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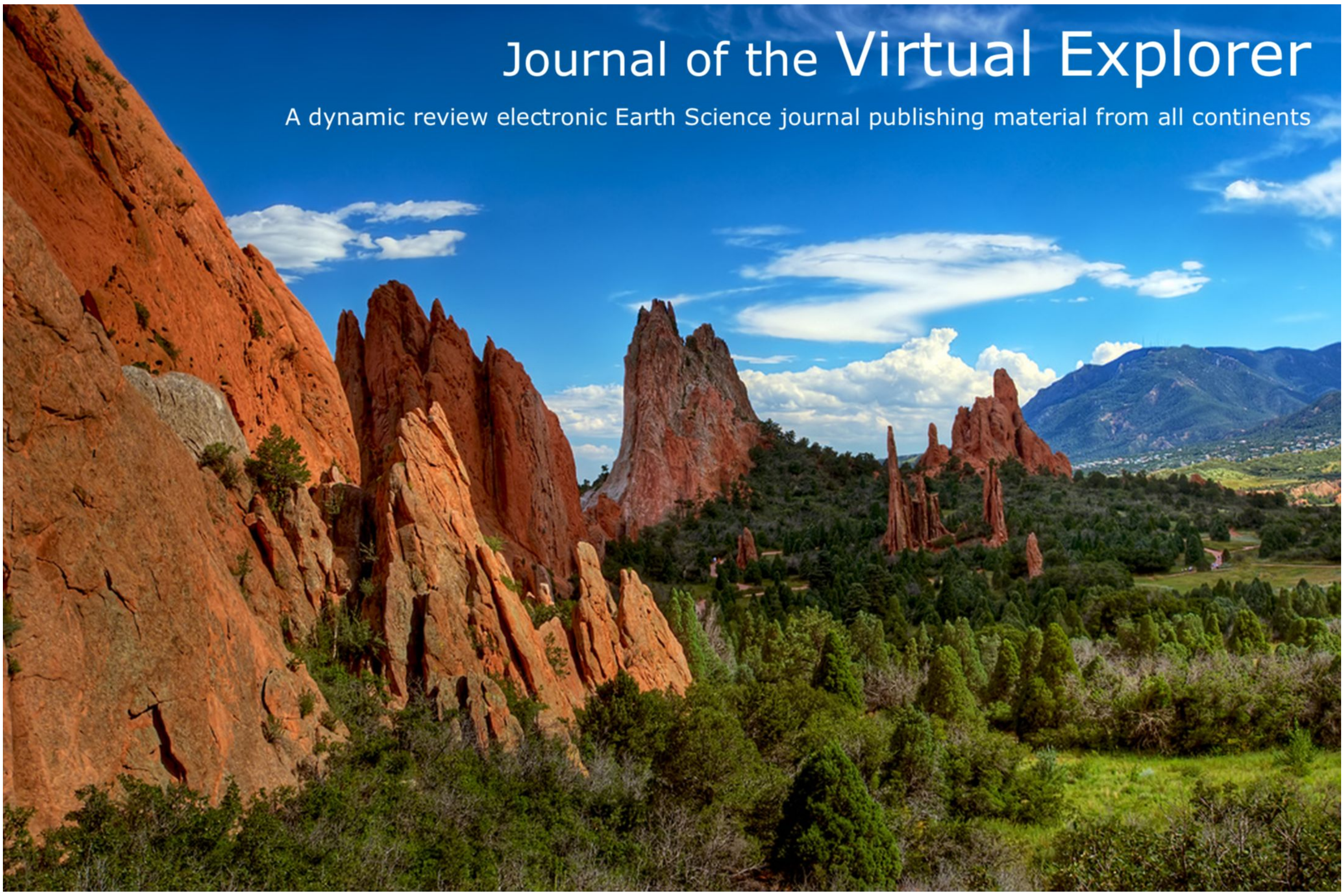

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The Carpathian–Balkan bends: an oroclinal record of ongoing Arabian–Eurasian collision

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Abstract: The Alpine orogen of southeastern Europe is characterized by two, coupled, highly arcuate segments; a northerly Carpathian segment characterized by a 150 degree, convex to the east arc, and a more southerly, 180 degree convex to the west Balkan segment. Regional paleomagnetic data are neither abundant enough, nor of sufficient quality to fully test the origin of these arcuate segments of the Alpine orogen. However, paleomagnetic studies of Cretaceous – Micoene rocks within the northern, Carpathian segment show significant time progressive clockwise rotations that are consistent with interpretation of the arcuate segments as oroclines that developed due to bending of a previously linear orogen. The Carpathian - Balkan region lies immediately north northeast of an Eastern Mediterranean region within which Late Eocene to Miocene rocks are characterized by anomalously shallow paleomagnetic inclinations. This Eastern Mediterranean Inclination Anomaly requires that the region moved 500 to 1000 km north at roughly the same time as the Carpathian - Balkan bending of the Alpine orogen. A geometrically constrained paleogeographic model shows that northward displacement of the Eastern Mediterranean region, together with an equal amount of westward displacement, can explain the observed Carpathian - Balkan oroclines as buckles of an originally linear orogen that was pinned to the southeast against the northwestwardly migrating East Mediterranean crustal block, and to the northwest against autochthonous Europe. The implied northwestward translation of the Eastern Mediterranean region is consistent with the observed ongoing tectonic escape of the Anatolian - Aegean region out of the Arabian - Eurasian collision zone.

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Introduction

The Alpine orogenic system stretches along the southern underbelly of Europe and provides a record of the complex interactions between the African and Eurasian plates. The orogenic system is characterized by a number of highly arcuate segments, including, from west to east, the Betic – Rif, the western Alps, the Calabrian Arc, and the Z-shaped bends of the Carpathian – Balkan belt (Fig. 1). The bends characterizing the Alpine system are commonly interpreted as primary features that reflect the paleo-topography of the European southern margin. It is, however, difficult to reconcile models of the bends as primary features with the continuity of the orogenic structures that extend around these bends. An alternative interpretation is that at least some of the arcuate segments of the Alpine system are secondary features that reflect oroclinal buckling of formerly linear segments of the orogen.

Our focus is on the bend pair that constitutes the Carpathian – Balkan belt. The most widely accepted tectonic models for the region focus on the convex to the east Carpathian segment, interpreting it as a primary embayment in the European margin, and invoking differing styles of terrane accretion into the embayment (e.g. Burchfiel, 1980; Channel and Horváth, 1976; Csontos and Vörös, 2004). Burtman (1986), based on preliminary paleomagnetic data, presented an alternative model in which the Carpathian – Balkan bends formed as a result of vertical axis rotation of an originally linear orogen.

Figure 1.

