocene)
12 Central Carpathian Paleogene
13 Gosau and Myjava Basins (Late Cretaceous to Eocene)
14 Tatric crystalline basement
15 Tatric sedimentary cover, Fatric and Hronic units
16 Veporic crystalline basement
17 Gemeric crystalline basement
18 Silicic unit
19 Dinaricum (Bukk Mts and Hungarian Central Range)
20 Uppony Szendro Paleozoic
Age of magnetization:
Cenozoic
Mesozoic primary
Mesozoic secondary
Palaeozoic

Fig. 4.

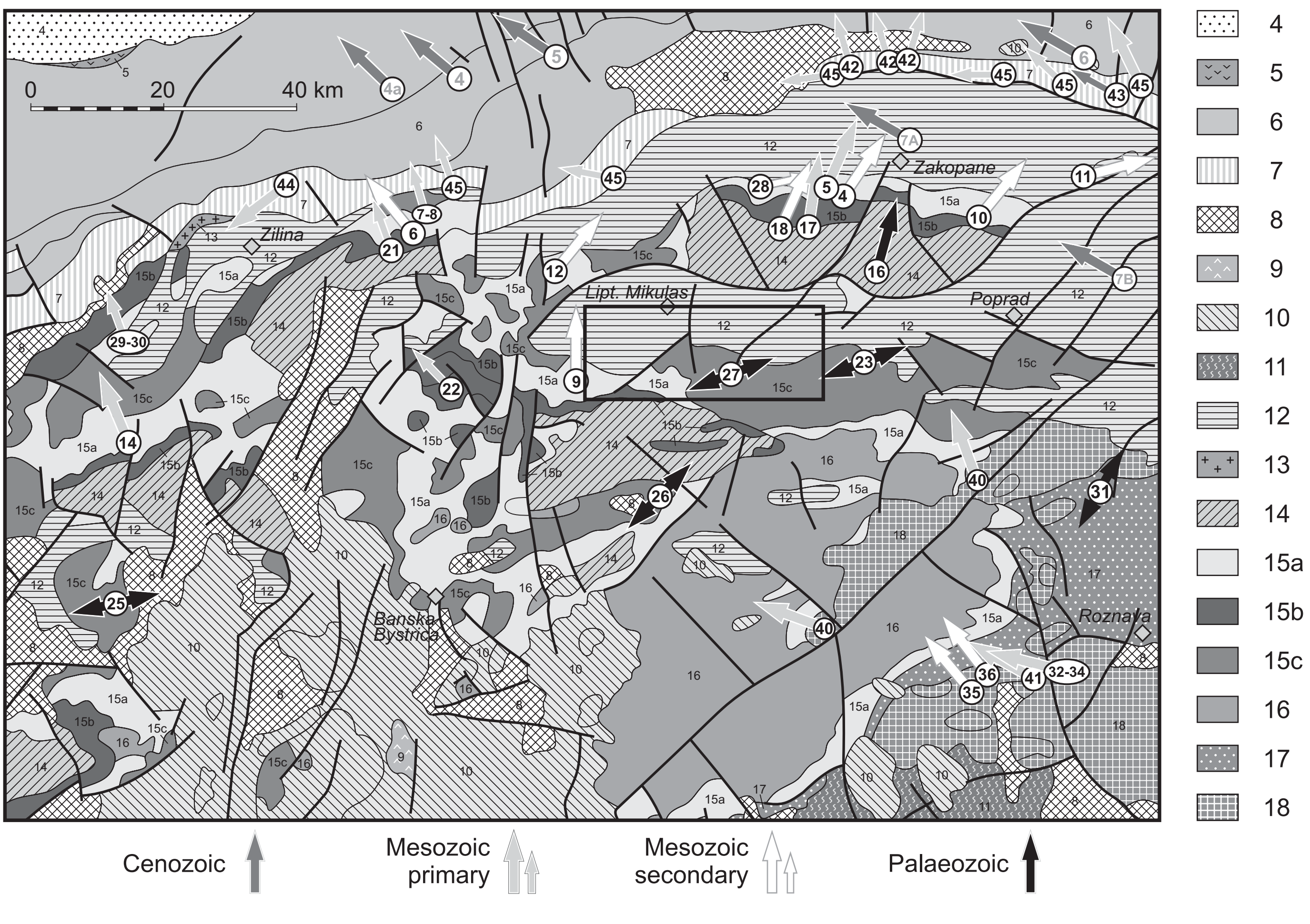

0
20
40 km
Zilina
Lipt. Mikulas
Zakopane
Poprad
Banska Bystrica
Roznava
4
5
6
7
8
9
10
11
12
13
14
15a
15b
15c
16
17
18
Cenozoic
Mesozoic primary
Mesozoic secondary
Palaeozoic

Fig. 5.

