Palaeomagnetism and palaeogeography of the Western Carpathians from the Permian to the Neogene

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Abstract: Geodynamic models for the Western Carpathians require evaluation of palaeomagnetic data from the Outer Carpathian flysch belt, from limestones of the Klippen Belt and from volcanic and sedimentary rocks of the Inner Carpathians. Palaeomagnetic data for the Permian to the Neogene are evaluated. The data indicate marked, mostly anticlockwise tectonic rotations of larger rock complexes and nappes. The distribution of palaeomagnetic poles is characteristic of a collision zone, and crosses the apparent polar wandering path for the African plate. Tectonic rotations are observed in both the Inner Carpathians and the Klippen Belt as well as in the Outer Carpathian flysch belt. Most drift occurred during the Permian to Triassic interval, with northward movement from initial southern equatorial latitudes. Drift decelerated from the Jurassic to the Neogene.

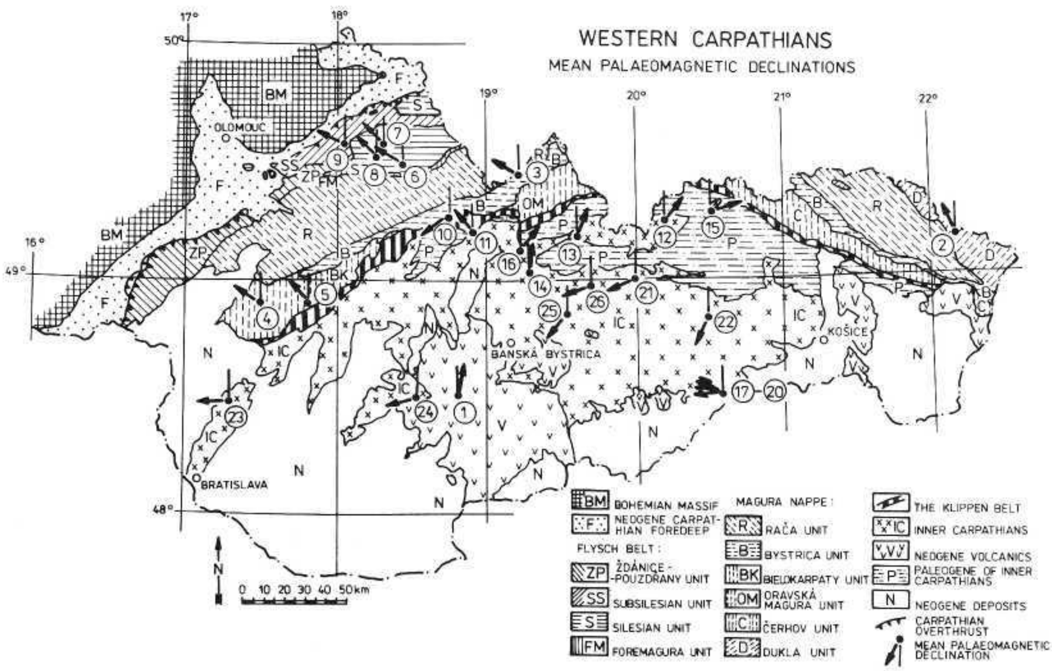

Fig. 1. Simplified geological map of the Western Carpathians, showing the localities mentioned in the text.

The Carpathian Mountains represent a complex Alpine fold and thrust belt which is over 1500 km long and has a pronounced arcuate shape. Figure 1 shows that part of the Western Carpathians within the territories of Slovakia and Moravia. The system can be subdivided into three main tectonostratigraphic zones, namely the Outer Zone or Outer Carpathian flysch belt, the Klippen Belt and the Inner Zone or Inner Carpathians. This paper summarizes palaeomagnetic data obtained in the Western Carpathians from units of Permian to Neogene age by various authors. These data come from flysch deposits of the Outer Carpathians, limestones of the Klippen Belt, and volcanic and sedimentary rocks of the Inner Carpathians, and mainly come

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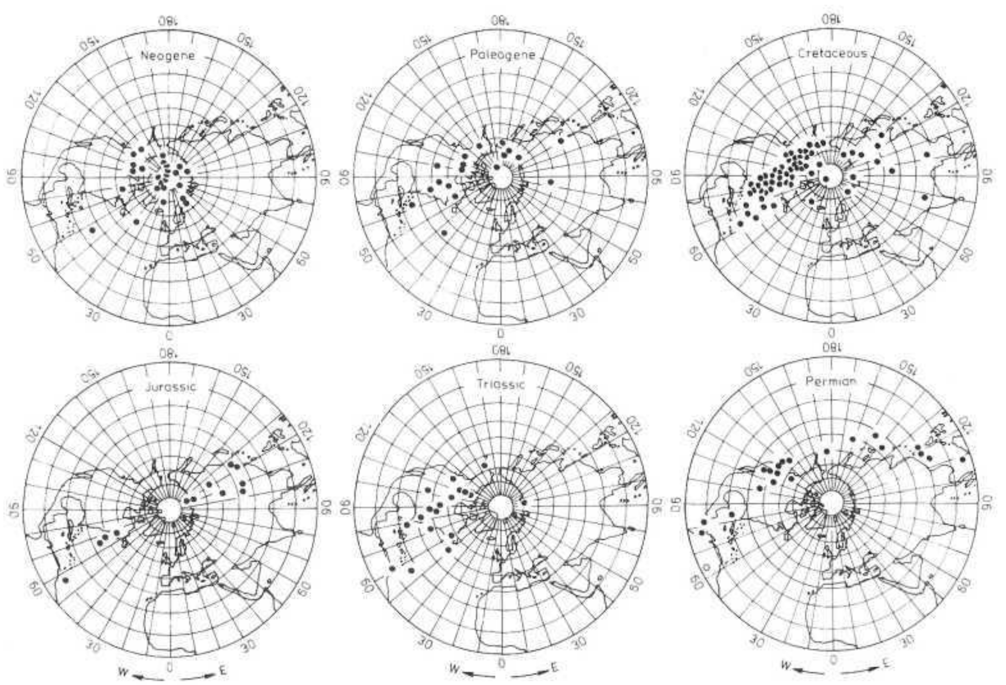