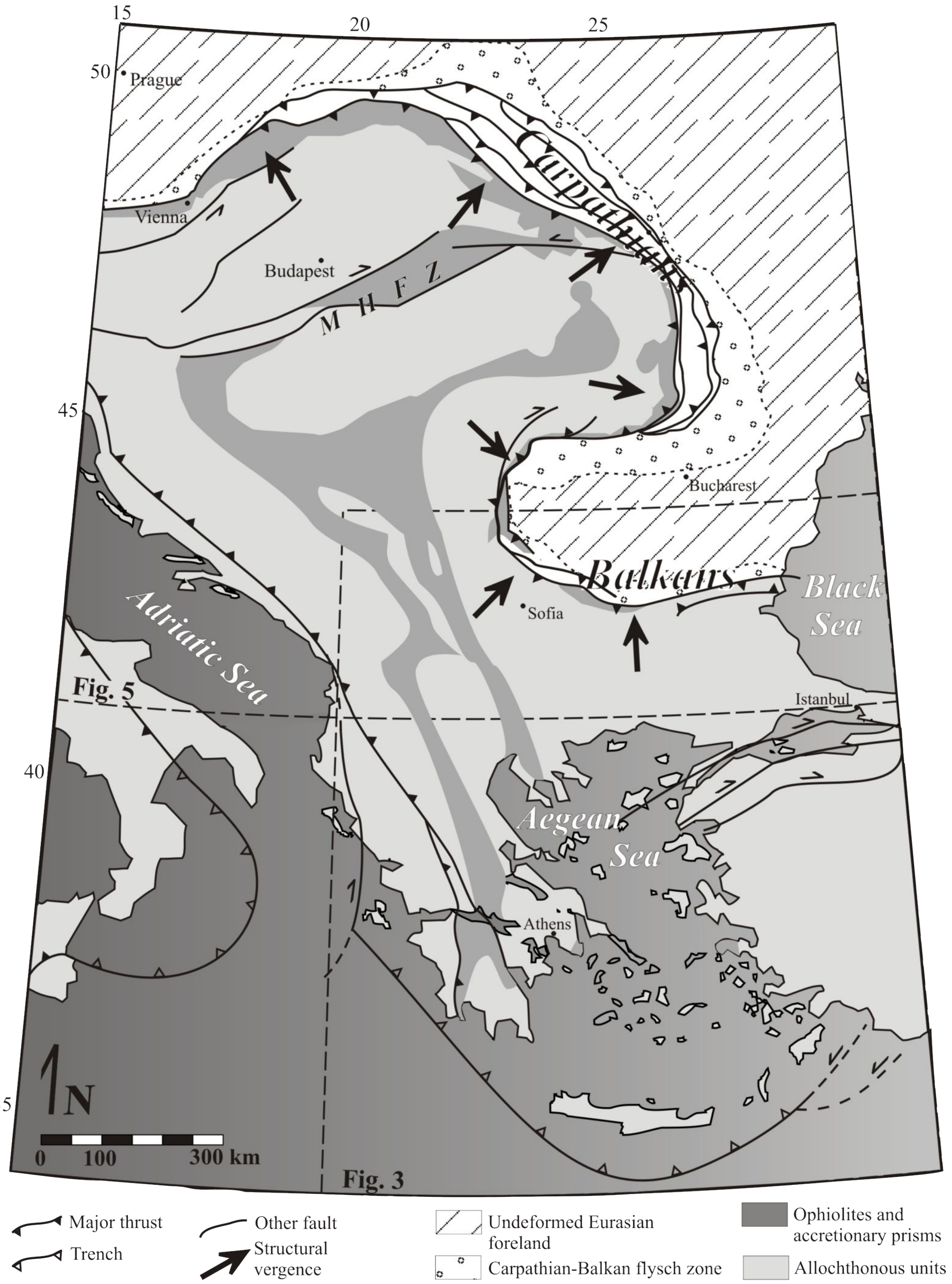
Satellite image of Europe overlain by the approximate traces of major orogenic fronts of the Alpine system (solid upper plate indicators), modern subduction trenches (hollow upper plate indicators) and major transform systems. Imagery courtesy of NASA earth observatory.

None of the published models consider regional paleomagnetic evidence for substantial northward translation, coeval with late-stage Alpine orogenesis, of the Eastern Mediterranean domain immediately to the south and southeast of the Carpathian – Balkan belt. Our goal is to determine if interpretation of the Carpathian - Balkan section of the Alpine orogenic belt as a secondary feature attributable to oroclinal buckling of an originally linear orogen can explain and be reconciled with the Eastern Mediterranean Inclination Anomaly (EMIA). Toward this goal, we (1) summarize the data that constrains the age and aerial extent of the EMIA, (2) assess the structural and available paleomagnetic data in order to test a secondary 'oroclinal' interpretation of the curvature through the Carpathian – Balkan belt, and (3) present a geometrically constrained paleogeographic model in which we invoke a cause and effect relationship between the EMIA and oroclinal buckling of an originally linear Carpathian – Balkan belt. Our model suggests that (1) an originally linear Carpathian – Balkan belt was characterized by a northwest-southeast trend, (2) northward translation of the eastern Mediterranean region recorded by the EMIA was accommodated by an equivalent amount of westward translation, and (3) deformation and translation, including oroclinal buckling of the Carpathian – Balkan belt, is explained by and provides a record of ongoing westward tectonic escape of the Aegean – Anatolian region out of the Arabian – Eurasion collision zones.

Geologic Setting

The Carpathians define a convex to the east arc that spans northeastern Austria through western Ukraine and tightens into a 150 degree bend in central Romania. The Carpathians link into a convex to the west, 180 degree, southern Balkan arc, and together the two arcuate segments of the Alpine chain define a Z-shaped system of coupled arcs. The Balkan arc links the Carpathians into the southerly, east-west trending Balkan Mountains, which terminate at the eastern margin of the Black Sea (Fig. 2). Deformation within the Carpathian-Balkan belt, like the Alpine system as a whole, is long lived, polyphase, and complex, spanning from at least the Mid-Cretaceous to recent times (e.g. Burchfiel, 1980, Royden and Burchfiel, 1986). Early (Middle Cretaceous) deformation in the Carpathian – Balkan system involved long distance nappe transport directed towards the Eurasian foreland, which, in present day coordinates, flanks the eastern side of the orogen. Nappe stacks were subsequently folded, and axial traces of this Late Cretaceous fold system run parallel to the modern arcuate trend of the orogen Carpathian – Balkan chain (Burtman, 1986 and references therein). Structural vergence in the belt is outward from the core of the northern Carpathian bend and inwards toward the core of the southern Balkan bend, consistently oriented towards the orogenic foreland and perpendicular to structural strike (Burtman, 1986; Csontos and Vörös, 2004). Cretaceous nappe emplacement has been interpreted as marking the closure of the Tethys in this region of the Alpine system (e.g. Burtamn, 1986). Alternatively, collision and accretion of the magmatic arc bearing upper plate to the southern Eurasian continental margin may not have terminated until Eocene times (Nemcock, 1998). It is generally agreed that subduction polarity was away from the Eurasian margin and toward the accreting arc, with oceanic closure involving slab roll-back toward the Eurasian margin (e.g. Burchfiel, 1980). What has been interpreted as the remnant-subducted slab has been imaged beneath the easternmost reaches of the Carpathian bend (Nemcock *et al.*, 1998). The western flanks of the orogen are characterized by accretionary sequences (including ophiolitic assemblages) that form a continuous band around the Z-shaped Carpathian – Balkan chain (Fig. 2) and have been previously interpreted as oceanic suture (Csontos and Vörös, 2004).

Figure 2.



Curvature in the Carpathian – Balkan orogen and its geographic relation to the Aegean Sea region. MHFZ – Mid Hungarian fault zone. Structural vergence after Csontos and Vörös (2004). Simplified geology in the Carpathian – Balkan belt modeled after Burchfiel (1980), Horvath (1993), and Tischler *et al.* (2005). Extent of Balkan flysch zone after Burtman (1986), extent of ophiolites and accretionary prisms north of the fortieth parallel after Tischler *et al.* (2008), and simplified from van Hinsbergen *et al.* (2005) for Greece. Extent of ophiolitic terranes in the Anatolian Structural vergence in the belt is plate not displayed.

The Eastern Mediterranean Inclination Anomaly (EMIA)

Paleomagnetic inclination data obtained from Late Eocenee to Miocene rocks within the greater north Aegean region reveal consistently shallow inclinations with respect to a stable Europe, indicating that the region has undergone geologically recent northward displacement. We review paleomagnetic data initially compiled by Beck *et al.* (2000). Paleomagnetic inclinations for the Eastern Mediterranean region are measured relative to expected values as calculated based on the European apparent polar wander path (APW) of Besse and Courtillot (1991) by Beck *et al.* (2000). The difference between observed and calculated values yields the amount of inclination shallowing (ΔI; listed in Table 1 and displayed relatively in Fig. 3.)

All paleomagnetic results compiled herein were obtained from igneous rocks, thus avoiding likely inaccuracies associated with retrieval of inclination data from sedimentary rocks (e.g. Krijgsman, W., and Tauxe, 2004). Following the reasoning of Beck and Schermer (1994), the EMIA must be attributable to either (1) errors in the applied APW path of Besse and Courtillot (1991), (2) irregularities within dipole of the Tertiary geomagnetic field of the Aegean region, (3) consistent procedural errors in sampling and/or laboratory analysis, or (4) northward directed crustal mobility of the Aegean region with respect to stable Europe. Beck and Schermer (1994) recalculated expected inclination for the Aegean region from all available APW paths and obtained results consistent with those calculated from the path of Besse and Courtillot (1991), concluding that the problem did not lie in the European APWP. Westphal (1993) suggested that the EMIA records a large (18°) and abrupt shift in the geomagnetic dipole. As noted by Beck and Schermer (1994), however, such a shift should be recorded in contemporaneous rocks worldwide, which is not the case. For example, no such shift is recorded in the well-constrained APW paths for North America. The extended time period and localized scale of the EMIA argue against its being attributable to geomagnetic irregularities such as dipole shifts or non-dipole components. Finally, the significant number of studies that record the anomaly negate the possibility of consistent procedural errors producing false results. We conclude that the EMIA provides a true record of northward translation of crust underlying the Eastern Mediterranean region.

