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ORIGIN OF STRUCTURAL ARCS OF THE CARPATHIAN–BALKAN REGION

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ABSTRACT

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The Late Cretaceous reconstruction shows that the inner zones of the West, East, and South Carpathians were adjacent to the Dinarides and Hellenides at that time, forming together with them a linear fold system with bilateral vergence. This fold system had a northwest strike. In Paleogene–early Miocene times the general deformation of the given part of the Alpine belt took place. It was caused by rotation of its Asia Minor–Balkan part relative to the more northern part of the belt. This rotation (30°–40° counter-clockwise) was accompanied by a shortening of the considered segment of the Alpine belt by 30%. Hence exfoliation of the Carpathian–Pontide and Dinaric–Tauride branches of the Alpine belt from each other, and their disharmonious plastic deformation, resulted in the formation of the Aegean and Tauride structural arcs and the Carpathian structural loop. During formation of the Carpathian loop, the Gemeric–Tatric tectonic block moved northwards along the Penninic oceanic substratum and rotated over 90° counter-clockwise relative to the Eastern Alps.

INTRODUCTION

The main characteristic of the structural plan of the Carpathian–Balkan region is the arcuate form of its folded systems (Fig. 1). The Carpathian loop and Aegean arc are the largest structural arcs in the region. The origin of structural arcs has been a subject of discussion for many years. During recent years, advances in paleomagnetic studies have provided data that enable us to elucidate this problem.

RECONSTRUCTION OF THE CRETACEOUS FOLD SYSTEM

In the greater part of the Carpathian–Balkan region, the phase of most intense overthrusting was in the middle of the Cretaceous, and Turonian or Senonian rocks rest as a neoautochthone on the Middle Cretaceous nappes. In the late Cretaceous the nappes and the neoautochthone were folded together producing the late Creta-

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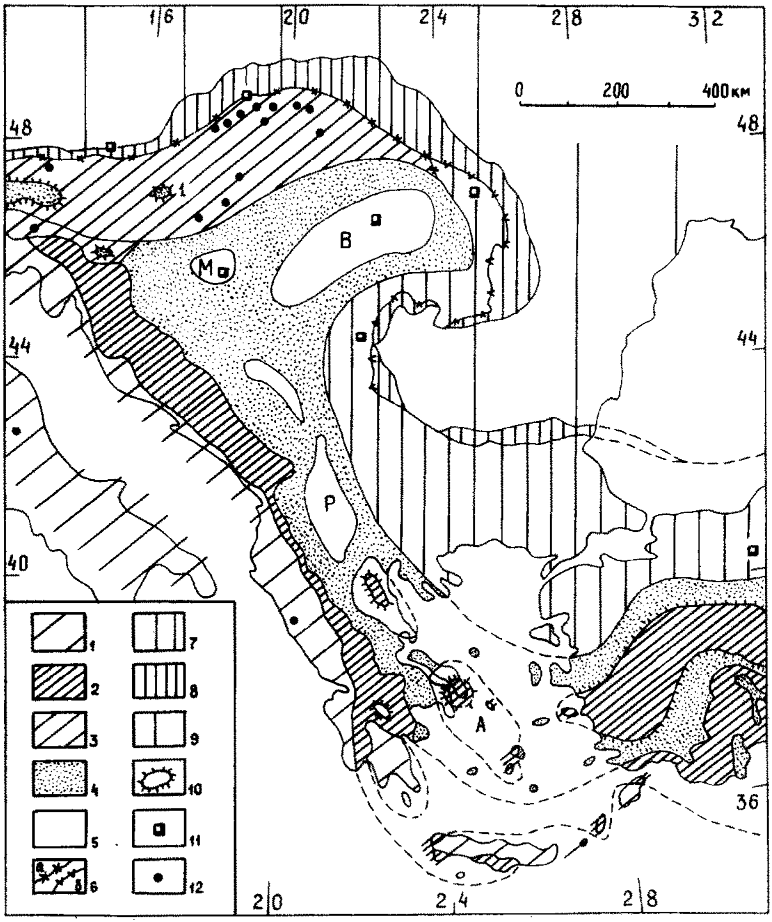

Fig. 1. General tectonic and biogeographical zonation of the Carpathian–Balkan region (Burtman, 1984). *1* = Apulian–Dalmatian zone, *2* = Dinaride–Tauride zone, *3* = Gemeric–Tatric zone, *4*–*5* = Pannonian–Anatolian zone of development of oceanic volcanics and ophiolites (*5* = massifs; *B*—Bihor massif, *M*—Mecsek massif, *P*—Pelagonian massifs, *A*—Attique–Cyclades massif), *6* = sutural zones (*a*—Pieninic, *b*—Kamennopotok–Porec), *7* = Rhodope–Pontide zones, *8* = Carpatho-Balkan flysch zone, *g* = extra-Alpine Europe and foredeep, 10 = main tectonic windows, *11*–*12* = localities of Liassic brachiopods (after Horvath et al., 1979; Vörös, 1977): *11* = European assemblages; *12* = Mediterranean assemblages.

ceous fold system. It is convenient to divide the task of reconstructing the fold system into two parts: determination of its strike, and reconstruction of its form.

The strike of the fold system

The strike of the fold system in the Late Cretaceous can be determined by paleomagnetic data on the Upper Cretaceous rocks that form the neoautochthone.

Paleomagnetism of Upper Cretaceous rocks was studied from more than thirty sites in the region. Not all the data from these studies can be used, however, because of the low quality of some of the paleomagnetic results, insufficient information on how the investigations were carried out, certain doubts concerning the age of the rocks, and the occasionally unfortunate choice of rocks to be studied (for instance, from tectonic mélange). The results were considered suitable for tectonic interpretation if they satisfied the following requirements: well-determined age of rocks, reasonable arguments for a primary or pre-folding origin of magnetization, and radius of error circle α_{95} not over 10°. Most areas for which such results have been obtained lie within the Carpathian–Pontide branch of the Alpine belt (Table 1, Fig. 2).