Fig. 2. Stereographic projection of pole positions for the Alpine–Carpathian–Pannonian zone from the Permian to the Neogene.

from Slovakia, east Moravia and north Hungary.

The first palaeomagnetic paper on this region suggested the presence of tectonic rotations of varying magnitudes and in different senses (Kotásek & Krs 1965). Subsequent syntheses explained the observed declinations in terms of rotational deformation of nappes or blocks during Alpine folding (Krs *et al.* 1982). A statistical evaluation of Phanerozoic palaeomagnetic data for the Eurasian and African continents outlined striking rotations about vertical axes for the whole Alpine belt. It was noted that Cretaceous rocks to the west of the Western Carpathians had experienced rotations in a predominant clockwise sense (Krs 1982). Subsequent syntheses of palaeomagnetic data from the region (Márton 1987; Márton *et al.* 1987; Márton & Mauritsch 1990) resulted in documentation of tectonic rotations in different parts of the Alpine-Carpathian-Pannonian zone.

The present paper summarises data presented in several publications (Mauritsch & Becke 1987; Irving *et al.* 1976; Márton *et al.* 1988; Pătrascu *et al.* 1990), and in others which are not easily obtainable outside the Czech Republic (e.g. Krs *et al.* 1982; Krs 1982; and internal reports of the Geological Institute of the Academy of Sciences and the Geofyzika Brno Company). In this review, only mean pole positions with values of $\alpha_{95} < 15°$ and $k > 5$ are considered to be statistically well defined. On this basis, reliable poles have been defined for nappes in the Northern Apennines, the Western, Southern, Eastern and Northeastern Alps, Istria, the Transdanubian Mountains, the Outer, Western and Eastern Carpathians, and the Inner Carpathians (including the Little Carpathian Mountains). These data verify the Gondwanan affinity of the Carpathian area during the Mesozoic. Palaeogeographic affinity to the African plate can also be proven for the Northern Apennines, Southern Alps, Istria and the Transdanubian Mountains, on the basis of sense of rotation (prevailingly anticlockwise) and on absolute values of palaeolatitudes. Some other areas exhibit similar affinity, such as the Eastern Alps and the Inner Carpathians, although the statistical reliability is lower. The Northern Apennines, Southern Alps and Istria show similar declinations from the Permian until the Cretaceous. An anomalous clockwise rotation occurs in the Northeastern Alps (shown by data from Jurassic and Cretaceous units) and the Outer Eastern Carpathians (shown by data from Jurassic units, and tentatively by data from

Cretaceous rocks). Tectonic rotations give rise to scatter of palaeomagnetic pole positions. Figure 2 shows the pole positions for the Alpine–Carpathian–Pannonian zone from the Permian to the Neogene, as inferred by different authors.

The results obtained from nappe systems in the Western Carpathians are interpreted within this framework of deformation of the wider Alpine–Carpathian–Pannonian system, where tectonic rotations are known to be a characteristic feature. These rotations can be simulated by a model for the entire Alpine–Carpathian–Pannonian zone and for the Western Carpathians.

Palaeomagnetic properties of rocks from the Western Carpathians

All samples analysed at our laboratory were subjected to detailed magnetic cleaning, generally by thermal demagnetization using a MAVACS system (which guarantees a high magnetic vacuum during heating). Pilot samples were studied petromagnetically to define magnetic carriers. Account was taken of the effect of local tectonics on the deviation of palaeomagnetic directions, and samples were not collected from highly tectonized nappes. Remanences were studied by multi-component analysis (Kirschvink 1980; Kent *et al.* 1983; McFadden & Schmidt 1986).

Palaeomagnetic studies in the Outer Carpathian flysch belt have focused on pelitic sediments, red and grey claystones and fine-grained sandstones. These rocks display important secondary components of magnetization. In most of these rocks, the magnetic carrier is fine-grained magnetite, with haematite being frequent in grey sediments. In most cases, the sampled units of the Outer Western Carpathians exhibit anticlockwise rotations. Rocks of the teschenite association and their contact margins record thermo-remanent magnetizations which also indicate anticlockwise rotation (References 2 to 9 in Table 1).