Early Miocene volcanic rocks from the island of Lesbos (site 6) have been the subject of several paleomagnetic studies, all of which yielded consistent results. These rocks record an average ΔI value of -5.1, corresponding to ca. 500 km northward displacement (Beck *et al.*, 2000). Lesbos volcanic rocks may, however, have erupted after the onset of northward translation and hence may not record its full extent; we accept 500 km as a minimum value for total possible northward displacement. A plot of ΔI versus average age can be used to (1) estimate the full extent of inclination shallowing and northward mobility and (2) constrain the timing of displacement (Fig. 4). Our line of best fit intersects the x-axis (i.e. modern latitude) at 3 Ma, corresponding with the age Volos volcanics (Site 1), the only locality for which inclination shallowing was not recorded. We therefore accept 3 Ma as an estimate for the end of northward displacement. Inclination shallowing in 30 to 35 Ma rocks is consistent with 1000 km of northward displacement. Assuming that this value of 1000 km represents the total amount of northward displacement of the Eastern Mediterranean region, and that translation began around 33 Ma and ended at 3 Ma, a moderate translation rate of just over 3 cm·yr^{-1} is implied.

Figure Table 1.

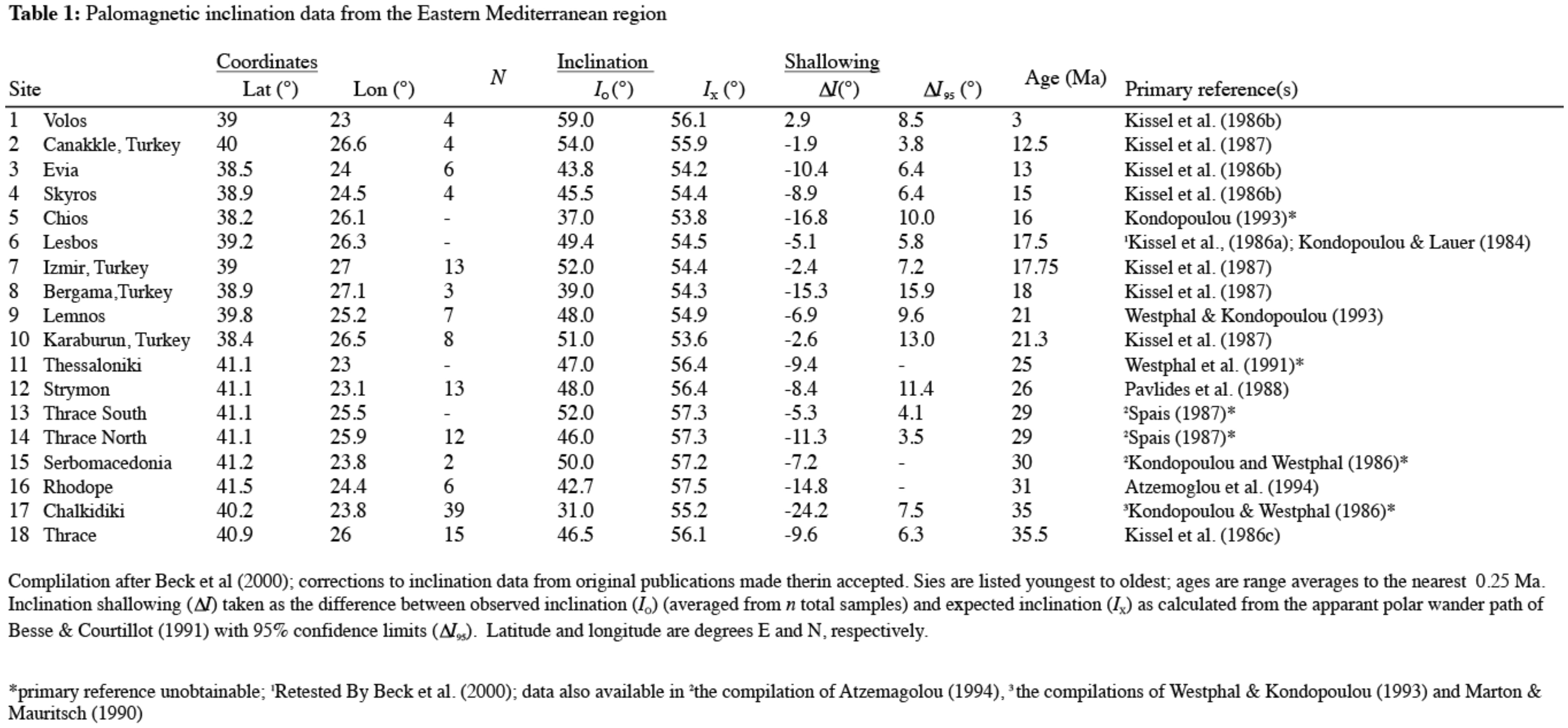


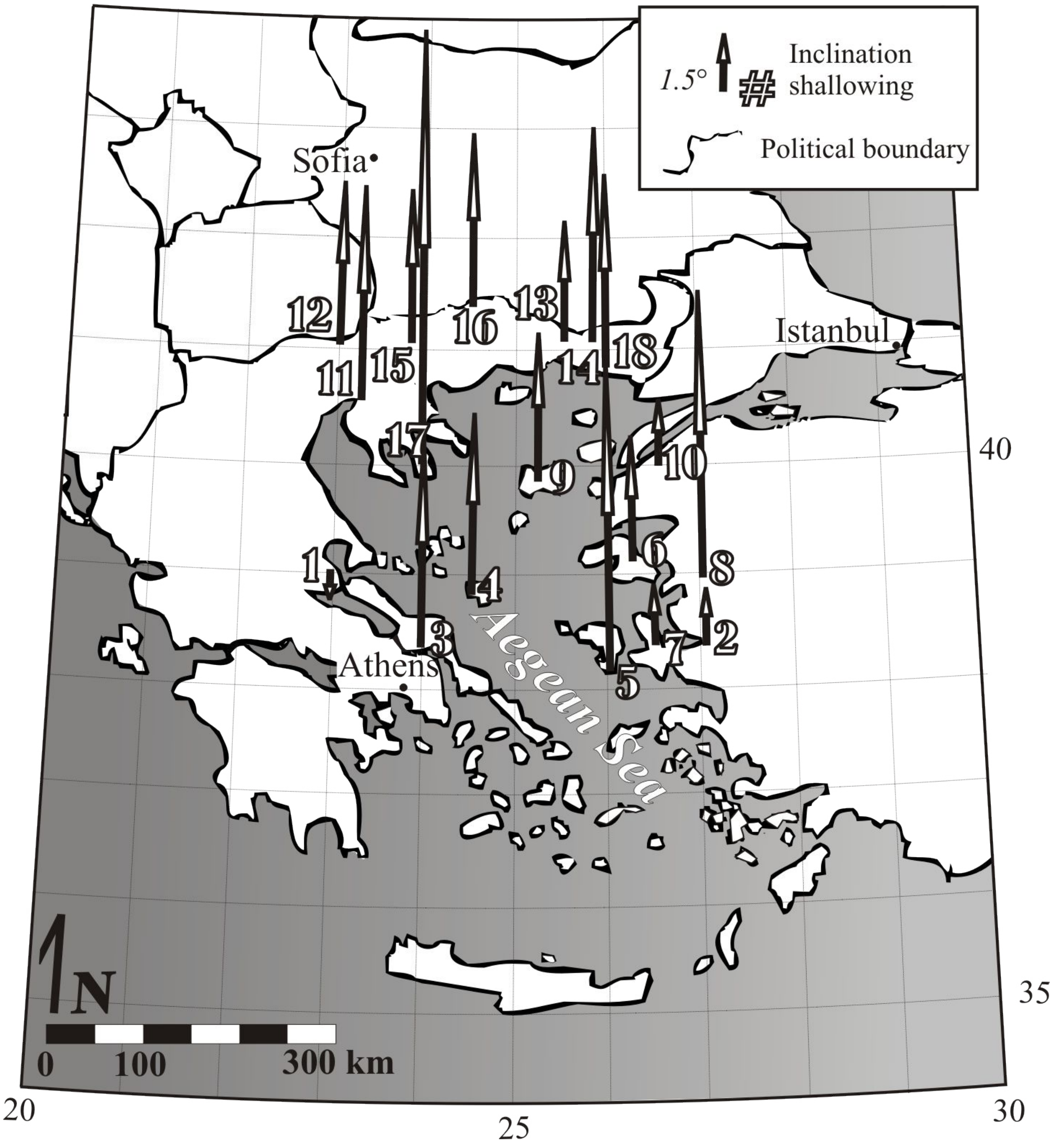
Table 1: Palomagnetic inclination data from the Eastern Mediterranean region