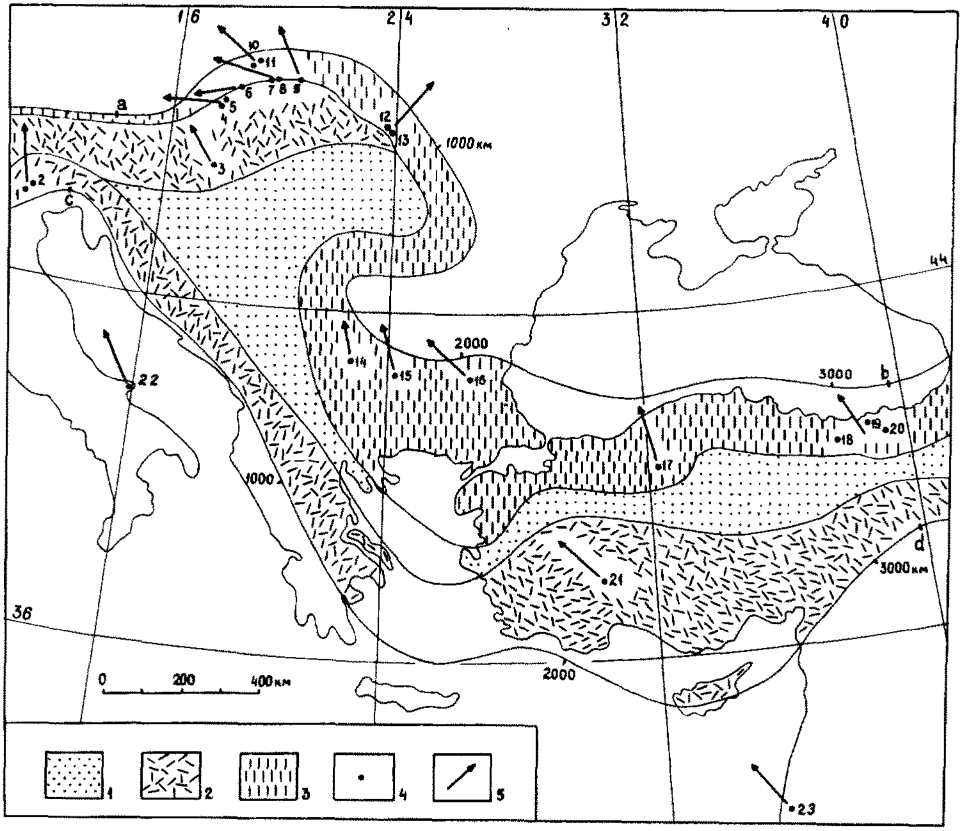

Fig. 2. Simplified scheme of the structure of the Alpine fold belt and the results of paleomagnetic investigations of late Cretaceous rocks (see Table 1). The boundaries of tectonic zones are drawn not along the front of the nappes but behind tectonic windows in which rocks underlying the allochthones are exposed. *1*–*3* = rocks of the meso-Tethys in fold belt: *1* = zone of development of oceanic volcanics and ophiolites, *2*–*3* = rocks of continental slopes and marginal seas (*2* = margin of Africa, *3* = margin of Eurasia); *4* = areas of paleomagnetic investigations; *5* = inclinations of paleomagnetic vectors.

TABLE 1

Results of paleomagnetic investigations of Upper Cretaceous rocks and the reconstruction of the Carpathian–Pontide form in the Late Cretaceous *

No. in Fig. 2 (1)	References (2)	Age (3)	N (4)	$R\%$ (5)	α_{95} (6)	I (7)	D (8)	ΔD_{95} (9)	λ_K (10)	β (11)	L_Q (12)	L_K (13)	GL_K (14)
1 **	Channell and Tarling (1975)	Sen	97	0	7	+41	343	9	11	+28	60	80	Alps: E-90
2	VandenBerg and Wonders (1976)	Tur–Sen	30	0	6	+44	344	8	11	+27	60	87	E-90
3	Marton and Marton (1983)	Sen	34	0	7	+55	318	11	13	+55	100	155	West Carpathians: SE-150
4	Bazhenov et al. (1980)	Sen	6	100	9	+41	278	12	13	+95	50	145	
5	Marschalko and Pagàc (1980)	Sen	8	100	9	+40	263	12	13	+110	50	160	
6	Bazhenov et al. (1980)	Sen	6	0	9	+49	256	13	13	+117	40	157	
7	Marschalko and Pagac (1980)	Sen	20	100	7	+53	308	12	14	+66	60	126	
8	Marschalko and Pagac (1980)	Sen	28	100	3	+35	260	4	14	+114	60	174	
9	Bazhenov et al. (1980)	U.K	38	10	10	+40	333	13	14	+41	100	141	
10	Krs et al. (1979)	Cen–Tur	228	0	3	+53	313	5	14	+61	80	141	
11	Krs et al. (1979)	Cen	94	0	10	+46	300	14	14	+74	80	154	
12	Bazhenov and Burtman (1980)	Tur–Sen	43	92	6	+42	52	8	15	−37	140	103	East Carpathians: SE-115
13	Bazhenov and Burtman (1980)	Tur–Sen	10	100	7	+29	28	8	15	−13	140	127	

14	Nozharov et al. (1977)	Sen	19	0	6	+60	344	12	14	+30	120	150	Balkanides:
15	Bazhenov et al. (1983)	Sen	23	0	6	+48	346	9	14	+28	110	138	SE-145
16	Nozharov et al. (1977)	Sen	16	100	5	+34	314	6	15	+51	90	141	
17	Lauer (1981)	U. K–L. Pg	6	0	3	+54	347	5	17	+30	80	110	Pontides:
18	Orbay and Bayburdi (1979)	U. K	34	0	10	+50	347	16	18	+31	90	121	SE-125
19	Van der Voo (1968)	U. K	4	100	8	+47	336	12	18	+42	90	132	
20	Van der Voo (1968)	U. K	31	100	5	+36	337	6	18	+41	90	131	
21	Lauer (1981)	Maa	42	83	8	+34	313	12					
22	VandenBerg (1983)	Tur–Sen	113		4	+38	328	5					
23	Helsley and Nur (1970)	U. K	15	100	5	−6	326	5					

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* N—number of paleomagnetic samples used, R—reversed polarity samples in percents to N, α_{95}—radius of error circle with probability 95%, I, D—paleomagnetic inclination and declination, ΔD_{95}—accuracy of inclination determination, λ_K—direction of the Cretaceous paleomeridian, β—anlge of rotation of the structural zone after late Cretaceous (plus—a counter-clockwise turn, minus—a clockwise turn), L_Q—present direction of structural zones, L_K—reconstruction of structural zones direction in late Cretaceous, GL_K—regional direction in late Cretaceous. In columns 10–14 their respective directions (in degrees) relative to the present-day meridian are tabulated.