The subhorizontal nappe of the White Carpathians has exposures of relatively undeformed sandstones, siltstones and mudstones. Magnetization components from these rocks display both normal and reverse polarities, which are defined with a high degree of confidence. Figure 3 shows typical results of thermal demagnetization, in which hematite is the magnetic carrier. Figure 4 gives mean palaeomagnetic directions derived by progressive thermal demagnetization and multi-component analysis. The data are given in Table 1 (Reference 5, White Carpathians, western Slovakia), after inverting reversed polarities through the origin, and again indicate an anticlockwise tectonic rotation.

The reliability of the interpretation of tectonic rotations can be enhanced by systematic magnetostratigraphic investigations. The magnetostratigraphy of the Tithonian-Berriasian boundary strata has been investigated at Brodno (near Žilina, W. Slovakia), in the Klippen Belt (see Houša *et al.* this volume). Palaeomagnetic directions from this unit indicate large anticlockwise tectonic rotation (Reference 10 in Table 1).

Samples from several rock complexes in the Western Carpathians indicate syn-tectonic remagnetization during Alpine folding, produced by long-lived metamorphism. The remanence of the Silica nappe (northern Hungary) has also been attributed to this mechanism (Márton *et al.* 1991). Folding causes both chemical remanent magnetization and thermo-viscous magnetization. A typical example is the Meliata series, which consists of Triassic and Jurassic radiolarian rocks, Ladinian and Carnian corneo-limestones, radiolarian rocks, grey slates and red limestones of Dogger age, and limestones (olistolites?) of Triassic age. Magnetic carriers with relatively low unblocking temperatures are observed, except in the red radiolarites and corneo-limestones, in which hematite is the magnetic carrier. Primary palaeomagnetic components are not preserved. For example, Fig. 5 gives the results of the mean directions of separated components of remanence in the temperature interval of 150–400°C for six sites. Similar results were obtained for the other 11 sites. Mean virtual poles for the Meliata series show an increase in dispersion after tilt correction (*in situ*: $\alpha_{95} = 8.5°$, $k = 18.6$; tilt corrected: $\alpha_{95} = 13.6°$, $k = 7.9$; $N = 17$). Thus, the separated remanence components in this temperature interval are post-folding in age and are of secondary origin. The pole position computed from the *in situ* mean directions (palaeolatitude $= 46.5°N$; palaeolongitude $= 299.0°$; $\alpha_{95} = 10.8°$; $k = 23.8$) is close to the pole positions derived for Cretaceous rocks in the Western Carpathians (see Table 1). All directions in the Meliata series are of normal polarity, suggesting that remagnetization occurred in the Cretaceous long normal polarity epoch, which persisted from the Aptian to the Santonian. The magnetization is probably of syntectonic origin and again indicates an anticlockwise tectonic rotation, in this case in the period after remagnetization.

Kruczyk *et al.* (1992) prove pre-tectonic magnetization components in Jurassic carbonates from the Križná nappe, using magnetomineralogical and other analyses. In contrast to the majority of data from the Western