Site		Coordinates		N	Inclination		Shallowing		Age (Ma)	Primary reference(s)
		Lat (°)	Lon (°)		I_o(°)	I_x (°)	ΔI(°)	ΔI_{95} (°)		
1	Volos	39	23	4	59.0	56.1	2.9	8.5	3	Kissel et al. (1986b)
2	Canakkle, Turkey	40	26.6	4	54.0	55.9	-1.9	3.8	12.5	Kissel et al. (1987)
3	Evia	38.5	24	6	43.8	54.2	-10.4	6.4	13	Kissel et al. (1986b)
4	Skyros	38.9	24.5	4	45.5	54.4	-8.9	6.4	15	Kissel et al. (1986b)
5	Chios	38.2	26.1	-	37.0	53.8	-16.8	10.0	16	Kondopoulou (1993)*
6	Lesbos	39.2	26.3	-	49.4	54.5	-5.1	5.8	17.5	[1]Kissel et al., (1986a); Kondopoulou & Lauer (1984)
7	Izmir, Turkey	39	27	13	52.0	54.4	-2.4	7.2	17.75	Kissel et al. (1987)
8	Bergama,Turkey	38.9	27.1	3	39.0	54.3	-15.3	15.9	18	Kissel et al. (1987)
9	Lemnos	39.8	25.2	7	48.0	54.9	-6.9	9.6	21	Westphal & Kondopoulou (1993)
10	Karaburun, Turkey	38.4	26.5	8	51.0	53.6	-2.6	13.0	21.3	Kissel et al. (1987)
11	Thessaloniki	41.1	23	-	47.0	56.4	-9.4	-	25	Westphal et al. (1991)*
12	Strymon	41.1	23.1	13	48.0	56.4	-8.4	11.4	26	Pavlides et al. (1988)
13	Thrace South	41.1	25.5	-	52.0	57.3	-5.3	4.1	29	[2]Spais (1987)*
14	Thrace North	41.1	25.9	12	46.0	57.3	-11.3	3.5	29	[2]Spais (1987)*
15	Serbomacedonia	41.2	23.8	2	50.0	57.2	-7.2	-	30	[2]Kondopoulou and Westphal (1986)*
16	Rhodope	41.5	24.4	6	42.7	57.5	-14.8	-	31	Atzemoglou et al. (1994)
17	Chalkidiki	40.2	23.8	39	31.0	55.2	-24.2	7.5	35	[3]Kondopoulou & Westphal (1986)*
18	Thrace	40.9	26	15	46.5	56.1	-9.6	6.3	35.5	Kissel et al. (1986c)

Compilation after Beck et al (2000); corrections to inclination data from original publications made therin accepted. Sies are listed youngest to oldest; ages are range averages to the nearest 0.25 Ma. Inclination shallowing (ΔI) taken as the difference between observed inclination (I_o) (averaged from *n* total samples) and expected inclination (I_x) as calculated from the apparant polar wander path of Besse & Courtillot (1991) with 95% confidence limits (ΔI_{95}). Latitude and longitude are degrees E and N, respectively.

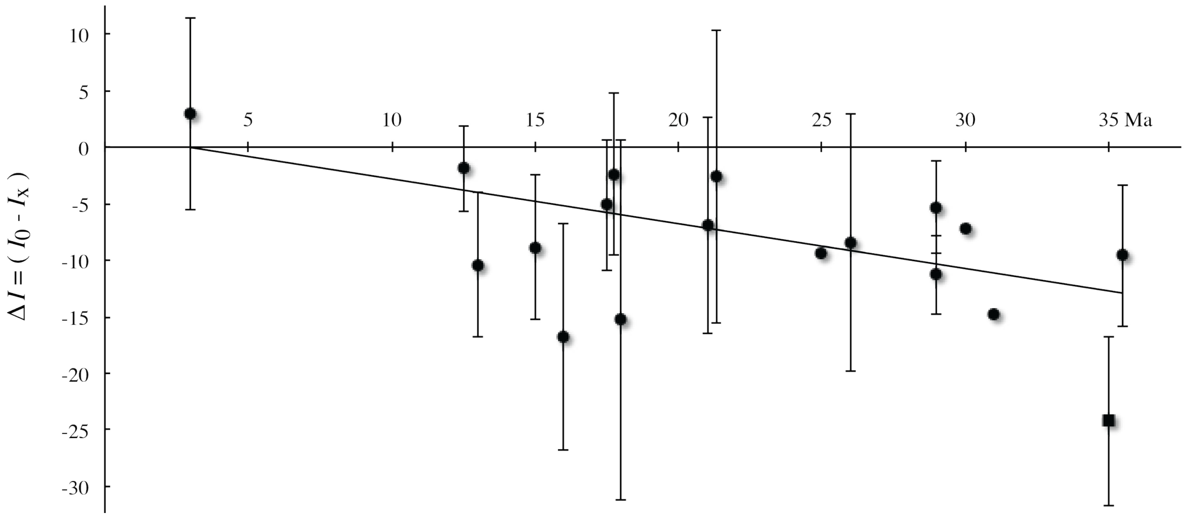
*primary reference unobtainable; [1]Retested By Beck et al. (2000); data also available in [2]the compilation of Atzemagolou (1994), [3]the compilations of Westphal & Kondopoulou (1993) and Marton & Mauritsch (1990)

Figure 3.



Scaled arrows represent degrees latitude of northward displacement within the Aegean region corresponding to calculated ΔI values, as listed in Table 1. Sites are numbered youngest (1) to oldest (18).

Figure 4.



Plot of ΔI versus average age estimates for sampled sites corresponding to date presented in Table 1, modified from Beck *et al.* (2000). Error bars are 95% confidence values; incalculable where not shown. The solid line of best fit, from which we estimate the rate and end time of northward displacement, excludes the outlying Chalkadiki plutonics (Site 17; plotted as a square).

The Carpathian – Balkan belt: paleomagnetic rotations and the orocline hypothesis

Interpretation of the arcuate, Z-shaped geometry of the Carpathian – Balkan chain as a product of oroclinal bending of a formerly linear orogen is suggested by the perpendicularity of structural vergence to local strike. In other words, structural vergence varies as a function of strike. Primary bend models that suggest terrane accretion driven by roll-back into a pre-existing embayment predict syn-accretionary strike-slip motion along its outer flanks, for which there is no supporting evidence. In addition, regional palinspastic restoration of crustal shortening within the Carpathian – Balkan fold and thrust belt is only possible after restoration of the orogen to a linear geometry. Not doing so implies an excess of line length around the Carpathian bend, requiring all nappes to restore to a common origin, and a line length deficit around the Balkan bend, requiring thrust nappes to have been originally discontinuous. The continuity of accreted terranes around both bends further supports a secondary, oroclinal origin for the bends. Models of terrane accretion to an arcuate European continental margin predict significant differences in length between the shorter accreting arcs and the much longer continental margin. There is, however, no indication of syn-accretionary strike parallel extension within the terranes, including ophiolites, which are continuous around the Carpathian – Balkan chain. The most commonly accepted test for the oroclinal nature of arcuate orogens involves plotting paleomagnetic declination against structural strike in order to determine if changes in structural strike resulted from rotations relative to the magnetic pole (Eldredge *et al.* 1985). Application of the test requires declination data of well constrained age from around the entire arcuate orogenic belt. Paleomagnetic declination data for the Carpathian-Balkan region are of limited quantity and poor quality (Table 2). Data are: commonly from rocks with broad age limits; supplied with inadequate coordinate data are; characterized by error values larger than reported rotations; and/or lacking discussion of standard methods and tests used to control paleomagnetic data accuracy, e.g. the fold test. As a result, paleomagnetic data from the Carpathian – Balkan belt are not abundant or well constrained enough for application of the orocline test. There are, however, sufficient data to enable us to test for, and constrain the timing of, rotations of the Carpathian chain. In our compilation of available paleomagnetic data, we rejected data characterized by the problems outlined above, and excluded data points for which reference poles were not available. We are left with a data set comparable to those previously compiled by Dupont-Nivet *et al.* (2005) and (van Hinsbergen, 2008) (Fig. 5).

Figure Table 2a.