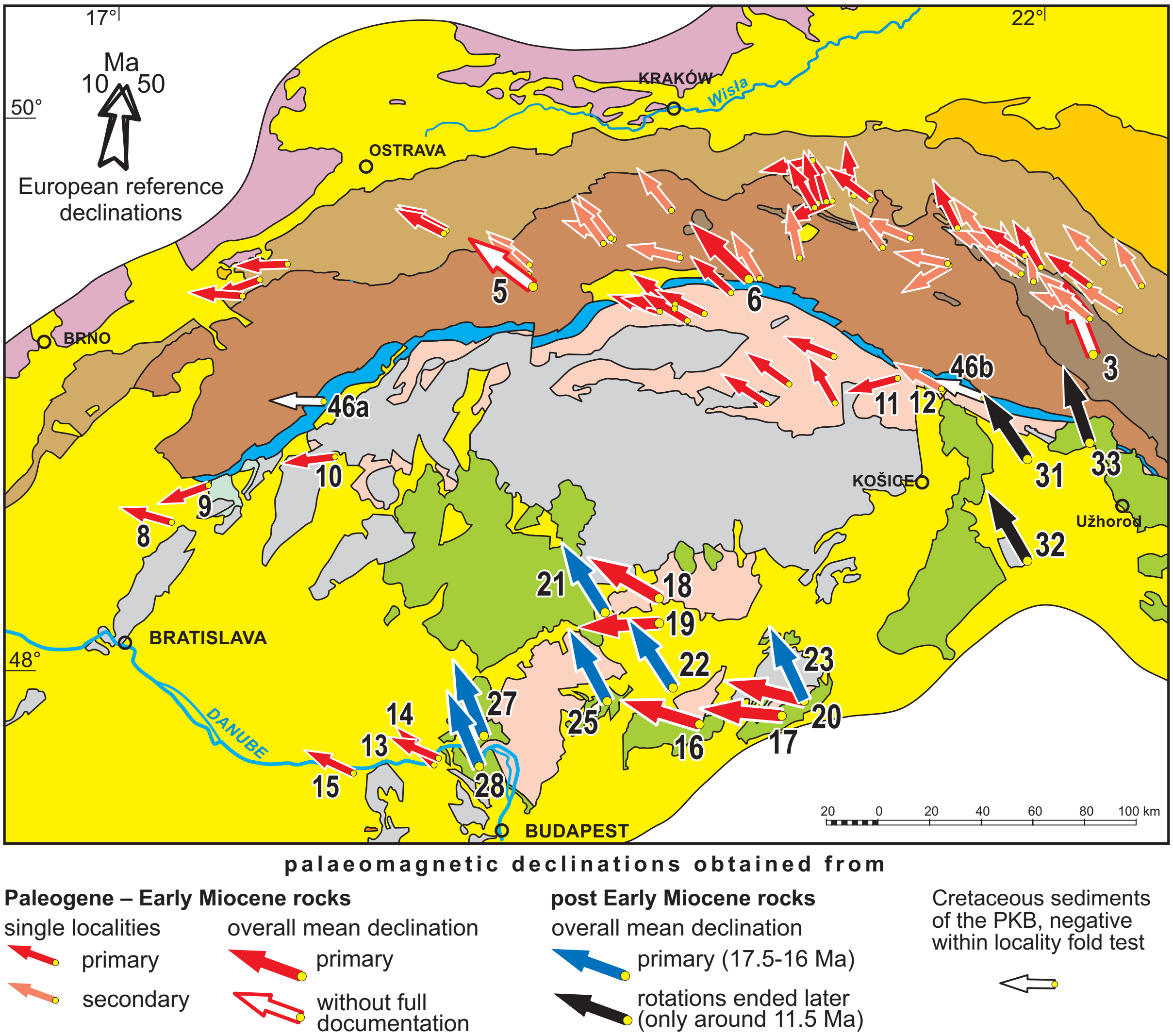
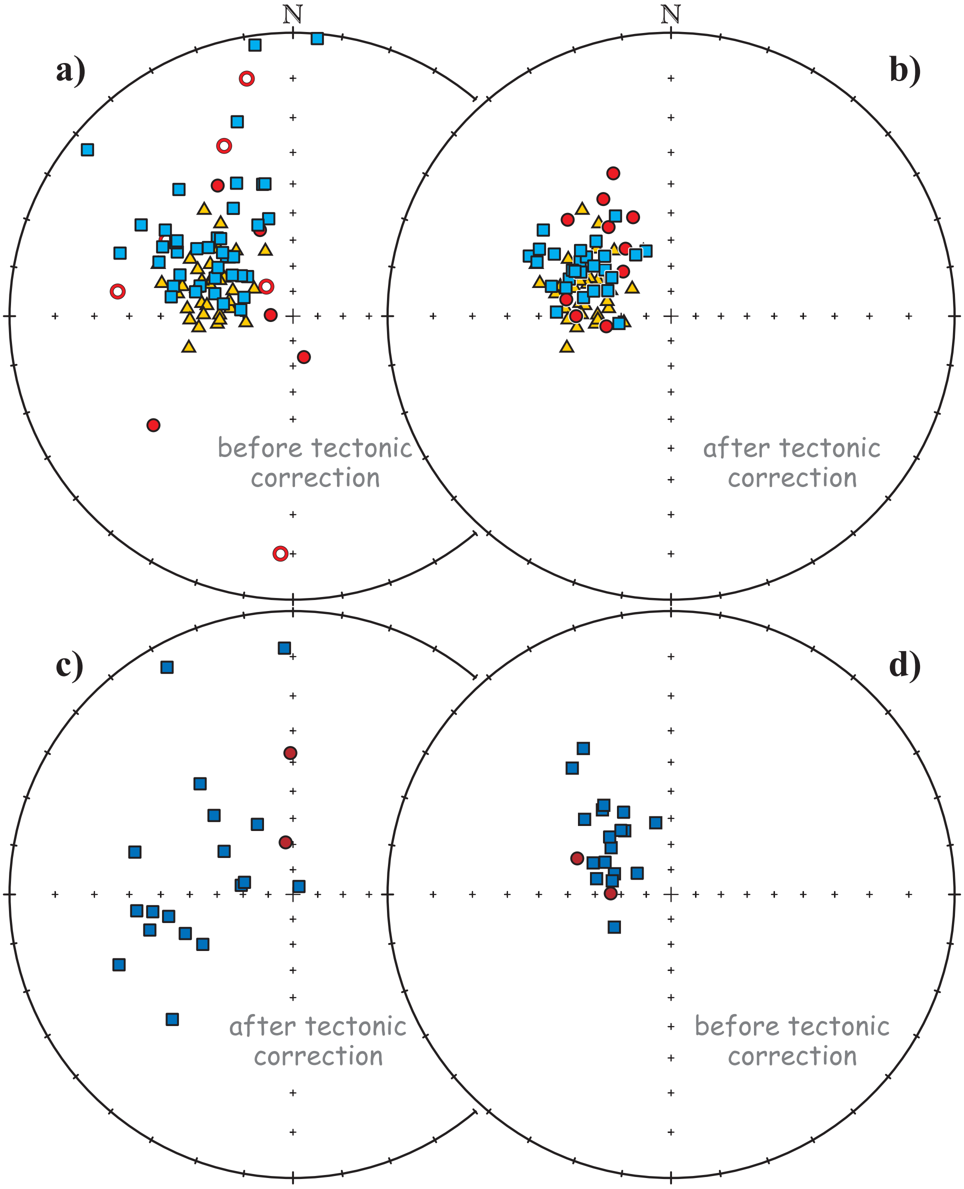