Table 1. *Palaeomagnetic data from the Western Carpathians.*

	Region	Age and lithology	Location		Mean direction						Pole position		Confidence		Reference
			Lat°N	Long°E	Dec	Inc	α_{95}	k	N	n	Lat (φ_P)	Long (λ_P)	δ_m	δ_P	
1	Central Slovakia	L Mio volcanics	48.5	18.8	9.2	64.7	7.7	53	70	280	83.5°N	122.3°E	12.4	10.0	Nairn in Irving *et al.* (1976)
2	Dukla, E Slovakia	E–M Eoc red clsts.	49.16	22.19	158.7	−40.1	3.6	10.4	5	165	58.8°S	62.4°E	4.3	2.6	Koráb *et al.* (1981)
3	Oravská Magura, N Slovakia	L Pal-M Eoc. clsts & ssts	49.42	19.21	122.9	−58.8	9.8	5.3	4	49	49.1°S	117.7°E	14.6	10.7	Krs *et al.* (1991)
4	SE Moravia (Louka, Nivnice)	L Pal ssts & clsts	48.94	17.55	121.0	−41.6	11.4	46.2	5	31	38.0°S	101.1°E	13.9	8.5	Krs *et al.* (1993)
5	White Carpathians W Slovakia	L Sen ssts & clsts	48.9	17.8	320.6	43.7	5.6	86.0	9	75	51.6°N	95.1°W	7.0	4.4	Krs *et al.* (1993)
6	NE Moravia, Silesia	Con grey ssts	49.48	18.43	300.3	46.0	10.0	3.1		94	39.8°N	74.7°W	12.8	8.2	Krs *et al.* (1978)
7	NE Moravia, Silesia Ondřejník Mt	Cen-E Tur red clsts	49.57	18.30	317.7	72.6	4.5	10.9		101	64.1°N	36.7°W	7.9	7.1	Krs *et al.* (1977)
8	NE Moravia, Silesia	Cen-E Tur red clsts	49.52	18.27	312.7	52.7	3.3	8.8		228	51.8°N	78.7°W	4.6	3.2	Krs *et al.* (1978)
9	NE Moravia, Silesia	Haut-Barr teschenites	49.57	18.07	295.1	55.7	5.6	6.4		116	42.2°N	63.3°W	8.1	5.8	Krs & Šmid (1979)
10	W. Slovakia, Brodno near Žilina	Tith-Berr carbs	49.26	18.75	236.3	45.4	5.6	9.8		104	1.1°N	29.2°W	7.1	4.5	
11	Malá Fatra, N Slovakia	M-L JUR carbs			321	44	3	96	21	173	58°N	253°E			Kruczyk *et al.* (1992)
12	Belanski Tatra, N Slovakia	M L JUR carbs	49.25	20.2	40	59	8	118	4	17	61°N	113°E	11.9	8.9	Kruczyk *et al.* (1992)
13	W Tatra, N Slovakia	M L JUR carbs			22	59	4.3	198	7		71.7°N	132.2°E			Kruczyk *et al.* (1992)
14	Low Tatra, N Slovakia	M JUR carbs	49.03	19.28	2	56	14	73	3	29	78°N	192°E	20.1	14.5	Kruczyk *et al.* (1992)
15	Spišská Magura, N Slovakia	M JUR carbs	49.28	20.53	75	46	12	114	3	12	30°N	102°E	15.3	9.8	Kruczyk *et al.* (1992)
16	Choč Hills, N Slovakia	E JUR carbs	49.12	19.23	39	63	12	104	3	15	63°N	105°E	18.9	14.8	Kruczyk *et al.* (1992)
17	Aggtelek Mts, Silica nappe, N Hungary	L TRI carbs	48.5	20.6	289	59	11	38	6	45	40.2°N	51.4°W	16.4	12.3	Márton *et al.* (1988)
18	Aggtelek Mts, Silica nappe, N Hungary	M TRI carbs	48.5	20.6	272	40	16	34	4	22	18.2°N	55.3°W	19.3	11.6	Márton *et al.* (1988)
19	Aggtelek Mts, Silica nappe, N Hungary	E TRI carbs	48.5	20.6	294	24	23	31	3	20	25.2°N	79.2°W	24.6	13.1	Márton *et al.* (1988)
20	Rudabánya Mts, Bódva nappe, N Hungary	M TRI carbs	48.5	20.6	298	43	17	20	5	40	36.8°N	72.2°W	21.1	13.1	Márton *et al.* (1988)
21	Choč nappe, Central Slovakia	L PER red shales	49.0	20.0	71.8	19.8	6.4	4.5	13	141	19.6°N	117.0°E	6.6	3.5	Kotásek & Krs (1965)
22	S of Sp. N. Ves, NW of Košice, E Slovakia	L PER red shales	48.83	20.50	29.2	16.9	5.3	4.6	9	195	42.9°N	159.3°E	5.5	2.8	Kotásek & Krs (1965) Krs (1966)
23	Little Carpathian Mts, W Slovakia	PER melaphyres	48.47	17.3	269.4	−2.3	18.9	13.5	6	46	1.2°S	73.0°W	18.9	9.5	Krs *et al.* (1982)
24	Tríbeč Mts, W Slovakia	PER melaphyres	48.49	18.53	254.8	−18.0	9.9	8.1	3	29	16.9°S	66.2°W	10.3	5.3	Krs *et al.* (1982)
25	South Low Tatra Mts, N Slovakia	PER melaphyres	48.85	19.55	222.8	−13.2	18.2	5.1	16	121	34.6°S	35.4°W	18.6	9.5	Krs *et al.* (1982)
26	North Low Tatra Mts, N Slovakia	PER melaphyres	48.97	19.70	249.7	−16.2	11.4	6.1	32	300	19.5°S	60.2°W	11.8	6.1	Krs *et al.* (1982)

Mio, Miocene; Pal, Palaeocene; Eoc, Eocene; Sen, Senonian; Con, Coniacian; Cen, Cenomanian; Tur, Turonian; Haut, Hauterivian; Barr, Barremian; Berr, Berriasian; JUR, Jurassic; TRI, Triassic; PER, Permian; L, Late; M, Middle; E, Early; carbs, carbonates; clsts, claystones; ssts, sandstones.