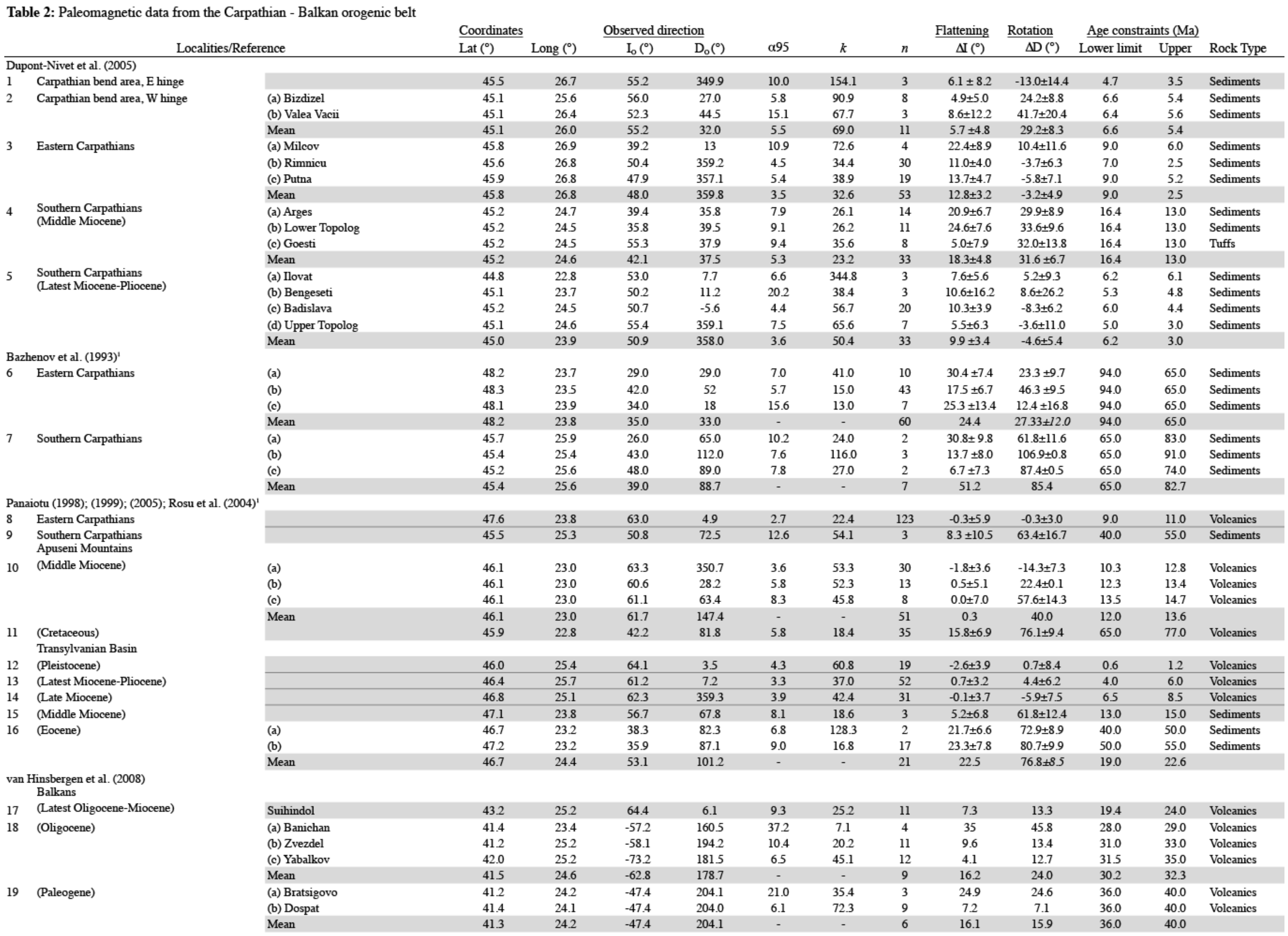


Table 2: Paleomagnetic data from the Carpathian - Balkan orogenic belt

	Localities/Reference		Coordinates		Observed direction					Flattening	Rotation	Age constraints (Ma)		
			Lat (°)	Long (°)	I_o (°)	D_o (°)	α95	*k*	*n*	ΔI (°)	ΔD (°)	Lower limit	Upper	Rock Type
Dupont-Nivet et al. (2005)														
1	Carpathian bend area, E hinge		45.5	26.7	55.2	349.9	10.0	154.1	3	6.1 ± 8.2	-13.0±14.4	4.7	3.5	Sediments
2	Carpathian bend area, W hinge	(a) Bizdizel	45.1	25.6	56.0	27.0	5.8	90.9	8	4.9±5.0	24.2±8.8	6.6	5.4	Sediments
		(b) Valea Vacii	45.1	26.4	52.3	44.5	15.1	67.7	3	8.6±12.2	41.7±20.4	6.4	5.6	Sediments
		Mean	45.1	26.0	55.2	32.0	5.5	69.0	11	5.7 ±4.8	29.2±8.3	6.6	5.4	
3	Eastern Carpathians	(a) Milcov	45.8	26.9	39.2	13	10.9	72.6	4	22.4±8.9	10.4±11.6	9.0	6.0	Sediments
		(b) Rimnicu	45.6	26.8	50.4	359.2	4.5	34.4	30	11.0±4.0	-3.7±6.3	7.0	2.5	Sediments
		(c) Putna	45.9	26.8	47.9	357.1	5.4	38.9	19	13.7±4.7	-5.8±7.1	9.0	5.2	Sediments
		Mean	45.8	26.8	48.0	359.8	3.5	32.6	53	12.8±3.2	-3.2±4.9	9.0	2.5	
4	Southern Carpathians (Middle Miocene)	(a) Arges	45.2	24.7	39.4	35.8	7.9	26.1	14	20.9±6.7	29.9±8.9	16.4	13.0	Sediments
		(b) Lower Topolog	45.2	24.5	35.8	39.5	9.1	26.2	11	24.6±7.6	33.6±9.6	16.4	13.0	Sediments
		(c) Goesti	45.2	24.5	55.3	37.9	9.4	35.6	8	5.0±7.9	32.0±13.8	16.4	13.0	Tuffs
		Mean	45.2	24.6	42.1	37.5	5.3	23.2	33	18.3±4.8	31.6 ±6.7	16.4	13.0	
5	Southern Carpathians (Latest Miocene-Pliocene)	(a) Ilovat	44.8	22.8	53.0	7.7	6.6	344.8	3	7.6±5.6	5.2±9.3	6.2	6.1	Sediments
		(b) Bengeseti	45.1	23.7	50.2	11.2	20.2	38.4	3	10.6±16.2	8.6±26.2	5.3	4.8	Sediments
		(c) Badislava	45.2	24.5	50.7	-5.6	4.4	56.7	20	10.3±3.9	-8.3±6.2	6.0	4.4	Sediments
		(d) Upper Topolog	45.1	24.6	55.4	359.1	7.5	65.6	7	5.5±6.3	-3.6±11.0	5.0	3.0	Sediments
		Mean	45.0	23.9	50.9	358.0	3.6	50.4	33	9.9 ±3.4	-4.6±5.4	6.2	3.0	
Bazhenov et al. (1993)[1]														
6	Eastern Carpathians	(a)	48.2	23.7	29.0	29.0	7.0	41.0	10	30.4 ±7.4	23.3 ±9.7	94.0	65.0	Sediments
		(b)	48.3	23.5	42.0	52	5.7	15.0	43	17.5 ±6.7	46.3 ±9.5	94.0	65.0	Sediments
		(c)	48.1	23.9	34.0	18	15.6	13.0	7	25.3 ±13.4	12.4 ±16.8	94.0	65.0	Sediments
		Mean	48.2	23.8	35.0	33.0	-	-	60	24.4	27.33±*12.0*	94.0	65.0	
7	Southern Carpathians	(a)	45.7	25.9	26.0	65.0	10.2	24.0	2	30.8± 9.8	61.8±11.6	65.0	83.0	Sediments
		(b)	45.4	25.4	43.0	112.0	7.6	116.0	3	13.7 ±8.0	106.9±0.8	65.0	91.0	Sediments
		(c)	45.2	25.6	48.0	89.0	7.8	27.0	2	6.7 ±7.3	87.4±0.5	65.0	74.0	Sediments
		Mean	45.4	25.6	39.0	88.7	-	-	7	51.2	85.4	65.0	82.7	
Panaiotu (1998); (1999); (2005); Rosu et al. (2004)[1]														
8	Eastern Carpathians		47.6	23.8	63.0	4.9	2.7	22.4	123	-0.3±5.9	-0.3±3.0	9.0	11.0	Volcanics
9	Southern Carpathians		45.5	25.3	50.8	72.5	12.6	54.1	3	8.3 ±10.5	63.4±16.7	40.0	55.0	Sediments
	Apuseni Mountains													
10	(Middle Miocene)	(a)	46.1	23.0	63.3	350.7	3.6	53.3	30	-1.8±3.6	-14.3±7.3	10.3	12.8	Volcanics
		(b)	46.1	23.0	60.6	28.2	5.8	52.3	13	0.5±5.1	22.4±0.1	12.3	13.4	Volcanics
		(c)	46.1	23.0	61.1	63.4	8.3	45.8	8	0.0±7.0	57.6±14.3	13.5	14.7	Volcanics
		Mean	46.1	23.0	61.7	147.4	-	-	51	0.3	40.0	12.0	13.6	
11	(Cretaceous)		45.9	22.8	42.2	81.8	5.8	18.4	35	15.8±6.9	76.1±9.4	65.0	77.0	Volcanics
	Transylvanian Basin													
12	(Pleistocene)		46.0	25.4	64.1	3.5	4.3	60.8	19	-2.6±3.9	0.7±8.4	0.6	1.2	Volcanics
13	(Latest Miocene-Pliocene)		46.4	25.7	61.2	7.2	3.3	37.0	52	0.7±3.2	4.4±6.2	4.0	6.0	Volcanics
14	(Late Miocene)		46.8	25.1	62.3	359.3	3.9	42.4	31	-0.1±3.7	-5.9±7.5	6.5	8.5	Volcanics
15	(Middle Miocene)		47.1	23.8	56.7	67.8	8.1	18.6	3	5.2±6.8	61.8±12.4	13.0	15.0	Sediments
16	(Eocene)	(a)	46.7	23.2	38.3	82.3	6.8	128.3	2	21.7±6.6	72.9±8.9	40.0	50.0	Sediments
		(b)	47.2	23.2	35.9	87.1	9.0	16.8	17	23.3±7.8	80.7±9.9	50.0	55.0	Sediments
		Mean	46.7	24.4	53.1	101.2	-	-	21	22.5	76.8±*8.5*	19.0	22.6	
van Hinsbergen et al. (2008)														
	Balkans													
17	(Latest Oligocene-Miocene)	Suihindol	43.2	25.2	64.4	6.1	9.3	25.2	11	7.3	13.3	19.4	24.0	Volcanics
18	(Oligocene)	(a) Banichan	41.4	23.4	-57.2	160.5	37.2	7.1	4	35	45.8	28.0	29.0	Volcanics
		(b) Zvezdel	41.2	25.2	-58.1	194.2	10.4	20.2	11	9.6	13.4	31.0	33.0	Volcanics
		(c) Yabalkov	42.0	25.2	-73.2	181.5	6.5	45.1	12	4.1	12.7	31.5	35.0	Volcanics
		Mean	41.5	24.6	-62.8	178.7	-	-	9	16.2	24.0	30.2	32.3	
19	(Paleogene)	(a) Bratsigovo	41.2	24.2	-47.4	204.1	21.0	35.4	3	24.9	24.6	36.0	40.0	Volcanics
		(b) Dospat	41.4	24.1	-47.4	204.0	6.1	72.3	9	7.2	7.1	36.0	40.0	Volcanics
		Mean	41.3	24.2	-47.4	204.1	-	-	6	16.1	15.9	36.0	40.0	