** Regions and areas of paleomagnetic investigations: 1, 2—Southern Alps (Lessini, Vicenza), 3—Pannonian basin (Bakony), 4–11—West Carpathians, Inner zone (4—Kosarska, 5—Brezova), Pienine belt (6—Vrsatec, 7-Siroka, 8-Dubova, Dunajec), and Flysch zone (10, 11), 12–13—East Carpathians, Marmaros zone (12—Tereblya, 13—Kuzya), 14–16—Balkanides, Srednogorie zone (14—Breznic, 15—Luda-Yana, 16—Yambol), 17–20—Pontides (17—Gerede, 18-Mesudiye, 19—Kozkoi, 20—Torul), 21—West Taurides (Isparta), 22—Apulian-Dalmatian zone (Gargano), 23—Arabian platform (Karmel). The rocks studied: limestones and dolomites (1, 2, 19, 21), marls (3–9, 12, 13, 15), claystones (10, 11), sandstones (11, 20), dacites (20), andesites (14, 16), basalts (17), volcanic tuffs (18).

U.K—Upper Cretaceous, Cen—Cenomanian, Tur—Turonian, Sen—Senonian, Maa—Maastrichtian, L. Pg—Lower Paleogene.

The change of strike of the tectonic structures within the northern arc of the Carpathians agrees with a change in directions of remanent magnetization (Fig. 2, points *4–13*), testifying to the secondary origin of that arc. The curvature of structures from the West Carpathians toward the Alps is accompanied by a corresponding counter-clockwise change in vectors of remanent magnetization (Fig. 2, points *1–6*). The data on the Balkanides (Fig. 2, points *14–16*) show that a change from a latitudinal strike to the more northwestern structures in the Western Srednogorie is accompanied by a clockwise rotation of the vector of remanent magnetization. The data thus enable us to conclude that the arcuate structures of the Carpathian–Balkan region are secondary and result from post-Cretaceous deformation. Unfortunately, there are no paleomagnetic data of the South Carpathians, but we assume that late Cretaceous paleomagnetic vectors of South Carpathian rocks will prove to have rotated clockwise.

In Table 1 and Fig. 3 the late Cretaceous Carpathian–Pontide strike is reconstructed on the basis of the paleomagnetic data. According to these data, the tectonic zones of the Carpathians, Balkans, and Pontides had a southeast strike in the Late Cretaceous, parallel, on the whole, to that of the present Dinarides.

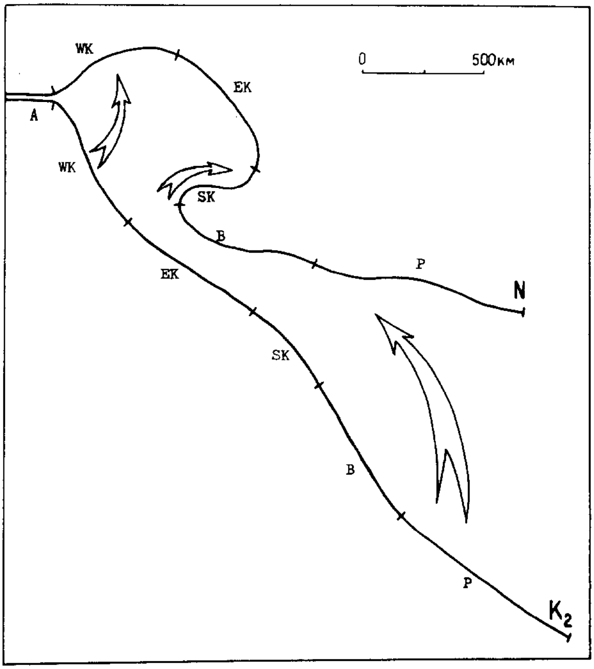

Fig. 3. Scheme of deformation of the Carpatho-Pontide branch of the Alpine belt during the Paleogene and early Miocene. Sectors: *A*—East Alpine, *WK*—West Carpathian, *EK*—East Carpathian, *SK*—South Carpathian, *B*—Balkan, *P*— Pontide. Arrows show the direction of rotation. N—Neogene, K_2—Upper Cretaceous.

The form of the fold system

We attempt to re-establish the form of the fold system and the main features of its inner structure by analyzing the distribution of the large early–middle Cretaceous nappes that formed in both branches of the Alpine belt. The inner part of the West Carpathians is a classical region of vast middle Cretaceous (Albian, Cenomanian and Turonian) nappes, composed of basement and cover rocks. The nappes were displaced northward for many tens of kilometers. To the west, in the South and East Alps, the role of early–middle Cretaceous nappes is negligible (Clar, 1973; Oxburgh, 1974), and in the Central Alps no nappes of this age are reliably known (Trümpy, 1973; Bernoulli et al., 1974).

In the East Carpathians, both the complex of nappes composing the Marmaros massif and the Kamennopotok nappe underlying it are of Middle Cretaceous age. The nappes of the Marmaros massif were formed before the accumulation of Cenomanian deposits which transgressively overlie them. An ensemble of Marmaros nappes and the Kamennopotok nappe overlie olistostrome strata that contain olistolites of rocks from these nappes. The time of overthrusting is not earlier than the Late Albian and probably not later than Turonian. The displacement is from west to east and northeast; the amplitude of thrusting may be more then 50 km (Burtman and Rudakov, 1982). In the South Carpathians the vast Geticum nappe formed in the middle of the Cretaceous was thrust southward over the lower Cretaceous flysch of the Severin zone. This nappe was traced to the meridional part of the South Carpathians. Its visible amplitude is 80 km. In the Apuseni mountains at the same time, both basement (Codru–Ariesani, Biharia–Muncel) and cover nappes formed. They were displaced north and northwest; the visible amplitude is again 80 km (Bleahu, 1976; Sandulescu, 1980).