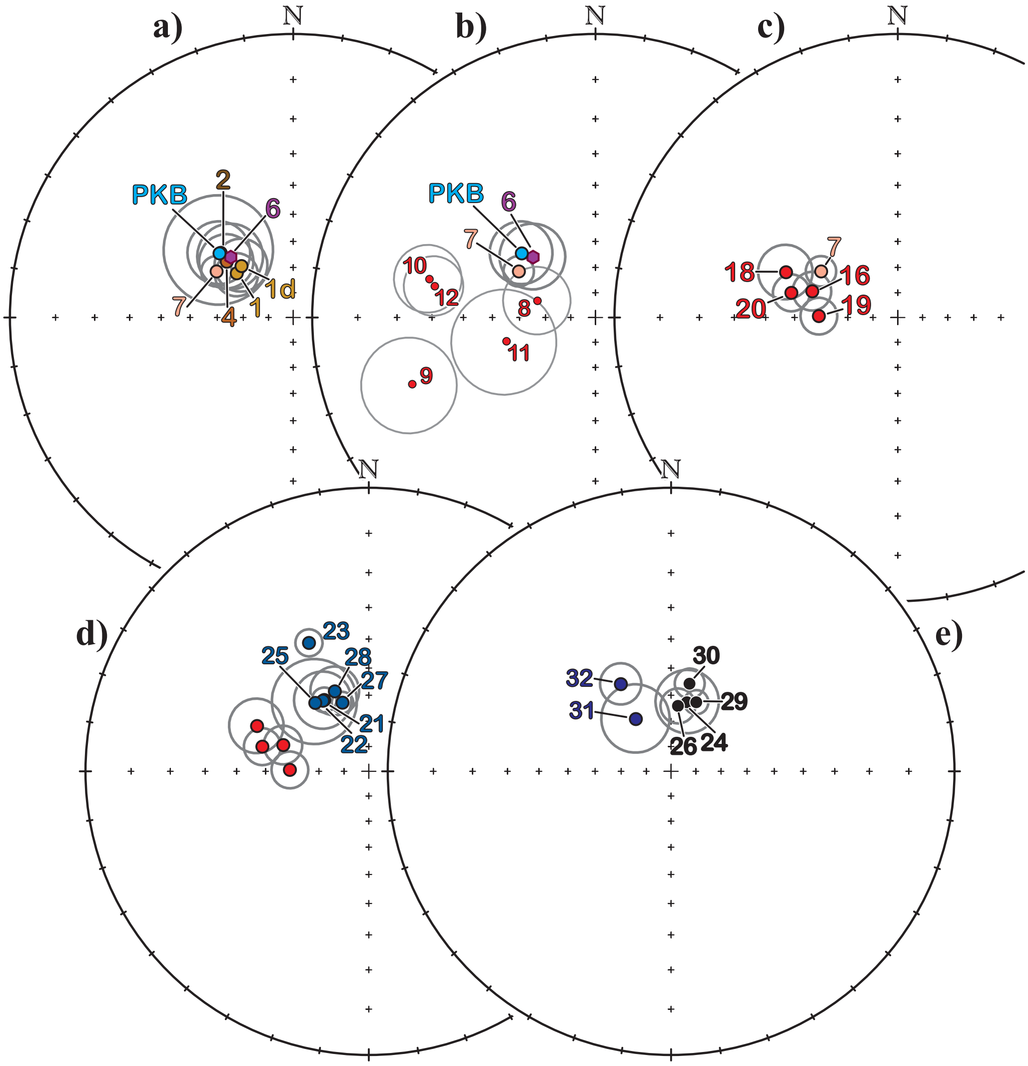