Figure Table 2b.

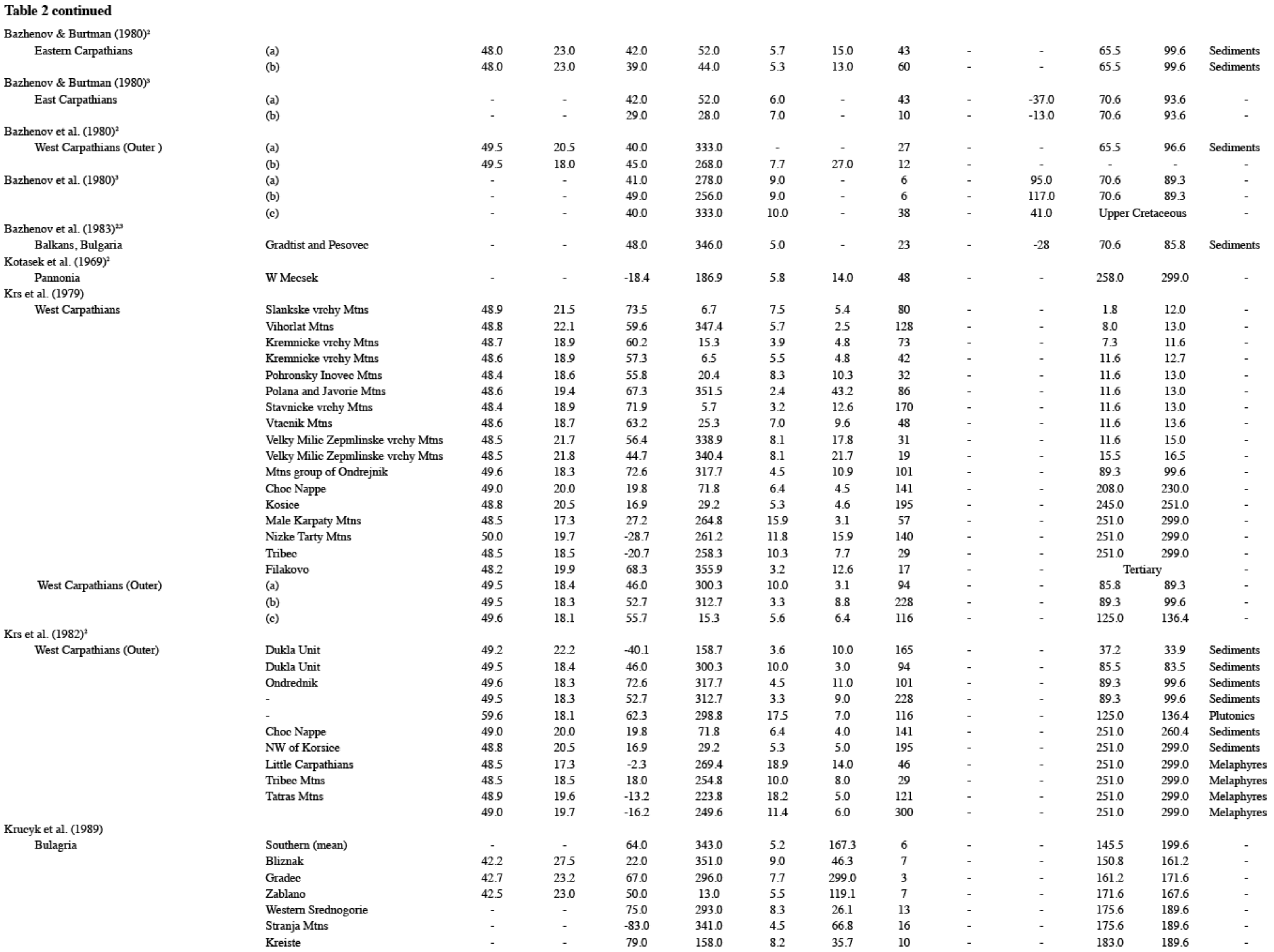


Table 2 continued

Bazhenov & Burtman (1980)[2]													
Eastern Carpathians	(a)	48.0	23.0	42.0	52.0	5.7	15.0	43	-	-	65.5	99.6	Sediments
	(b)	48.0	23.0	39.0	44.0	5.3	13.0	60	-	-	65.5	99.6	Sediments
Bazhenov & Burtman (1980)[3]													
East Carpathians	(a)	-	-	42.0	52.0	6.0	-	43	-	-37.0	70.6	93.6	-
	(b)	-	-	29.0	28.0	7.0	-	10	-	-13.0	70.6	93.6	-
Bazhenov et al. (1980)[2]													
West Carpathians (Outer)	(a)	49.5	20.5	40.0	333.0	-	-	27	-	-	65.5	96.6	Sediments
	(b)	49.5	18.0	45.0	268.0	7.7	27.0	12	-	-	-	-	-
Bazhenov et al. (1980)[3]	(a)	-	-	41.0	278.0	9.0	-	6	-	95.0	70.6	89.3	-
	(b)	-	-	49.0	256.0	9.0	-	6	-	117.0	70.6	89.3	-
	(c)	-	-	40.0	333.0	10.0	-	38	-	41.0	Upper Cretaceous		-
Bazhenov et al. (1983)[2,3]													
Balkans, Bulgaria	Gradtist and Pesovec	-	-	48.0	346.0	5.0	-	23	-	-28	70.6	85.8	Sediments
Kotasek et al. (1969)[2]													
Pannonia	W Mecsek	-	-	-18.4	186.9	5.8	14.0	48	-	-	258.0	299.0	-
Krs et al. (1979)													
West Carpathians	Slankske vrchy Mtns	48.9	21.5	73.5	6.7	7.5	5.4	80	-	-	1.8	12.0	-
	Vihorlat Mtns	48.8	22.1	59.6	347.4	5.7	2.5	128	-	-	8.0	13.0	-
	Kremnicke vrchy Mtns	48.7	18.9	60.2	15.3	3.9	4.8	73	-	-	7.3	11.6	-
	Kremnicke vrchy Mtns	48.6	18.9	57.3	6.5	5.5	4.8	42	-	-	11.6	12.7	-
	Pohronsky Inovec Mtns	48.4	18.6	55.8	20.4	8.3	10.3	32	-	-	11.6	13.0	-
	Polana and Javorie Mtns	48.6	19.4	67.3	351.5	2.4	43.2	86	-	-	11.6	13.0	-
	Stavnicke vrchy Mtns	48.4	18.9	71.9	5.7	3.2	12.6	170	-	-	11.6	13.0	-
	Vtacnik Mtns	48.6	18.7	63.2	25.3	7.0	9.6	48	-	-	11.6	13.6	-
	Velky Milic Zepmlinske vrchy Mtns	48.5	21.7	56.4	338.9	8.1	17.8	31	-	-	11.6	15.0	-
	Velky Milic Zepmlinske vrchy Mtns	48.5	21.8	44.7	340.4	8.1	21.7	19	-	-	15.5	16.5	-
	Mtns group of Ondrejnik	49.6	18.3	72.6	317.7	4.5	10.9	101	-	-	89.3	99.6	-
	Choc Nappe	49.0	20.0	19.8	71.8	6.4	4.5	141	-	-	208.0	230.0	-
	Kosice	48.8	20.5	16.9	29.2	5.3	4.6	195	-	-	245.0	251.0	-
	Male Karpaty Mtns	48.5	17.3	27.2	264.8	15.9	3.1	57	-	-	251.0	299.0	-
	Nizke Tarty Mtns	50.0	19.7	-28.7	261.2	11.8	15.9	140	-	-	251.0	299.0	-
	Tribec	48.5	18.5	-20.7	258.3	10.3	7.7	29	-	-	251.0	299.0	-
	Filakovo	48.2	19.9	68.3	355.9	3.2	12.6	17	-	-	Tertiary		-
West Carpathians (Outer)	(a)	49.5	18.4	46.0	300.3	10.0	3.1	94	-	-	85.8	89.3	-
	(b)	49.5	18.3	52.7	312.7	3.3	8.8	228	-	-	89.3	99.6	-
	(c)	49.6	18.1	55.7	15.3	5.6	6.4	116	-	-	125.0	136.4	-
Krs et al. (1982)[2]													
West Carpathians (Outer)	Dukla Unit	49.2	22.2	-40.1	158.7	3.6	10.0	165	-	-	37.2	33.9	Sediments
	Dukla Unit	49.5	18.4	46.0	300.3	10.0	3.0	94	-	-	85.5	83.5	Sediments
	Ondrednik	49.6	18.3	72.6	317.7	4.5	11.0	101	-	-	89.3	99.6	Sediments
	-	49.5	18.3	52.7	312.7	3.3	9.0	228	-	-	89.3	99.6	Sediments
	-	59.6	18.1	62.3	298.8	17.5	7.0	116	-	-	125.0	136.4	Plutonics
	Choc Nappe	49.0	20.0	19.8	71.8	6.4	4.0	141	-	-	251.0	260.4	Sediments
	NW of Korsice	48.8	20.5	16.9	29.2	5.3	5.0	195	-	-	251.0	299.0	Sediments
	Little Carpathians	48.5	17.3	-2.3	269.4	18.9	14.0	46	-	-	251.0	299.0	Melaphyres
	Tribec Mtns	48.5	18.5	18.0	254.8	10.0	8.0	29	-	-	251.0	299.0	Melaphyres
	Tatras Mtns	48.9	19.6	-13.2	223.8	18.2	5.0	121	-	-	251.0	299.0	Melaphyres
		49.0	19.7	-16.2	249.6	11.4	6.0	300	-	-	251.0	299.0	Melaphyres
Krucyk et al. (1989)													
Bulagria	Southern (mean)	-	-	64.0	343.0	5.2	167.3	6	-	-	145.5	199.6	-
	Bliznak	42.2	27.5	22.0	351.0	9.0	46.3	7	-	-	150.8	161.2	-
	Gradec	42.7	23.2	67.0	296.0	7.7	299.0	3	-	-	161.2	171.6	-
	Zablano	42.5	23.0	50.0	13.0	5.5	119.1	7	-	-	171.6	167.6	-
	Western Srednogorie	-	-	75.0	293.0	8.3	26.1	13	-	-	175.6	189.6	-
	Stranja Mtns	-	-	-83.0	341.0	4.5	66.8	16	-	-	175.6	189.6	-
	Kreiste	-	-	79.0	158.0	8.2	35.7	10	-	-	183.0	189.6	-

Figure Table 2c.