Thus, the structure of the inner part of the West, East, and South Carpathians is dominated by vast Middle Cretaceous nappes of great amplitude. In the Balkanides and Pontides on the other hand, middle Cretaceous nappes are not well developed; they are distributed sporadically, and their amplitude is small, usually several kilometers, though they occasionally reach 10 to 20 km (Karagjuleva et al., 1982). On the whole, in the Carpathian–Pontide branch of the Alpine belt vast nappes of Middle Cretaceous age are representative of the Carpathians only. Their front passes along the Pienine klippen zone to the Marmaros massif, and then along the outer margin of this massif and the Geticum allochthone, stretching over 1500 km along the belt (*a–b* in Fig. 4A).

In the Dinaric–Tauride branch of the Alpine belt, overthrusts of early–middle Cretaceous age form a wide zone embracing the Dinarides and Hellenides. The direction of displacement is southwest, and the amplitude is tens of kilometers. In the north, the zone of early–middle Cretaceous overthrusts ends at the boundary with the South Alps, where such overthrusts are absent. In the south it is hidden under the waters of the Aegean and Cretan Seas. The Cyclades massif is frequently

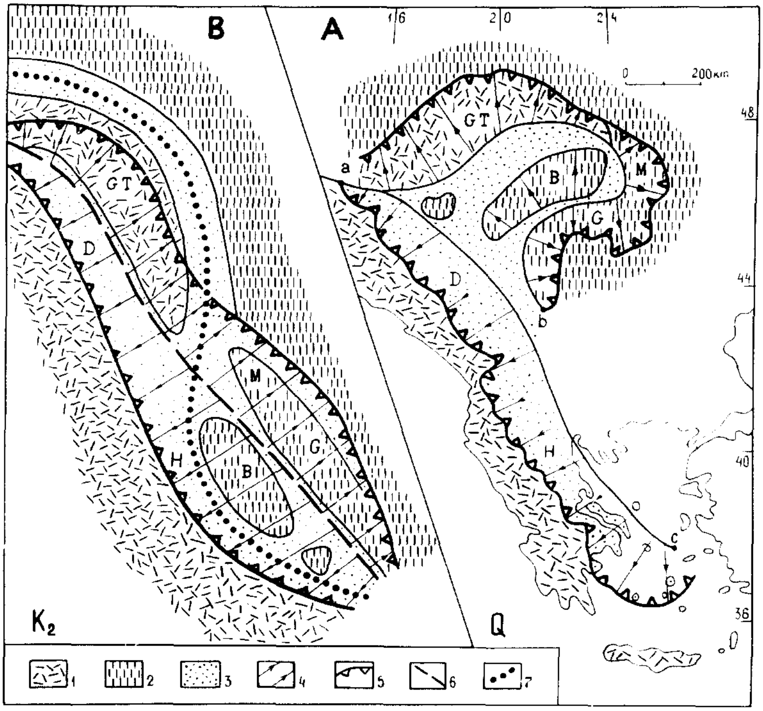

Fig. 4. Areas where early–middle Cretaceous nappes are developed now (A) and reconstruction of the late Cretaceous fold system (B). *1* = rocks of the African margin, *2* = rocks of the Eurasian margin, *3* = zone of development of oceanic rocks, *4* = areas where large early–middle Cretaceous nappes are developed (arrows show the vergence), *5* = nappe fronts, *6* = axis of the late Cretaceous fold system, *7* = track of Jurassic meso-Tethys deep-sea zone. *GT*—Gemeric–Tatric block, *D*—Dinarides, *H*—Hellenides, *B*—Bihor massif, *M*—Marmaros massif, *G*—Geticum massif.

regarded as an analogue of the Pelagonian massifs; if so, the zone of Cretaceous nappes may extend to the middle of the Aegean Sea. Thus this belt of early–middle Cretaceous nappes would also extend for 1500 km (*a–c* in Fig. 4A). Farther eastward—in the Western Taurides—the role of Cretaceous nappes is insignificant, and they are present only as slices within the ophiolitic complex (Juteau, 1979). Vast ophiolitic and other nappes in the Western and Lycian Tauride are of Paleogene and Neogene age (Graciansky, 1972).

Consequently, both branches of the Alpine belt contain zones where early–middle Cretaceous nappes are developed in belts of approximately equal extent and opposite vergence. When the late Cretaceous structure is reconstructed, the Carpathian and Dinaride–Hellenide zones of early–middle Cretaceous nappes coincide well, forming a linear folded system with bilateral vergence (Fig. 4B).

The history of formation of the Cretaceous fold system

In the Jurassic and early Cretaceous, the Dinarides–Taurides and Carpatho-Pontides were margins of the African–Arabian and Eurasian continents respectively. These continents were separated by the oceanic structure of meso-Tethys, which in the region concerned was an ensemble of marginal seas, gulfs, and microcontinents. The Gemeric–Tatric microcontinent was located near Africa; the Bihor, Marmaros, Rhodope, and other microcontinents near Eurasia. In the middle of the Cretaceous, during convergence of the African and Eurasian continents, a linear folded system with bilateral vergence originated with a northwestern strike.

The analysis of nappe vergence shows that the axis of symmetry of the Cretaceous fold system did not coincide with the Jurassic deep-sea axis of the meso-Tethys (Fig. 4B). The latter axis passes between rocks of the African continent and the Bihor block, between rocks of the Eurasian continent and the Gemeric–Tatric microcontinent.

The Cretaceous overthrust did not extend beyond the northeast boundary of the Gemeric–Tatric block. Northeast of that boundary was the Pienine basin where the formation of pelagic deposits continued until the Maastrichtian.

DEFORMATION OF THE ALPINE BELT DURING THE PALEOGENE

Paleomagnetic data on Paleogene rocks are few and contradictory. More definite conclusions can be based on paleomagnetic investigations of Miocene rocks carried out in the northern arc of the Carpathians and in the Pannonian basin (Table 2 and Fig. 5). The declinations of vectors of Miocene remanent magnetization determined beyond the Alpine belt, in the Western Carpathians, and in the northwestern part of the Pannonian basin are close to each other, and lie more or less along the Neogene meridian. In the northeastern part of the Pannonian basin the vectors of remanent magnetization deviate a litte to the north-northwest. The results of the paleomagnetic study of Neogene rocks show that the Carpathian structural loop was formed not later than early Miocene.