17°
22°
50°
48°
Ma
10
50
European reference declinations
KRAKÓW
Wisła
OSTRAVA
BRNO
BRATISLAVA
DANUBE
KOŠICE
Užhorod
BUDAPEST
5
6
3
46a
46b
8
9
10
11
12
31
32
33
13
14
15
16
17
18
19
20
21
22
23
25
27
28
20 0 20 40 60 80 100 km
palaeomagnetic declinations obtained from
Paleogene – Early Miocene rocks
single localities
primary
secondary
overall mean declination
primary
without full documentation
post Early Miocene rocks
overall mean declination
primary (17.5-16 Ma)
rotations ended later (only around 11.5 Ma)
Cretaceous sediments of the PKB, negative within locality fold test

Fig. 6.



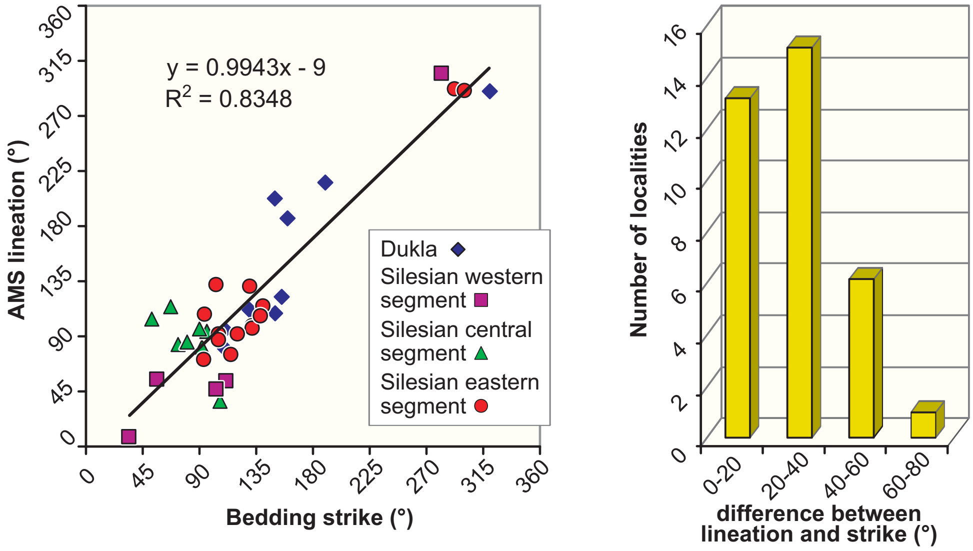
N
N
a)
b)
before tectonic correction
after tectonic correction
c)
d)
after tectonic correction
before tectonic correction

Fig. 7.



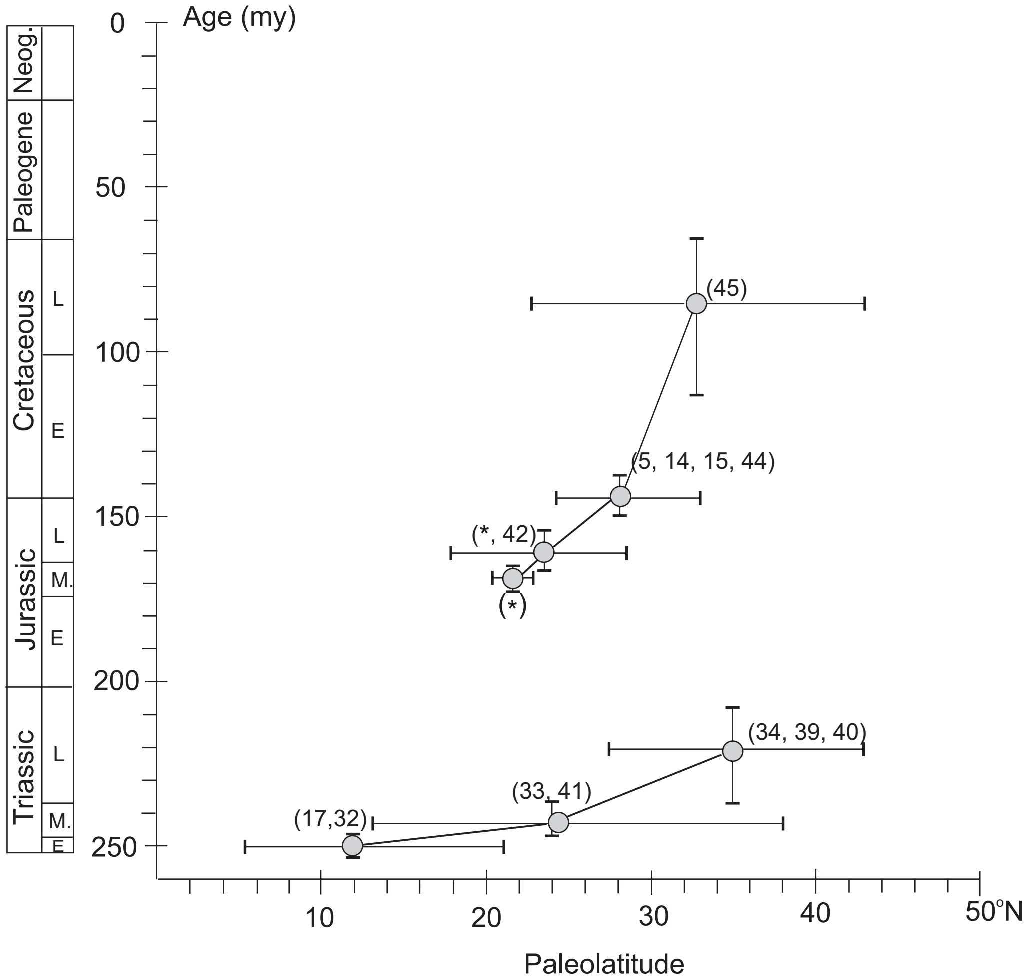
a)
b)
c)
d)
e)
N
PKB
2
6
7
4
1
1d
10
12
8
11
9
18
16
20
19
23
25
28
27
21
22
32
31
30
29
26
24

Fig. 8.



y = 0.9943x - 9
R2 = 0.8348
AMS lineation (°)
Bedding strike (°)
Dukla
Silesian western segment
Silesian central segment
Silesian eastern segment
Number of localities
difference between lineation and strike (°)
0-20
20-40
40-60
60-80

Fig. 9.



Age (my)
0
50
100
150
200
250
Neog.
Paleogene
Cretaceous
L
E
Jurassic
L
M.
E
Triassic
L
M.
E
(45)
(5, 14, 15, 44)
(*, 42)
(*)
(34, 39, 40)
(33, 41)
(17,32)
10
20
30
40
50°N
Paleolatitude

Table 1.