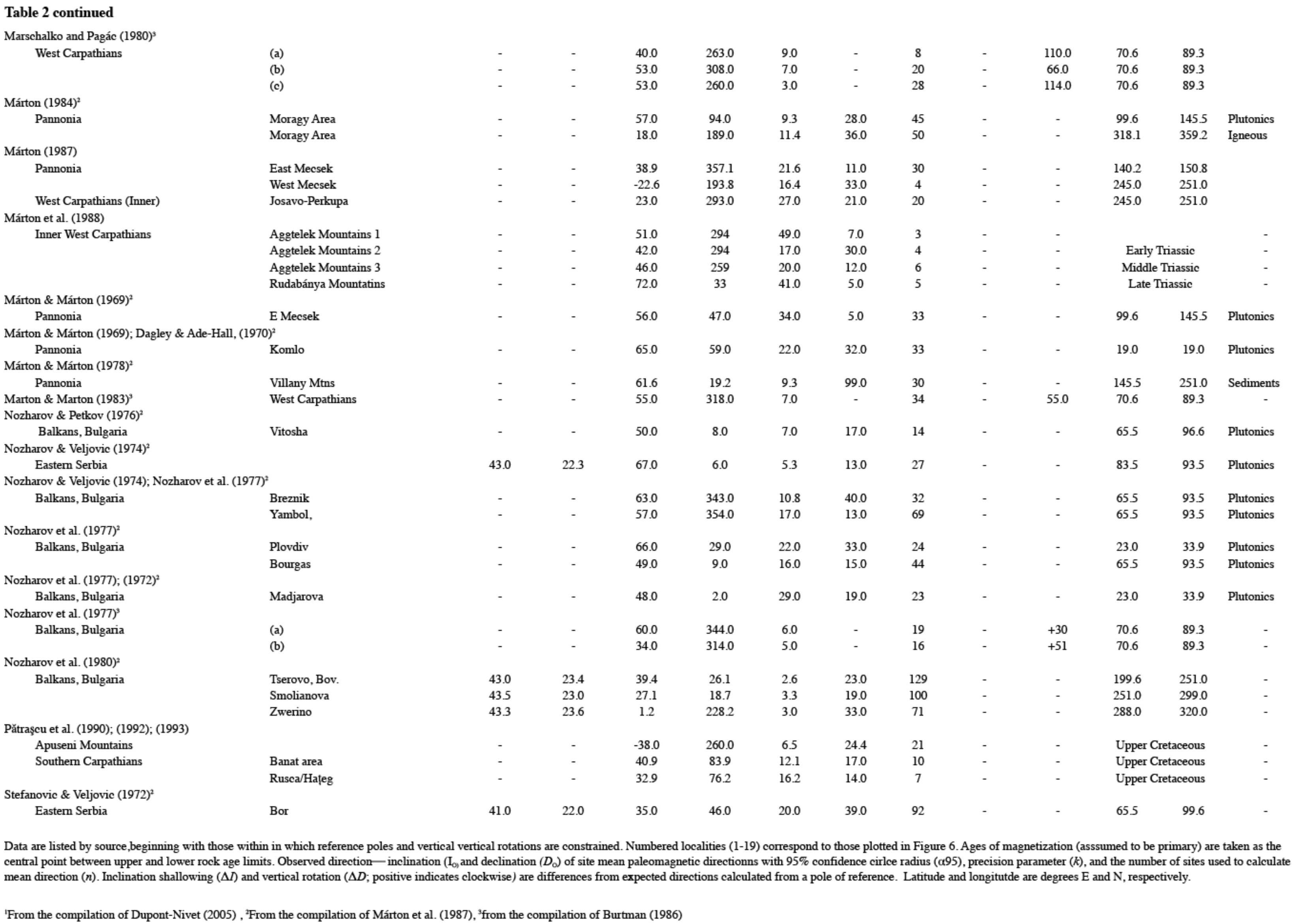


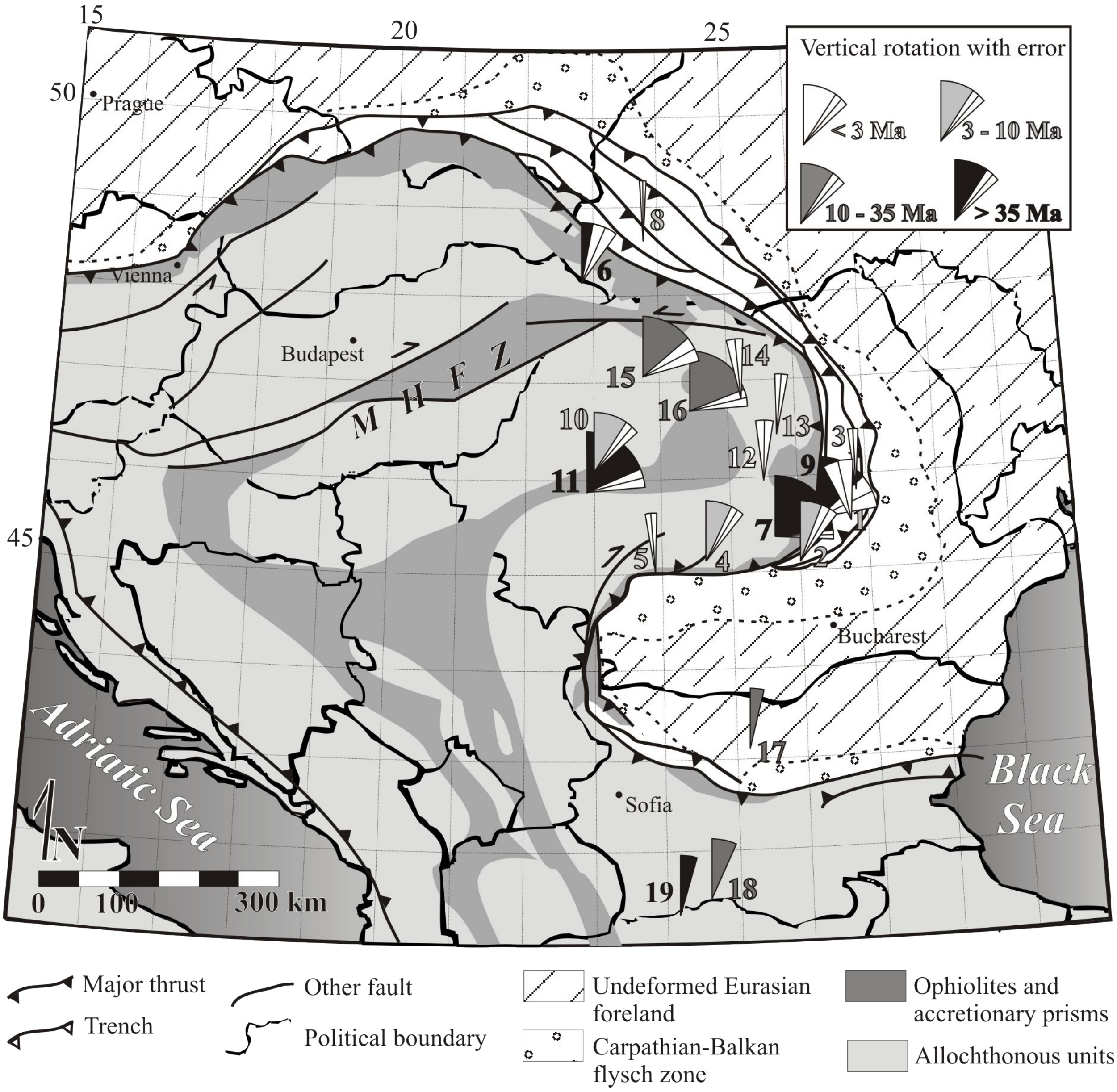
Table 2 continued

Marschalko and Pagác (1980)[3]													
West Carpathians	(a)	-	-	40.0	263.0	9.0	-	8	-	110.0	70.6	89.3	
	(b)	-	-	53.0	308.0	7.0	-	20	-	66.0	70.6	89.3	
	(c)	-	-	53.0	260.0	3.0	-	28	-	114.0	70.6	89.3	
Márton (1984)[2]													
Pannonia	Moragy Area	-	-	57.0	94.0	9.3	28.0	45	-	-	99.6	145.5	Plutonics
	Moragy Area	-	-	18.0	189.0	11.4	36.0	50	-	-	318.1	359.2	Igneous
Márton (1987)													
Pannonia	East Mecsek	-	-	38.9	357.1	21.6	11.0	30	-	-	140.2	150.8	
	West Mecsek	-	-	-22.6	193.8	16.4	33.0	4	-	-	245.0	251.0	
West Carpathians (Inner)	Josavo-Perkupa	-	-	23.0	293.0	27.0	21.0	20	-	-	245.0	251.0	
Márton et al. (1988)													
Inner West Carpathians	Aggtelek Mountains 1	-	-	51.0	294	49.0	7.0	3	-	-			-
	Aggtelek Mountains 2	-	-	42.0	294	17.0	30.0	4	-	-	Early Triassic		-
	Aggtelek Mountains 3	-	-	46.0	259	20.0	12.0	6	-	-	Middle Triassic		-
	Rudabánya Moutatins	-	-	72.0	33	41.0	5.0	5	-	-	Late Triassic		-
Márton & Márton (1969)[2]													
Pannonia	E Mecsek	-	-	56.0	47.0	34.0	5.0	33	-	-	99.6	145.5	Plutonics
Márton & Márton (1969); Dagley & Ade-Hall, (1970)[2]													
Pannonia	Komlo	-	-	65.0	59.0	22.0	32.0	33	-	-	19.0	19.0	Plutonics
Márton & Márton (1978)[2]													
Pannonia	Villany Mtns	-	-	61.6	19.2	9.3	99.0	30	-	-	145.5	251.0	Sediments
Marton & Marton (1983)[3]	West Carpathians	-	-	55.0	318.0	7.0	-	34	-	55.0	70.6	89.3	-
Nozharov & Petkov (1976)[2]													