According to many scientists, the Carpathian loop has existed more or less in its present form since the Mesozoic; they attribute its formation to the middle Cretaceous or earlier orogeny (Biju-Duval et al., 1978; Beer, 1980; Sandulescu, 1980; Kovacs, 1982; and others). Others assume that the Carpathian loop formed simultaneously with the Pannonian and Transylvanian basins during Neogene–Quaternary time (Boccaletti et al., 1974; Horvàth et al., 1981). Both ideas are contradicted by the paleomagnetic studies carried out in the West and East Carpathians.

Judging from the available paleomagnetic data, the Carpathian loop originated in the Paleogene and the early Miocene. Geological data suggest that the main deformations took place at the end of this interval, just when the Pienine zone

TABLE 2

Results of paleomagnetic investigations of Miocene rocks *

No. in Fig. 5	References	Age	N	R%	α_{95}	I	D	ΔD_{95}
1 *	Peterson et al., (1965)	M. Mio (15 m.y.)	111	100	2	+60	11	4
2	Pohl and Soffel (1977)	U. Oli–L. Mio (16–41 m.y.)	316	68	6	+59	12	12
3	Nairn and Wollstadt (1968)	U. Oli–L. Mio (23–32 m.y.)	167	83	7	+63	20	16
4	Birkenmajer and Nairn (1968)	L. Mio	52	100	9	+73	12	32
5	Krs et al. (1979)	U. Mio	48	100	7	+63	25	16
6	Krs et al. (1979)	U. Mio	32	84	8	+56	20	14
7	Krs et al. (1979)	U. Mio	170	43	3	+72	6	10
8	Andro et al. (1979)	Mio	321	52	7	+60	1	14
9	Krs et al. (1979)	U. Mio	42	21	5	+57	6	9
		M. Mio	73	56	4	+60	15	8
10	Krs et al. (1979)	U. Mio	86	27	2	+67	352	5
11	Dagley and Ade-Hall, (1970)	M. Mio (12–16 m.y.)	72	60	8	+55	0	14
12	Nairn (1967)	Mio	170	55	7	+64	359	16
13	Dagley and Ade-Hall, (1970)	U. Mio (9–13 m.y.)	96	40	10	+66	353	25
14	Krs et al. (1979)	U. Mio	31	58	8	+56	339	14
			16	100	8	+45	340	11
15	Krs et al. (1979)	U. Mio	128	63	6	+60	347	12
16	Dagley and Ade-Hall, (1970)	U. Mio	18	0	2	+63	21	4

* N, R, α_{95}, I, D, ΔD_{95}—see Table 1.

** Regions and areas of paleomagnetic study: 1–3—Extra-Alpine Europe (1—Nordlinger, 2—Oberpfalz, Heldburg, 3—Lausitz), 4—Outer Carpathians, Magura zone (Wzar), 5–16—Inner Carpathians and Pannonian basin (5–Vtacnic, 6—Pohronsky-Inovec, 7—Stiavnick, 8—Borzony, 9—Kremnicke–Vrchy, 10—Polana, Javorie, 11—Matra, 12—Slanske-Vrchy, 13–Tokaj, Zemplin, 14—Velky-Milic, 15—Vihorlat, 16—Metsek). The rocks studied: tuffites (1), basalts (2, 3), andesites and dacites (4–16). Ages: Oli—Oligocene, Mio—Miocene, L.—Lower, M.—Middle, U.—Upper.

acquired the state of a megabreccia, flysch basins in the Carpathians were closed, and formation of the molasse began. Oligocene–early Miocene nappes in both branches of the Alpine belt appear to have developed synchronously with formation of the Carpathian loop and other arc structures of the Carpathian–Balkan region.

The main feature of the inner structure of the Alpine fold belt in the region concerned is the disharmony between its Carpathian–Pontide and Dinaric–Tauride branches, particularly pronounced around the Pannonian basin. Yet, despite this disharmony, the two branches of the Alpine belt are of the same length (line *a–b* is

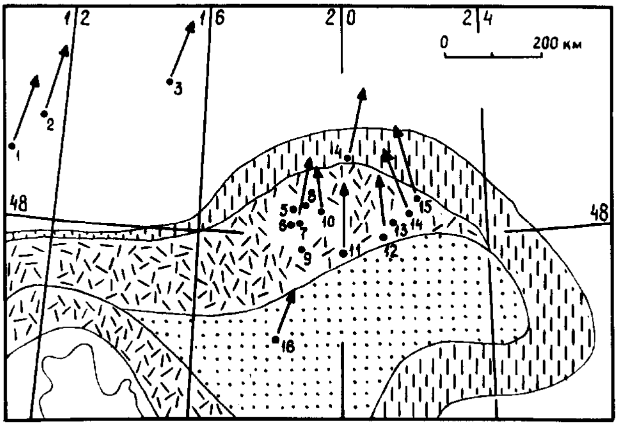

Fig 5. Results of paleomagnetic investigations of Neogene rocks (see Table 2). Symbols as in Fig. 2.

equal to line *c–d*, Fig. 2), as observed by Brunn (1960) long ago, providing a significant clue to the kinematics of the deformation.

We shall analyze the general deformation of this part of the Alpine belt using the data of the Carpathian structural loop. The secondary structural loop could have originated in three possible ways. In the first hypothesis, the Carpathian parts of the Carpathian–Pontic fold system could have been extended autonomously, forming the structural loop by a horizontal punch (for instance, continental margins) or for other reasons. If so, formation of the structural loop would have more than doubled the length of the tectonic zones of the Carpathians (from 700 to 1500 km) and the Carpathian–Pontic branch of the belt would have been much more extended than the Dinaride–Tauride branch. Yet they are equal. Thus, the equal length of the zones of development of Cretaceous nappes in the two branches of the Alpine belt (line *a–b* is equal to line *a–c*, Fig. 4), contradicts the first hypothesis.