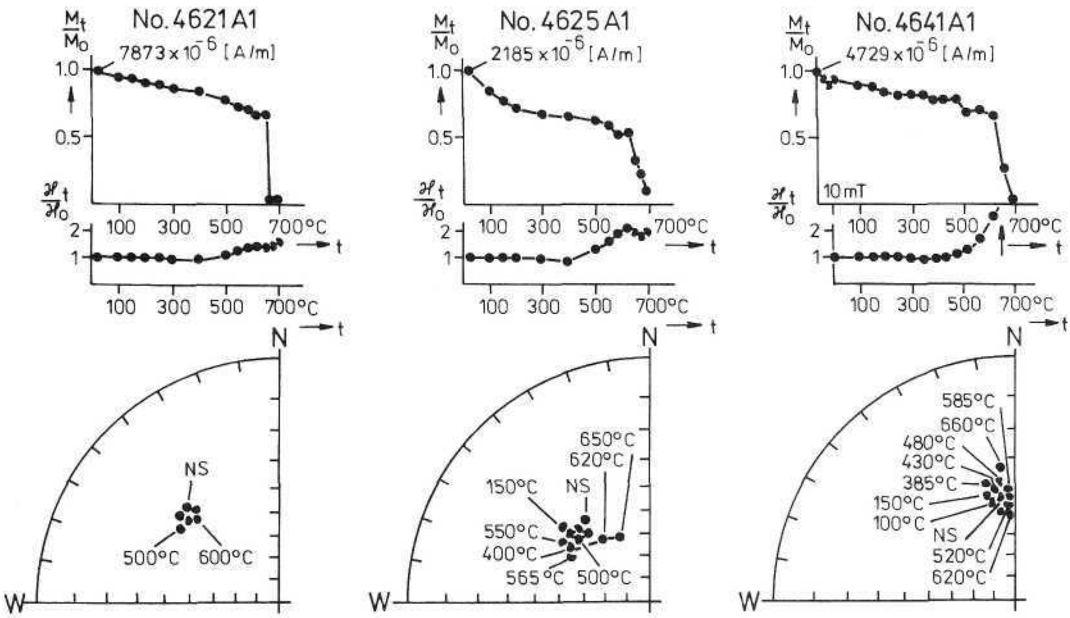

Fig. 3. Thermal demagnetization of representative samples of Late Senonian grey sandstone, White Carpathians, western Slovakia.

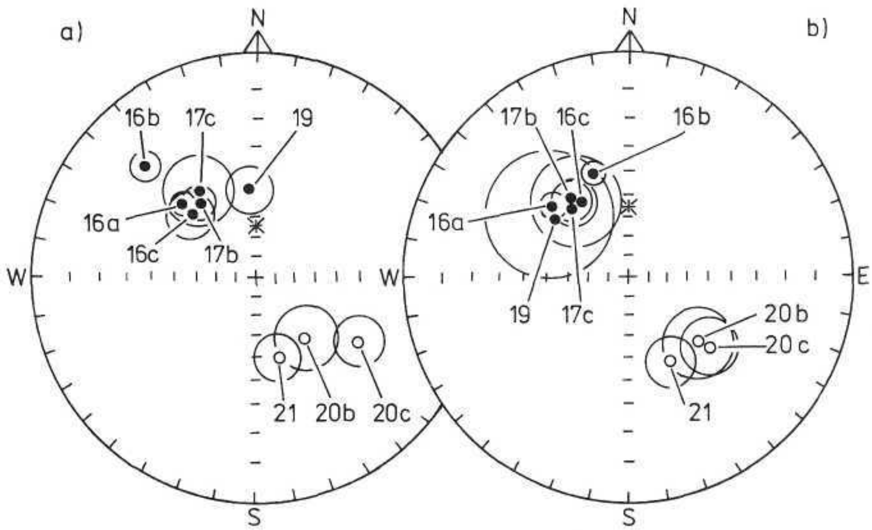

Fig. 4. Stereographic projection of the mean palaeomagnetic directions for sites in the Late Senonian sandstones and claystones of the Javorina Formation, White Carpathians, western Slovakia. (**a**) Mean directions with the optimum Fisherian grouping during progressive thermal demagnetization; (**b**) mean directions derived by multi-component analysis.

Carpathians, both anticlockwise and clockwise tectonic rotations occur in different parts of this nappe.

In the Aggtelek–Rudabánya Mountains, in the southernmost part of the Inner Carpathians on the territory of North Hungary, anticlockwise tectonic rotation occurred in the period following the Triassic, probably in the Neogene

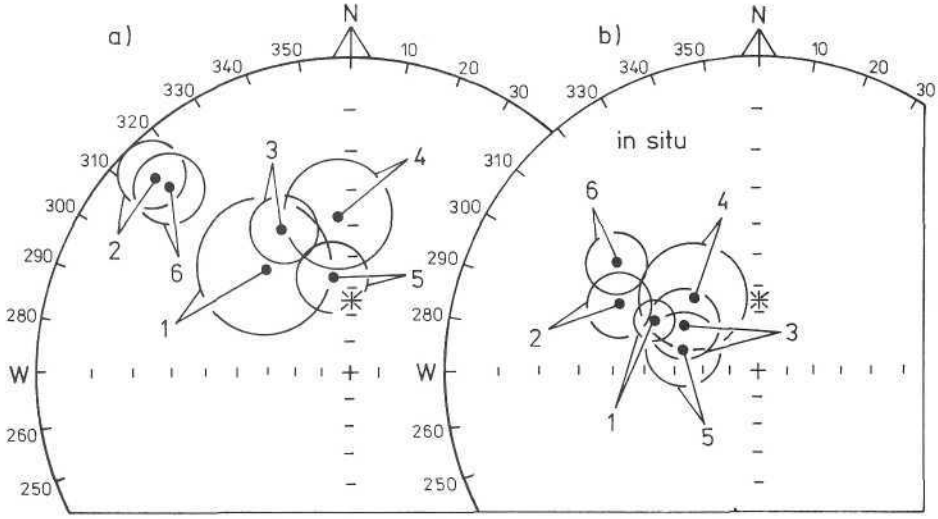

Fig. 5. Mean directions of remanence components separated by multi-component analysis for 6 sites in the Meliata series, southern Slovakia. (**a**) tilt corrected results; (**b**) *in situ* results.