		Lat.N° Lon.E°	Age of rocks	N/No	n/no	D°	I°	k	α_{95}	D_C°	I_C°	k	α_{95}°	rot.°	Pole lat.°N	Pole lon.°E	δp°	δm°	remark	ref
Križna nappe																				
1	Tatra Mts – Bobrowiec + Havran unit	49.3 19.8	J2 – J3	7/8		-	-	-	-	22	59	198	4	+22±8	72	132	5	6	*?	1
2	Tatra Mts – Bobrowiec and Gladkie unit	49.3 19.9	Oxfordian	4/5		159	79	17	23	37	53	96	9	+37±15	59	125	9	13	*	2
3	Tatra Mts – Suchy Wierch unit	49.3 20.0	T2	2/2	14/14	163	55	10	13	62	67	83	4	+62±10	-	-	-	-	F+, *	3
4	Tatra Mts – Bobrowiec unit	49.3 19.8	T3 – K1	7/8		176	80	46	9	34	60	74	7	+34±14	65	116	8	11	*	3
5	Tatra Mts	49.3 19.8	Berriasian	3/3	.	346	84	182	9	23	47	499	5	+23±7	63	152	5	7	f+, R_B	4
6	Mala Fatra	49.24 19.16	J2-J3	21 sites		328	85	66	4	321	44	96	3	-39±4	58	253	?	?	*?	5
7	Mala Fatra – Zázrivská Dolina	49.24 19.15	J2-J3	1	15/?	-	-	-	-	331	42	55	5	-29±7	56	252	4	6		6
8	Mala Fatra – Zázrivská Dolina	49.23 19.16	Hettangian	1	14/?.	-	-	-	-	358	43	35	7	-2±10	66	203	5	8		6
9	Low Tatra	49.03 19.28	J2	3 sites		35	76	243	8	2	56	73	14	+2±25	78	192	?	?	*?	5
10	Belanski Tatra	49.25 20.20	J2-J3	4 sites		190	73	58	12	40	59	118	8	+40±16	61	113	?	?	*?	5
11	Magura Spisska	49.28 20.53	J2	3 sites		312	70	28	24	75	46	114	12	+75±17	30	102	?	?	*?	5
12	Choč hills	49.12 19.23	J1	3 sites		116	80	104	12	39	63	104	12	+39±26	63	105	?	?	*?	5
13	Strážov Mts (component B)	48.94 18.47	Tithonian – Hauterivian	3/3		137	54	38	20	28	75	317	7	+28±27	-	-	-	-	*, f+	7
14	Strážov Mts (component C)	48.94 18.47	Tithonian – Berriasian	2/3	18/64	177	84	12	10	338	49	75	4	-22±6	65	247	4	5	f+	7
15	Male Karpaty	48.51 17.36	Tithonian – Berriasian	1	34/47	215	65	15	7	307	49	17	6	-53±9	46	282	5	8		8
Tatricum																				
Tatra Mts.																				
16	Tatra Mts – crystalline core	49.2 20.1	C1 (345-340Ma?)	4/7		193	17	59	12	194	47	59	12	+4±18	-12	7	10	15		9
17	Tatra Mts (parautochthon)	49.2 19.9	T1	6/8		10	63	47	10	8	21	213	5	+8±5	51	188	3	6	f+,	10
18	Tatra Mts (parautochthon)	49.2 19.9	J2-K1	4/8		211	76	29	17	23	50	256	6	+23±9	64	149	5	8	*, f+	11
19	Tatra Mts (allochthon)	49.25 19.87	J2-J3	1	18/?	301	50	5	48	312	48	48	5	-48±7	49	279	-	-	*?	11

20	Tatra Mts (parautocht. + allochton)	49.2 19.9	J3-K1	2/10	28/?	70	-68	-	-	180	-69	-	-	-110±??	27	339	-	-	**?	11
Mala and Velka Fatra																				
21	Lúčivná	49.21 19.17	Berriasian	1	15/?.	-	-	-	-	341	54	39	6	-19±10	69	250	6	9		6
22	Došná Dolinka	48.97 19.09	Callovian – Oxfordian	1	13/?.	-	-	-	-	316	48	11	13	-44±19	51	274	11	17		6
Ckhoč nappe																				
23	Central Slovakia, red shales	49.0 20.0	P1	13		-	-	-	-	72	20	4	6	?	-20	297	3	7		12
24	Male Karpaty, melaphyres	48.47 17.3	P	6		265	17	13	19	269	-2	13	19	?	1	287	9	19		13
25	Tribec Mts, melaphyres	48.49 18.53	P	3		258	-21	8	10	255	-18	8	10	?	-17	294	5	10		13
26	Low Tatra S melaphyres	48.85 19.55	P	16		242	-24	4	20	223	-13	5	18	?	-35	325	9	19		13
27	Low Tatra N melaphyres	48.97 19.70	P	32		262	-21	7	10	250	-16	6	11	?	-19	300	6	12		13
28	Tatra Mts, Reifling limestone	49.27 19.82	T2	1	5/5	144	38	109	7	100	60	89	8	+100±16	24	75	-	-	*	3
Manin nappe																				
29	Záskalie	49.14 18.52	Albian	1	14/?.	-	-	-	-	334	48	53	14	-26±21	62	252	5	7		6
30	Butkov	49.02 18.36	Oxfordian	1	26/?	-	-	-	-	343	46	14	8	-17±11	65	237	6	10		6
Gemericum																				
31	Eastern Slovakia, red shales	48.83 20.50	P1	9		-	-	-	-	29	17	5	5	+29±5	-43	339	5	3		12
Silica nappe																				
32	Aggtelek Mts.		T1	3		294	51	7	49	294	24	31	23	-66±25	25	281	13	25	f+	14
33	Aggtelek Mts.		T2	4		294	42	30	17	272	40	34	16	-88±44	18	305	12	19	f+	14
34	Aggtelek Mts.		T3	6		259	46	12	20	289	59	38	11	-71±21	40	309	12	16	f+	14
35	Slovak Karst	48.5 20.3	T2-T3	5/5		299	57	22	17	320	42	168	6	-40±8	50	267	-	-	Synf*	15
36	Slovak Karst normal	48.5 20.3	T2-T3	5/6		318	50	22	16	322	50	66	9	-38±14	56	273	-	-	Synf*.	16
37	Slovak Karst reversed	48.5 20.3	T3	1/6	69/?	98	-69	12	5	89	-54	12	5	-82±14	41	328	-	-		16
38	Slovak karst Silicka Brezova LBT	48.5 20.5	T3	8		318	61	64	7	316	43	48	8	-42±14	60	295	8	11		17
39	Slovak karst Silicka Brezova HBT	48.5 20.5	T3	8		319	64	46	8	316	46	112	5	-44±7	50	274	4	7	f+	17
40	Stratenska Hornatina (North. Gemericum)	48.8 20.1	Carnian	2/8		308	44	-	-	314	55	-	-	-46±??	54	286	-	-		15
Bódva nappe																				
41	Rudabánya Mts.		T2	5		33	72	5	41	298	43	20	17	-62±23	37	288	13	21	f+	14