In the second hypothesis, the structural loop formed as a result of the deformation of the entire Carpathian–Pontic fold system (Fig. 3). The equal length of the two branches of the Alpine belt between the Alpine and the Erzerum "necks" (Figs. 2 and 6) and the equal extension of the zones of development of Cretaceous nappes in both branches (Fig. 4) support this hypothesis.

In the third hypothesis, masses within the fold system were redistributed plastically. If a structural loop is formed in this way, masses will arrive at the loop (flow plastically) from neighboring parts of the belt, where compensatory thinning or extension may be expected. Such processes would help solve the problem of filling the inner space of the structural loop. That the Pannonian part of the Pannonian–Anatolian zone expanded considerably agrees with such a conclusion.

During formation of the Carpathian loop the Gemeric–Tatric block rotated counter-clockwise (Table 1) around an axis situated at the boundary between the

Western Carpathians and Eastern Alps and moved northward over a cosiderable distance. Like the Austro-Alpine nappes, the Gemeric–Tatric block probably moved along the Penninic oceanic substratum, which is exposed in tectonic windows near Wechsel and Maltern in Austria and near Koseg in Hungary (*1* in Fig. 1), 100 km south of the northern margin of the Gemeric–Tatric zone (Wein, 1978), suggesting that the Gemeric–Tatric zone is probably entirely allochthonous. As a result of this northward movement, the Pienine basin was closed and partly crushed as the Gemeric–Tatric block converged with the margin of the Eurasian continent. The Pienine suture zone contains relics of this deep-sea basin, is clearly associated with the outer margin of the Gemeric–Tatric block, and naturally ends at the eastern end of that block.

The question naturally arises as to what tectonic structures were situated in the place at present occupied by the Carpathian loop. Argand (1924) suggested that the Carpathian loop appeared in place of a gulf that cut deep into Eurasia but was filled in the Oligocene with nappes of African origin. In the model by Balla (1982), in place of the Pannonian depression there was an oceanic basin, into which the microcontinents were pushed from the west in the Neogene. The structural data show that the existence of such a gulf with oceanic crust is not an obligatory condition for forming the Carpathian loop, but that two other solutions to the space problem are possible.

According to the first solution, the autochthonous tectonic elements were crushed and squeezed as the loop formed. Both the Pienine zone and the tight folding and overthrusting in the Carpathian flysch zone testify to such a process. The Paleogene flysch basin was from 300 to 600 km wide, but it was deformed into a fold zone not more than 100 km wide; that is, the Carpathian flysch zone was shortened transversely by several hundred kilometers.

The second solution would be large-scale thrusting over the East-European platform. The thrusting of the Carpathian flysch zone over the platform is well known; the minimum amplitude as determined by borehole data in the Western and Eastern Carpathians is 30 km, and the real dimensions could be several times larger. Hence the Carpathian loop probably developed in both ways.

One may conclude that as the structural loop formed, the marginal structures of the Eurasian continent were folded, piled up, partly crushed, and overthrust far over the continent. In other words, the Carpathian loop is rather surficial. Only newly-formed structures that originated in Pliocene–Quaternary time and pre-Neogene structures in the autochthone penetrate into deep parts of the crust and mantle.

The formation of the Carpathian loop is the result of lengthways displacement of the Carpatho-Pontide relative to the Dinaric–Tauride branch of the Alpine belt. This displacement was characterized by a left-lateral shift, whose largest amplitude was along the Vardar zone, and was simultaneous with general bending of the Alpine belt, as the southeastern (Asia Minor–Balkan) part of the belt rotated 30°–40° counter-clockwise relative to its more northern part. If the movement had

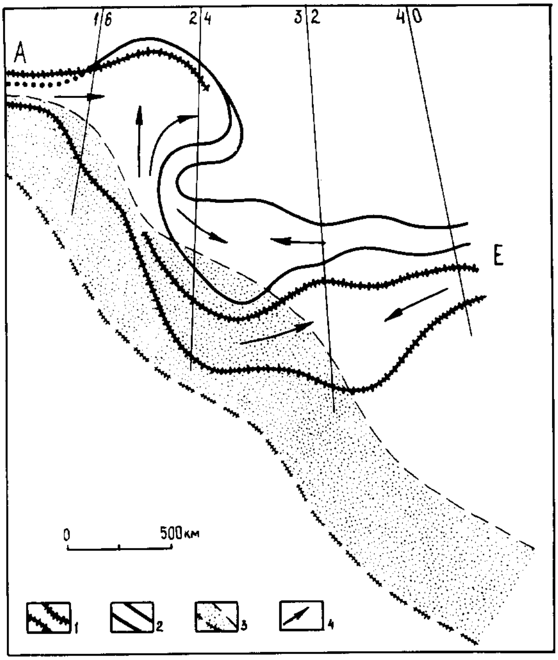

Fig. 6. Scheme of deformation of the Alpine belt in Paleogene–early Miocene time. *A* and *E*—Alpine and Erzerum "necks" of the fold belt. *1–2* = present-day position of the meso-Tethys structures (*1* = African margin, *2* = European margin), *3* = boundaries of the belt in late Cretaceous time, *4* = direction of mass flow during deformation of the belt.

been pure rotation, the Asia Minor-Balkan part of the belt should have moved northeast, but displacement proceeded northward and northwestward (Figs. 3, 6). Thus, the original length of the folded belt was too great to fit into its new position, and rotation of the Asia Minor–Balkan part required shortening of the considered segment of the Alpine belt by more than 30%, the shortening being accompanied by general disharmonic deformation and producing the structural arcs of the Carpathian-Balkan region.

The present scheme stands close to Brunn's (1960) concepts, based on the idea of migration of masses along the Alpine belt. Brunn believed that such migration was caused by pressure of the Arabian shield, so that the masses moved westward along the belt, and then to the north, reaching the Carpathian region. A new element in the present model is the conclusion that the lengthwise decrease of the fold belt results from a rotation of the Asia Minor–Balkan part of the belt relative to its more northern part. The general disharmonic deformation of the Alpine belt resulting from a change of its form was accompanied by the flow of masses inside the belt in different directions (Fig. 6), unlike in Brunn's scheme (1960).