(Márton *et al.* 1988). The remanence components used in this interpretation were derived in higher temperature intervals, show both normal and reverse polarities and pass a fold test (References 17–20 in Table 1).

Summary of palaeolatitudes and rotations

Figure 6 presents values of palaeomagnetic declination, inclination and palaeolatitude plotted against age. Permian to the Early–Mid-Eocene rocks from the Western Carpathians experienced predominantly anticlockwise rotations. Lower inclination values were generally found, indicating that the rocks were deposited at lower palaeolatitudes. Because most studied rocks of the Western Carpathians are from the flysch formation, and so were deposited on inclined sedimentation surfaces, the magnetic inclination of these rocks is weighted with an error. The tilt of the sedimentation surfaces, however, attained only a few degrees (M. Rakús and M. Potfaj, pers. comm.). Large changes in palaeolatitude occurred during the Permian and Triassic. Similar changes in palaeolatitude also occurred for the European plate in the Permian and Triassic, and were caused by the drift of the Laurasian plate (cf. Dercourt *et al.* 1993).

Anticlockwise rotations prevail throughout the Western Carpathians in Slovakia, East Moravia and North Hungary, except in the Jurassic rocks of the Križná nappe. Up to 110° rotation occurred in the Permian rocks and the flysch formation shows about 60° anticlockwise rotation.

Separation of components of tectonic rotation

Figure 2 shows that palaeomagnetic pole positions for rocks of the same or similar age from the Alpine-Carpathian-Pannonian zone display specific distributions, indicating rotation of the whole zone as suggested by Márton (1987), Márton & Mauritsch (1990) and Mauritsch & Becke (1987). Similar results were obtained in the Western Carpathians (Kotásek & Krs 1965; Krs *et al.* 1982; Márton *et al.* 1991).

The scatter of poles can be explained using a model in which movements are partitioned into two components: the first relating to rotation of the major plate to which the unit is attached (rotation about a distant rotation pole); the second relating to rotation during Alpine collision of the smaller-scale tectonic block containing the unit (rotation about a proximal pole of rotation). We computed parameters of small circles centred on the Western Carpathians (50°N, 13°E). These represent the loci of poles of equal distance from the study area. Poles lying on a certain circle may differ in declination but not in inclination. Localised rotations without translation will result in a dispersion of poles along a small circle, whereas large-scale movements will also produce movement of poles from one small circle to another. Six pole trajectories

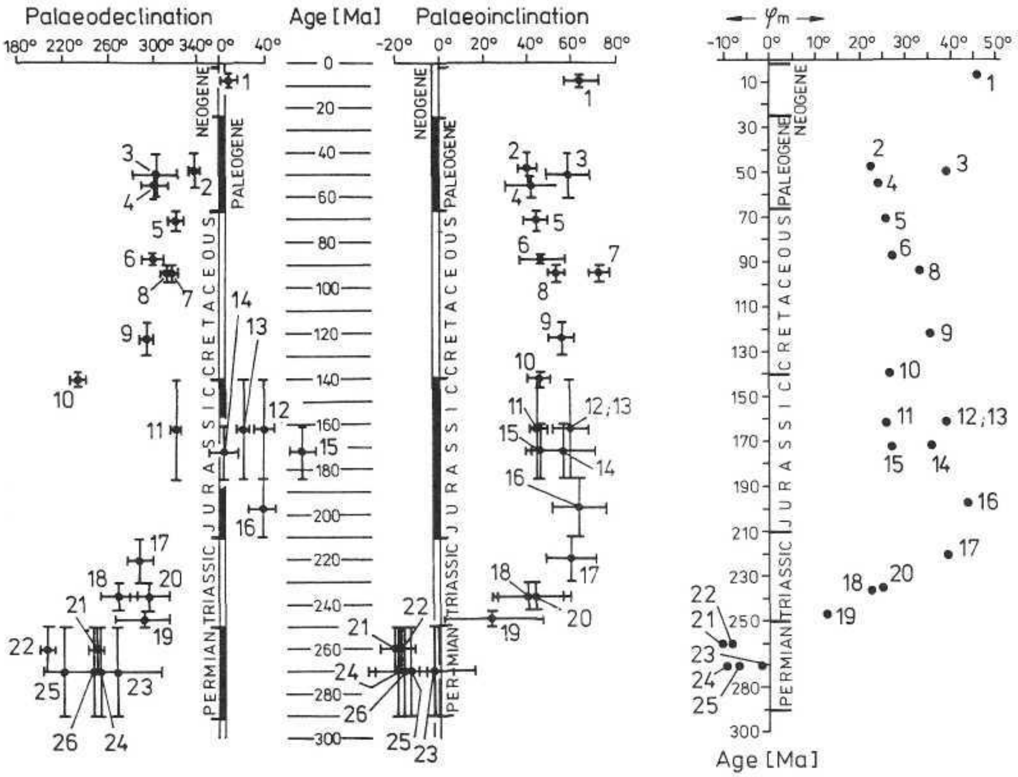

Fig. 6. Variation of declination, inclination and palaeolatitude with age for the Western Carpathians.