Pieniny Klippen Belt																				
42	Czorsztyn unit – Primary component	49.4 20.0	J2-J3	3/5	·	354	5	6	55	353	40	29	23	-7±30	63	215	17	28	f+	18
43	Czorsztyn unit – Secondary component	49.4 20.4	J2-J3	2/5		120	-67	-	-	166	-65	-	-	-60±??	52	314	-	-		18
44	Brodno	49.26 18.75	Tithonian – Berriasian	1	104	-	-	-	-	236	45	10	6	-124±14	1	331	4	7		19
45	Red marls	48.6-49.25 17.3-21.3	K2	11/14		301	13	2	62	311	53	17	11.3	-49±28	51	284	11	15	f+	20
46a	Red marls, secondary magnetization, W	49.00 18.10	K2		8	91	-66	20	13	352	69	6	24	-89±32	35	324	17	21	f-	20
46b	Red marls, secondary magnetization, E	49.01 21.58	K2		10/14	111	-51	48	7	179	-37	37	8	-69±11	37	296	6	9	f-	20
Outer West Carpathians, Magura unit																				
47	Biele Karpaty	48.9 17.8	K2	9		327	56	12	16	321	44	86	6	-39±8	52	265	4	7	f+	21
Outer West Carpathians, Silesian unit																				
48	NE Moravia, Silesia, Grey sandstones	49.48 18.43	Coniacian	no data	94	-	-	-	-	300	46	3	10	-60±14	40	285	8	13		13
49	NE Moravia , Silesia, Ondrejnik Mts, red claystones	49.57 18.30	Cenomanian - Turonian	no data		-	-	-	-	318	73	11	4	-42±14	64	323	7	8		13
50	NE Moravia, Silesia, Red claystones	49.52 18.27	Cenomanian - Turonian	no data		-	-	-	-	313	53	9	3	-47±5	52	281	3	5		13
51	NE Moravia, Silesia teschenites	49.57 18.07	K1	no data		-	-	-	-	295	56	6	6	-65±11	42	297	6	8		22
52a	Teschenitic rocks Poland, E, Świętoszówka	49.7 18.9	K1	2		345	55	-	-	7	59	-	-	+7±??					f+, **?	23
52b	Teschenitic rocks Poland, E, Żywiec	49.6 19.2	K1	3		298	-29	1	139	13	69	272	7	+13±20	81	82	11	13	f+, **?	23
53	Teschenitic rocks Poland, W	49.6 18.6	K1	3		335	67	1	149	319	66	26	24	-41±59	63	301	32	40	**?	23
Outer West Carpathians, Sub-Silesian unit																				
54	Węglówka marls	49.8 21.8	K2	4/6		191	11	4	50	194	-18	21	20	?	48	181	11	21		24

Table 1. Summary of palaeomagnetic results from Palaeozoic and Mesozoic rocks in the Western Carpathians

Key: Lat.N°, Lon.E°: Geographic coordinates; N/No (n/no:): number of used/collected localities (samples, if only one locality is tabulated); D°, I° (Dc°, Ic°): declination, inclination before (after) tectonic/tilt correction; k and α_{95}: statistical parameters (Fisher 1953); Values in heavy letters are interpreted in terms of tectonics; rot° : angle of rotation with error, with respect to the present north Pole; Lat.N°, Lon.E°: palaeomagnetic poles with statistical parameters (dp, dm). Remarks: R: classification of reversal tests (McFadden & McElhinny 1990), a, b, c: positive, -: negative, i: test with isolated observation; rev: the population has originally reversed polarity (in the table shown as normal); f: fold test (Enkin 2003) +: positive, -: negative: i: indeterminate. * - Late Cretaceous remagnetization; ** - Paleogene – Neogene remagnetization; Synf* - synfolding remagnetization. References: 1 – Kądziałko-Hofmokl & Kruczyk 1987; 2 – Grabowski 1995; 3 – Grabowski 2000; 4 – Grabowski 2005; 5 – Kruczyk *et al.* 1992; 6 – Pruner *et al.* 1998; 7 – Grabowski *et al.* 2009; 8 – Grabowski *et al.* 2010; 9 – Grabowski & Gawęda 1999; 10 – Szaniawski *et al.* 2012; 11 – Grabowski 1997; 12 – Kotasek & Krs 1965; 13 – Krs *et al.* 1982; 14 – Márton *et al.* 1988; 15 – Márton *et al.* 1991; 16 – Kruczyk *et al.* 1998; 17 – Channell et al. 2003; 18 – Grabowski *et al.* 2008; 19 – Krs *et al.* 1996; 20 – Márton *et al.* 2013; 21 – Krs *et al.* 1993; 22 – Krs & Smid 1979; 23 – Grabowski *et al.* 2006; 24 – Szaniawski *et al.* 2013.

Table 2.