MOST RECENT DEFORMATION OF THE ALPINE BELT

The present-day form of the tectonic zones originated as a result of Cenozoic deformations, including the deformations that led to the present-day relief. The form of these tectonic zones was used in analyzing the Paleogene–Miocene deformations, but the question arises to what extent that form was distorted in Pliocene–Quaternary time.

The more recent deformations resulted in a certain narrowing of the outer tectonic zones. These deformations in the two branches of the Alpine belt were commensurable, and they have not altered the structural pattern of the region.

Two large basins—the Aegean and Pannonian—were superimposed on all other structures of the region during Pliocene–Quaternary time. The Pannonian basin is superimposed on all the zones of the Carpathian–Pontide branch of the Alpine belt, as well as on the Bosnian, Karst, and ophiolitic zones of the Dinarides. The sharply superimposed character of the basin, in whose basement all the tectonic zones can be traced, is indirect evidence that its formation did not change appreciably the structural pattern of the Carpathian loop. Similarly, the paleomagnetic data on Miocene rocks show that the Carpathian loop already existed as far back as the Miocene.

To be sure, Miocene paleomagnetic vectors in the northeastern part of the mountain frame of the Pannonian basin (points *13–15* in Table 2 and Fig. 5) deviate northwest, as compared to the data on the Western Carpathians (points *5–9* in Table 2 and Fig. 5), and reflect post-Miocene deformation which caused the northern arc of the Carpathians to unbend. It would be natural to relate this deformation to expansion of the Pannonian basin. Data on the Aegean basin suggest its southward expansion, accompanied by deformation of the Hellenides–Cretan folded system (Angelier et al., 1982; Lai et al., 1982).

Thus, development of the Pannonian basin is related to deformation of the Carpathian–Pontide branch of the belt, but development of the Aegean basin to deformation of the Dinaric–Tauride branch. These late deformations in the two branches of the belt are simultaneous and approximately compensate each other, and they do not prevent our comparing the Carpatho-Pontides and Dinaric-Taurides in order to reconstruct the pre-Pliocene structures. Possibly the relative lengthwise displacement of the two branches of the Alpine belt continued into the late Cenozoic, helping to form the Pannonian and Aegean basins. Such a model for the development of the basins would agree well with the idea of mantle diapirs beneath the two basins, as commonly postulated to explain the young volcanism, the high heat flow, and specific features of the seismic refraction profiles of the crust under the basins. Moreover, downwarping of the Pannonian and Aegean basins and elevation of the mantle diapirs may reflect the latest left-lateral shifting of the Carpatho-Balkan and Dinaric–Hellenian fold systems relative to each other.

REFERENCES

Andro, J., Krs, K., Marton, E. and Marton, P., 1977. Paleomagnetism of the Borzsony Mountains (Hungary). Pure Appl. Geophys., 115 (4): 979–987.

Argand, E., 1924. La tectonique de l'Asie. Congr. Géol. Int., 13, Bruxelles, 1922, C.R., pp. 169–371.

Angelier, J., Lybéris, N., Le Pichon, X., Barrier, E. and Huchon, P., 1982. The tectonic development of the Hellenic arc and the Sea of Crete: a synthesis. Tectonophysics, 86 (1–3): 159–196.

Balla, Z., 1982, Development of the Pannonian basin basement through the Cretaceous–Cenozoic collision: a new synthesis. Tectonophysics, 88 (1–2): 61–102.

Bazhenov, M.L. and Burtman, V.S., 1980. On nature of the Carpathian northern arc. Dokl. Akad. Nauk SSSR, 255 (3): 681–685. (in Russian).

Bazhenov, M.L., Began, A., Birkenmajer, K. and Burtman, V.S., 1980. Paleomagnetic evidence of the tectonic origin of the curvature of the West Carpathian Arc. Bull. Acad. Pol. Sci., Ser. Sci. Terre, 28 (4): 281–290.

Bazhenov, M.L., Burtman, V.S. and Karagjuleva, J., 1983. A study of the Upper Cretaceous rocks from Panagjuriste strip by paleomagnetic methods. Geotectonics, Tectonophysics, Geodynamics, Sofia, 15: 47–52 (in Russian).

Beer, M.A., 1980. Peculiarities of geodynamics of the Carpatho-Dinaric region. In: M.V. Muratov (Editor), Tectonics of the Mediterranean Belt. Nauka, Moscow, pp. 146–155 (in Russian).

Bernoulli, D., Laubscher, H.P., Trümpy, R. and Wenk, E., 1974. Central Alps and Jura Mountains, In: A.M. Spencer (Editor), Mesozoic–Cenozoic Orogenic Belts. Scottisch Academic Press, Edinburgh, pp. 85–108.

Biju-Duval, B., Letouzey, J. and Montadert, L., 1978. Structure and evolution of the Mediterranean basins. Rep. Deep Sea Drilling Proj. 42, Pt. 1, pp. 951–984.

Birkenmajer, K. and Nairn, A.E.M., 1968. Studia paleomagnetyczne skal Polskich: neogenskie skaly Ogniwe Pienun. Rocz. Pol. Tow. Geol., 38 (4): 475–489.

Bleahu, M., 1976. Structure géologique des Apuseni septentrionaux Rev. Roum. Géol., Géophys. Géogr., Ser. Géol., 20 (1): 27–39.

Boccaletti, M., Manetti, P. and Peccerillo, A., 1974. Hypothesis on the plate tectonic evolution of the Carpatho-Balkan arcs. Earth Planet. Sci. Lett., 23 (2): 193–198.

Brunn, J.H., 1960. Les zônes helléniques internes et leur extension. Reflexion sur l'orogenèse alpine. Bull. Soc. Géol. Fr. Sér. 7, 2: 470–486.

Burtman, V.S., 1984. Kinematics of the Carpathian structural loop. Geotectonica, 3: 17–31 (in Russian).

Burtman, V.S. and Rudakov, S.G., 1982. On the boundary between the Inner and Outer Carpathians in the Chivchin mountains. Dokl. Akad. Nauk SSSR, 264 (4): 911–915 (in Russian).

Channell, J.E.T. and Tarling, D.H., 1975. Paleomagnetism and the rotation of Italy. Earth Planet. Sci. Lett., 25 (2): 177–188.