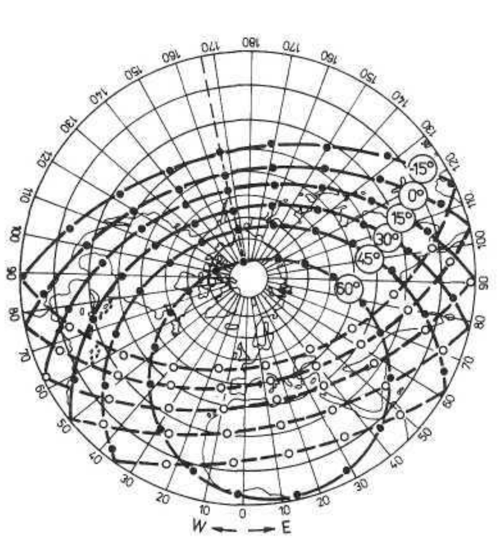

Fig. 7. Model distribution of pole positions calculated for rocks with different values of inclination = −15°, 0°, 15°, 30°, 45° and 60°, roughly corresponding to the time span from the Permian to the Neogene. Solid (dashed) lines and solid (open) symbols indicate projection onto the upper (lower) hemisphere.

were calculated (Fig. 7), with inclinations corresponding to −15°, 0°, 15°, 30°, 45° and 60°. This range of inclinations corresponds to that observed from the Permian to the youngest rocks studied.

Figure 8 shows pole positions for Permian rocks of the Inner Carpathians relative to pole positions from Permian rocks in other parts of the Alpine–Carpathian–Pannonian zone. This indicates a translation of Permian rocks from equatorial and subequatorial zones, and also a rotation of nappes resulting from Alpine collision. Figure 9 shows pole positions derived from Jurassic carbonates from the Križná nappe (References 11 to 16, Table 1) and a pole position derived from the Ţithonian–Berriasian boundary at Brodno, near Žilina (Reference 10, Table 1). Although of widely different position, poles from both areas approach the theoretical trajectory for inclination = 45°, indicating the influence of vertical axis rotation. Kruczyk *et al.* (1992) suggested this difference results from oroclinal bending of the Inner Western Carpathians. Though seemingly anomalous, the pole position derived in the Tithonian-Berriasian carbonates adheres to the path for Jurassic

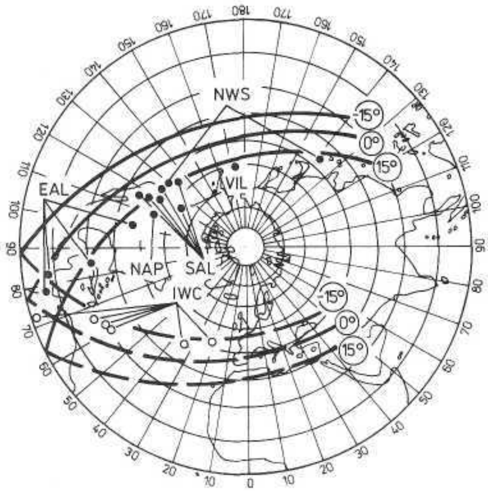

Fig. 8. Distribution of pole positions obtained from Permian rocks in the Inner Western Carpathians (IWC), the region of Villany (VIL), the Southern Alps (SAL), NW Slavonia (NWS), the Northern Apennines (NAP) and the Eastern Alps (EAL). Solid (dashed) lines and solid (open) symbols indicate projection onto the upper (lower) hemisphere.

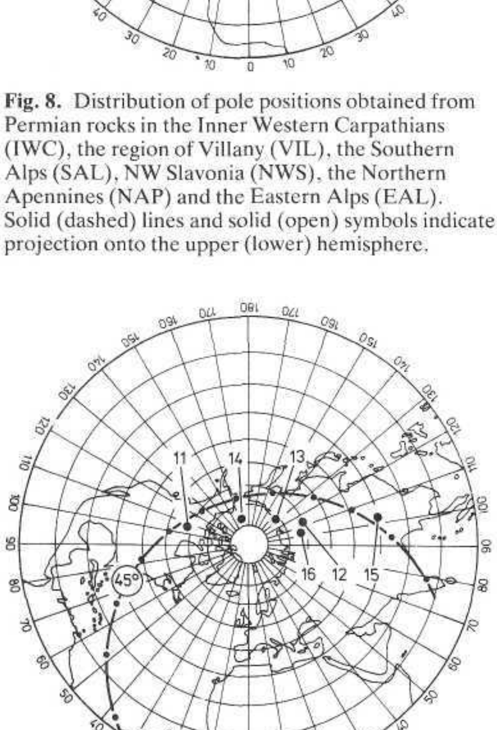

Fig. 9. Distribution of pole positions obtained from Jurassic carbonates from the Križná nappe system (Reference 11–16, Table 1) and in Tithonian-Berriasian limestones at the locality of Brodno, near Žilina (Reference 10, Table 1). Solid (dashed) line indicates theoretical distribution of pole positions for rocks with inclination = 45°.