		Lat.N° Lot.E°	Age of rocks	N/No	n/no	D°	I°	k	α_{95}	D_c°	I_c°	k	α_{95}°	rot.°	Pole lat.°N	Pole lon.°E	δp°	δm°	remark	ref
Outer Carpathian Nappes																				
1	Silesian nappe Claystone, siltstone	49.3-49.9 17.6-22.4	Oligocene (1 locality Miocene)	17/25		328	40	8	13.1	307	62	20	8.2	-53±17	54	302	10	13	Rb, f+	1, 0
1a	Silesian nappe W Claystone, siltstone	49.3-49.6 17.6-18.7	Oligocene	5/6		304	49	20	17.6	279	64	48	11.2	-81±26	38	318	14	18	Rc, f+	1
1b	Silesian nappe C Claystone, siltstone	49.7-49.9 20.7-21.9	Oligocene	7/8		331	45	13	17.4	317	67	20	13.8	-43±35	63	307	19	23	Rc, f+	1
1c	Silesian nappe E Claystone, siltstone	49.3-49.6 21.6-22.4	Oligocene (1 locality Miocene)	5/11		342	19	8	29.8	318	49	46	11.4	-42±17	53	277	10	15	Rc, f+	1, 0
1d	Silesian nappe E Claystone, siltstone	49.3-49.6 21.6-22.4	Oligocene, postfolding	5/11		315	61	59	10.0	279	42.8	4	44.6	-45±16	58	296	12	15	f-	1
2	Dukla nappe Claystone, siltstone	49.3-49.5 21.2-22.1	Oligocene	7/10		327	48	8	23.1	312	52	11	19.5	-48±32	51	285	18	27	syntilt	0
3	Dukla nappe Red Claystone	49.16 22.19	Mid-Late Eocene	5/15						339	40			-21±??	59	242	3	4		2
4	Magura nappe Claystone, siltstone	49.5-49.7 19.1-21.4	Late Eocene- Oligocene, postfolding	13/34		310	56	18	10.0	284	52	6	18.4	-50±18	52	290	10	14	f-	1
4a	Magura nappe W Claystone, siltstone	49.5-49.6 19.1-19.6	Late Eocene- Oligocene	5/10		314	53	26	15.2	310	60	14	21.5	-46±25	53	282	15	21	fi	1
4b	Magura nappe C Claystone, siltstone	49.5-49.7 20.0-20.6	Late Eocene- Oligocene	4/17		323	53	14	25.8	306	48	5	47.6	-37±43	58	274	25	36	fi	1
4c	Magura nappe E Claystone, siltstone	49.5-49.6 21.1-21.4	Late Eocene- Oligocene	4/7		290	60	18	22.2	248	32	22	20.2	-70±44	42	310	25	34	fi	1
5	Oravska Magura Sandstone	49.3-49.5 19.1-19.4	Late Paleocene – Middle Eocene	4/15						307	59	41	14.4	-53±28	52	295	16	21		3
Pieniny Klippen Belt																				
6	Pieniny intrusions Andesite	49.4-49.6 20.2-20.5	25 Ma ? – 11 Ma ?	7/13		314	56	26	12.1	314	56	26	12.1	-46±21	55	287	12	17	Rbi	4
Central Carpathian Paleogene Basin																				
7	Podhale+Levoca basin Claystone, siltstone	48.9-49.4 19.9-21.2	Eocene – Oligocene	10/18		299	55	39	7.8	301	55	76	5.6	-59±10	46	295	6	8	Rci, f+	5
7a	Podhale basin Claystone, siltstone	49.3-49.4 19.9-20.3	Oligocene	6/10		298	54	37	11.1	298	53	121	6.1	-62±10	42	295	6	8	f+	6
7b	Levoca basin Claystone, siltstone	48.9-49.2 20.5-21.2	Eocene - Oligocene	4/8		302	56	32	16.4	308	59	55	12.5	-52±24	52	296	14	19	Rci, fi	5
8	Sološnica limestone	48.47 17.23	Eocene		11/15	163	62	13	13	286	66	13	13	-74±32	43	316	17	21	rev.	7
9	Roh Motel siltstone	48.66 17.50	Eocene		6/6	21	6	29	13	250	21	29	13	-110±14	-5	310	7	14		7
10	Omastiná flysch	48.78 18.39	Eocene		10/25	265	25	26	10	283	28	24	10	-77±11	20	289	6	11	rev.	8
11	Demjata flysch	49.11 21.32	Eocene		9/13	295	12	18	13	255	54	9	19	-105±32	17	325	19	27	rev.	8