Clar, E., 1973. Review of the structure of the Eastern Alps. In: K.A. De Jong and R. Scholten (Editors), Gravity and Tectonics. Wiley, New York–London–Sydney–Toronto, pp. 253–270.

Dagley, P. and Ade-Hall, J.M., 1970. Cretaceous, Tertiary and Quaternary paleomagnetic results from Hungary. Geophys. J., R. Astron. Soc., 20 (1): 65–87.

Graciansky, P.C., 1972. Recherches géologiques dans la Taurus Lucien occidental. Thèse Doct. Sci., Univ. Paris, Orsay, Sér A, 986: 571 pp.

Helsley, C.E. and Nur, A., 1970. The paleomagnetism of Cretaceous rocks from Israel. Earth Planet. Sci. Lett., 8 (6): 403–410.

Horvàth, E., Vörös, A. and Onioha, K.M., 1979. Plate-tectonics of the western Carpatho-Pannonian region: a working hypothesis. Acta Geol. Acad. Sci. Hung., 21 (4): 207–221.

Horvàth, E., Berckhemer, H. and Stegena, L., 1981. Models of Mediterranean back-arc basin formation. Philos. Trans., R. Soc. London, Ser. A, 300: 383–401.

Juteau, T., 1979. Ophiolites des Taurides: essai sur leur histoire océanique. Rev. Géol. Dyn. Géogr. Phys., 21 (3): 191–214.

Karagjuleva, J., Gocev, P. and Pironkov, P., 1982. Types and features of alpine nappes in Bulgaria. In: M. Mahel (Editor), Alpine Structural Elements: the Carpathian–Balkan–Caucasus–Pamir Orogene Zone. VEDA, Publishing House of the Slovak Academy of Science, Bratislava, pp. 57–74.

Kovàcs, S., 1982. Problems of the "Pannonian Median Massif" and the plate tectonic concept. Contributions based on the distribution of Late Paleozoic–Early Mesozoic isopic zones. Geol. Rundsch., 71 (2): 617–640.

Krs, M., Muska, P., Orlicky, O. and Pagac, P., 1979. Paleomagnetic investigations in the West Carpathians. In: J. Vanec (Editor), Geodynamic Investigations in Czechoslovakia. VEDA, Publishing House of the Slovak Academy of Science, Bratislava, pp. 207–214.

Laj, C., Jamet, M., Sorel, D. and Valente, J.P., 1982. First paleomagnetic results from Mio-Pliocene series of the Hellenic sedimentary arcs. Tectonophysics, 86, (1–3): 45–67.

Lauer, J.-P., 1981. L'évolution géodynamique de la Turquie et de Chypre déduite de l'étude paléomagnétique. Univ. Louis Pasteur, Strasbourg, 299 pp.

Marschalko, R. and Pagàc, P., 1980, Preliminary results of paleomagnetic study of varied Upper Cretaceous sediments of the Pienine, Manín and central blocks of the west Carpathians (north-west Slovakia). Slovak. Acad. Sci., Geophys. Inst. Contr., 10: 77–83.

Marton, E. and Marton, P., 1983. A refined apparent polar wander curve for the Transdanubian Central Mountains and its bearing on the Mediterranean tectonic history. Tectonophysics, 98 (1–2): 43–57.

Nairn, A.E.M., 1967. Paleomagnetic investigations of the Tertiary and Quaternary igneous rocks: a paleomagnetic study of the east Slovak Province. Geol. Rundsch., 56 (2): 408–419.

Nairn, A.E.M. and Wollstadt, H., 1968. Paleomagnetic investigations of the Tertiary and Quaternary igneous rocks: the Tertiary volcanics of the Lausitz area, Germany. Geol. Rundsch., 57 (2): 385–402.

Nozharov, P.B., Veljovic, D. and Petkov, N.I., 1977. Results of paleomagnetic studies of some magmatic rocks in Srednogoriye and Strandja. Bulgar. Acad. Sci., Proc., 30 (4): 531–533.

Orbay, N. and Bayburdi, A., 1979. Palaeomagnetism of dykes and tuffs from the Mesudiye region and rotation of Turkey. Geophys. J., R. Astron. Soc., 59 (3): 437–444.

Oxburgh, E.R., 1974. Eastern Alps. In: A.M. Spencer (Editor), Mesozoic–Cenozoic Orogenic Belts. Scottish Academic Press, Edinburgh, pp. 109–126.

Peterson, N., Soffel, H., Pohl, J. and Helburg, K., 1965. Rockmagnetic research at the Institut für Angewandte Geophysik, Universität München. J. Geomagn. Geoelectr., 17 (3–4): 363–372.

Pohl, J. and Soffel, H., 1977. Paleomagnetic and rockmagnetic investigations of Tertiary volcanics in Northern Bavaria. J. Geophys., 42 (5): 459–474.

Sandulescu, M., 1980. Analyse géotectonique des chaînes alpines situées autour de la Mer Noire Occidentale: Annu. Inst. Géol. Géophys., Bucarest, 56: 5–54.

Trümpy, R., 1973. The timing of orogenic events in the Central Alps. In: K.A. De Jong and R. Scholten (Editors), Gravity and Tectonics. Wiley, New York-London-Sydney-Toronto, pp. 299–252.

Van der Voo, R., 1968. Jurassic, Cretaceous and Eocene pole positions from northeastern Turkey. Tectonophysics, 6 (3): 251–269.

VandenBerg, J., 1983. Reappraisal of paleomagnetic data from Gargano (South Italy). Tectonophysics, 98 (1–2): 29–41.

VandenBerg, J. and Wonders, A.A.H., 1976. Paleomagnetic evidence of large fault displacement around the Po-basin. Tectonophysics, 33 (3–4): 301–320.

Vörös, A., 1977. Provinciality of the Mediterranean Lower Jurassic brachiopod fauna: causes and plate tectonic implications. Palaeogeogr., Palaeoclimatol., Palaeoecol., 21 (1): 1–16.

Wein, G., 1978. A Kárpát-medence alpitektogenezise. Magy. All. Földt. Intéz. Evk, 1976: 245–256.