rocks, and indicates a distinct anticlockwise tectonic rotation with respect to the Križná nappe. Similar rotation has been deduced from another magnetostratigraphic profile across

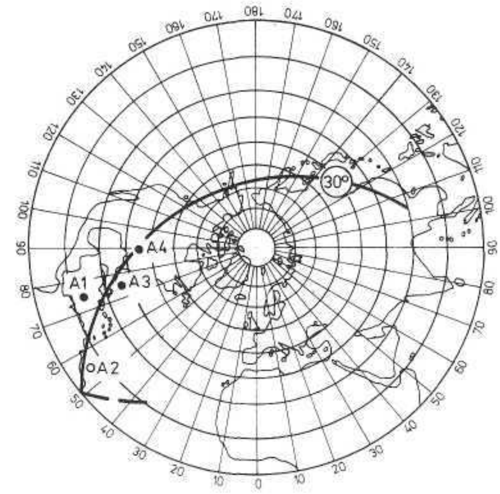

Fig. 10. Distribution of pole positions obtained from Early Triassic carbonates from the Aggtelek–Rudabánya Mountains. Solid (dashed) line indicates theoretical distribution of pole positions for rocks with inclination = 30°.

Tithonian–Berriasian carbonates at Štramberk, North Moravia (Outer Western Carpathians).

This analysis suggests tectonic rotation on the scale of entire nappe systems. To judge the possibility of tectonic rotations within a smaller area, virtual pole positions were calculated for two areas, and their distributions compared with the modelled small circles. The data of Márton *et al.* (1988) were used to compute virtual pole positions for Early Triassic carbonates of the Aggtelek Mountains. These poles lie close to the small circle corresponding to inclination = 30°, and are distributed along the circle as a result of small-scale tectonic rotations (Fig. 10). Similarly, virtual pole positions for Late Senonian rocks of the White Carpathians (Reference 5, Table 1) show a distribution which also suggests significant small-scale tectonic rotations (Fig. 11), even within the single sampled nappe which contains subhorizontal beds.

Conclusions

The palaeomagnetic data from the Western Carpathians indicate a marked tectonic rotation of larger rock units, predominantly in an anticlockwise sense. These rotations are observed in the rocks of the Inner Carpathians, the Klippen Belt, and the Outer Carpathian flysch belt. Tectonic rotations lead to the formation of a specific pole distribution which runs across the apparent polar wander path (in this case for the African plate). A similar distribution also occurs

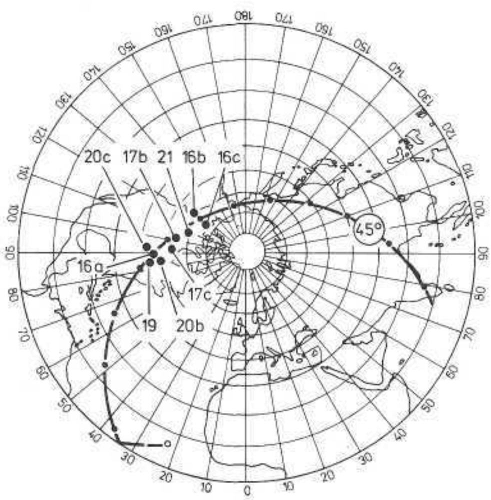

Fig. 11. Distribution of pole positions observed in Late Senonian sediments from the White Carpathians, western Slovakia, within subhorizontal beds in the same nappe. The mean pole position for this nappe is given under Reference 5 in Table 1. Solid (dashed) line indicates theoretical distribution of pole positions for rocks with inclination = 45°.

in the West European and Central European Hercynian belt (Edel 1987; Krs *et al*. 1995). In the Western Carpathians, tectonic rotations occur on a range of scales, from those affecting the whole region to those affecting single nappes/parts of nappes.

The most pronounced palaeolatitudinal drift occurred in the Permian and Triassic, and the drift began decelerating from the Jurassic until the Neogene (Fig. 6). Similar variations have been established for other regions of the Tethyan realm, e.g. the Iberian Meseta and adjacent mobile belts, Corsica and Sardinia, Italy including Sicily and the adjacent parts of the Alps, Greece and Southern Bulgaria, the Transdanubian Mountains in Hungary, and Turkey including the eastern Aegean territory and Cyprus (Van der Voo 1993).

Rotations of individual fault blocks induce large scatters of palaeomagnetic pole positions even though they may affect only small units. In contrast, changes in pole positions due to drift of larger units are generally smaller, though the translations involved are appreciable. For instance, for the Permian rocks of the Western Carpathians these translations reach values of up to 6000 km since the Permian to the present time. These differences in the magnitude of pole movements reflect two different types of rotation, i.e. those around rotation poles close to and far removed from the study area, respectively.

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