12	Lada claystone	49.04 21.36	20-18Ma		20/21	289	57	14	9	281	30	14	9	-79±10	19	294	6	10		9
Internal Carpathian Paleogene Basin																				
13	Esztergom Castle hill siltstone	47.79 18.73	Oligocene		9/25	279	43	24	11	293	33	24	11	-67±13	29	284	7	12	rev.	7
14	Esztergom town marl	47.80 18.74	Oligocene		10/10	303	38	44	7	315	49	44	7	-45±11	51	278	6	9		7
15	Lábatlan limestone	47.72 18.52	Eocene		23/30	312	53	41	11	295	48	75	9	-65±13	37	292	8	12		7
16	Recsk, Lahóca hill andesite & contact metamorphosed Anisian limestone	47.9-47.9 20.1-20.1	Late Eocene	8/10		287	55	62	7.1	287	55	62	7.1	-73±12	36	305	7	10	rev.	10
17	Bükk limestone, turbidite, clay	47.9-48.0 20.4-20.6	Late Eocene - Oligocene	3/3		295	39	28	23.6	275	55	33	21.9	-85±38	29	313	22	31	fi, Roi	10
18	Nógrád + S. Slovak basin bentonite, clay, siltstone, sandstone	48.0-48.4 19.4-20.3	20.0-18.0 Ma	8/9		303	45	37	9.3	300	43	43	8.5	-60±12	38	286	7	11	fi, Rc	11, 14
19	Nógrád + S. Slovak basin Rhyolite, tuff, ignimbrite	48.0-48.2 19.7-19.9	21.0-18.5 Ma	9/9		267	57	33	9.0	267	57	33	9.0	-93±16	25	318	10	13	rev.	11, 10
20	Bükk Mts Ignimbrite & tuff	47.8-48.0 20.3-20.7	21.0-18.5 Ma	11/11		283	48	51	6.5	283	48	51	6.5	-77±10	30	302	6	8	rev.	10, 12, 13
21	Ipolytarnóc sediment & ignimbrite	48.2-48.3 19.6-19.7	17.5-17.2 Ma	15/15		328	57	70	4.6	328	57	70	4.6	-32±8	64	277	5	7	Rb	14
22	Bükk & Cserhát Mts aleurit, fluviatile silt	47.8-48.3 19.7-20.6	18.0-13.0 Ma	4/4		324	56	96	9.4	327	57	76	10.6	-33±19	64	279	11	15	Fi	10
23	Bükk Mts Ignimbrite & tuff	47.9-48.1 20.4-20.8	17.5-16.0 Ma	28/28		335	37	40	4.4	335	37	40	4.4	-25±5	56	246	3	5	Rb	10, 13
24	Bükk & Mátra Mts Ignimbrite & tuff	47.8-48.3 19.7-20.6	14.0-13.0 Ma	5/6		13	62	42	11.9	13	62	42	11.9	+13±26	80	133	14	19	Rci	10, 13, 15
24a	Demjén, Nagyeresztvény Rhyolite tuff	47.84 20.35	14.0 Ma		21/22	8	50	92	3.3	8	50	92	3.3	+8±5	72	178	3	4	rev.	10
24b	Felsőnyárád Dacie tuff	48.33 20.60	13.7-14.0 Ma		5/6	18	50	20	18	18	50	20	18	+18±28	68	156	16	24		13
24c	Felnémet, quarry Dacitic ignimbrite	47.93 20.38	14.0-14.1 Ma		10/10	25	71	523	2.1	25	71	523	2.1	+25±6	73	75	3	4	rev.	13
24d	Felnémet, Bajusz-völgy Dacite-rhyolite tuff	47.93 20.39	14.0-14.1 Ma		8/9	353	75	210	3.8	353	75	210	3.8	-7±15	76	7	6	7	rev.	13
24e	Tar Dacite tuff	47.95 19.76	13.0-13.9 Ma		12/12	15	64	54	6	15	64	54	6	+15±14	80	116	8	10	rev.	15
24f	Lénárddaróc Rhyolite tuff	48.15 20.36	13.5-11.5 Ma		8/9	354	23	33	10.0	354	23	33	10.0	-6±11	53	210	6	11		10
25	Cserhát Mts. andesite, ignimbrite	47.9-48.1 19.5-19.7	16.6-14.7 Ma	6/7		322	56	19	15.6	322	56	19	15.6	-38±28	60	281	16	22	rev.	10, 16

26	Cserhát Mts. andesite, andesite tuff	47.9-48.1 19.5-19.7	14.5-12.0 Ma	7/7		6	64	81	6.7	6	64	81	6.7	+6±15	85	137	8	11	Rc	16
27	Börzsöny Mts. dacite tuff & andesite	47.8-48.1 18.8-19.1	16.5-14.5 Ma	40/42		339	61	31	4.1	339	61	31	4.1	-21±8	75	275	5	6	Ra	17, 18
28	Visegrád Mts. dacite tuff & andesite	47.7-47.8 18.8-19.1	15.5-15.3 Ma	12/12		337	56	21	9.0	337	56	21	9.0	-23±16	70	264	9	13	rev.	18, 19, 20
29	Börzsöny Mts. dacite tuff & andesite	47.8-48.1 18.8-19.1	younger than 13.7 Ma	23/24		20	61	44	4.6	20	61	44	4.6	+20±9	75	124	5	7	Ra	17, 18
30	Visegrád Mts. andesite & dacite	47.7-47.8 18.8-19.1	younger than 14.5 Ma	17/17		12	55	43	5.5	12	55	43	5.5	+12±9	75	159	6	8	rev.	18, 19
31	East Slovak Basin Zeolithized tuff	48.7-48.9 21.7-21.8	16.0-11.5 Ma	5/8		351	53	12	23.1	326	65	35	13.1	-34±31	67	300	17	21	f+, Ri-	9
32	Zemplín Mts & East Slovak Lowland andesite, rhyolite, rhyodacite, tuff, zeolithized tuff	48.3-48.5 21.7-22.0	16.0-11.5 Ma	23/23		330	51	18	7.4	330	51	18	7.4	-30±12	62	266	7	10	R-	21
33	Vihorlatské Mts. andesite & rhyodacite	48.8-49.0 21.9-22.4	12.6-11.9 Ma	5/5		341	46	21	17.1	341	46	21	17.1	-19±25	64	243	14	22	Ra	22
34	Vihorlatské Mts. andesite & rhyodacite	48.8-49.0 21.9-22.4	11.9-9.4 Ma	4/4		0	59	119	8.4	0	59	119	8.4	0±16	81	202	9	12	rev.	22

Table 2. Summary of palaeomagnetic results from Cenozoic rocks in the Western Carpathians

Key: as for Table 1. References: 0 – Márton *et al.* unpublished; 1 – Márton *et al.* 2009 *a*; 2 – Korab *et al.* 1981; 3 – Krs *et al.* 1981; 4 – Márton *et al.* 2004; 5 – Márton *et al.* 2009 *b*; 6 – Márton *et al.* 1999; 7 – Márton *et al.* 1992; 8 – Túnyi & Márton 1996; 9 – Márton *et al.* 2000; 10 – Márton & Márton 1996; 11 – Márton *et al.* 1996; 12 – Márton & Pécskay 1998; 13 – Márton *et al.* 2007 *b*; 14 – Márton *et al.* 2007 *a*; 15 – Zelenka *et al.* 2004; 16 – Póka *et al.* 2004; 17 – Karátson *et al.* 2000; 18. Balla & Márton 1979; 19 – Karátson *et al.* 2007; 20 – Lantos pers.com.; 21 – Orlicky 1996, 22 – Túnyi *et al.* 2004.