Balkans, Bulgaria	Vitosha	-	-	50.0	8.0	7.0	17.0	14	-	-	65.5	96.6	Plutonics
Nozharov & Veljovic (1974)[2]													
Eastern Serbia		43.0	22.3	67.0	6.0	5.3	13.0	27	-	-	83.5	93.5	Plutonics
Nozharov & Veljovic (1974); Nozharov et al. (1977)[2]													
Balkans, Bulgaria	Breznik	-	-	63.0	343.0	10.8	40.0	32	-	-	65.5	93.5	Plutonics
	Yambol,	-	-	57.0	354.0	17.0	13.0	69	-	-	65.5	93.5	Plutonics
Nozharov et al. (1977)[2]													
Balkans, Bulgaria	Plovdiv	-	-	66.0	29.0	22.0	33.0	24	-	-	23.0	33.9	Plutonics
	Bourgas	-	-	49.0	9.0	16.0	15.0	44	-	-	65.5	93.5	Plutonics
Nozharov et al. (1977); (1972)[2]													
Balkans, Bulgaria	Madjarova	-	-	48.0	2.0	29.0	19.0	23	-	-	23.0	33.9	Plutonics
Nozharov et al. (1977)[3]													
Balkans, Bulgaria	(a)	-	-	60.0	344.0	6.0	-	19	-	+30	70.6	89.3	-
	(b)	-	-	34.0	314.0	5.0	-	16	-	+51	70.6	89.3	-
Nozharov et al. (1980)[2]													
Balkans, Bulgaria	Tserovo, Bov.	43.0	23.4	39.4	26.1	2.6	23.0	129	-	-	199.6	251.0	-
	Smolianova	43.5	23.0	27.1	18.7	3.3	19.0	100	-	-	251.0	299.0	-
	Zwerino	43.3	23.6	1.2	228.2	3.0	33.0	71	-	-	288.0	320.0	-
Pătraşcu et al. (1990); (1992); (1993)													
Apuseni Mountains		-	-	-38.0	260.0	6.5	24.4	21	-	-	Upper Cretaceous		-
Southern Carpathians	Banat area	-	-	40.9	83.9	12.1	17.0	10	-	-	Upper Cretaceous		-
	Rusca/Haţeg	-	-	32.9	76.2	16.2	14.0	7	-	-	Upper Cretaceous		-
Stefanovic & Veljovic (1972)[2]													
Eastern Serbia	Bor	41.0	22.0	35.0	46.0	20.0	39.0	92	-	-	65.5	99.6	-

Data are listed by source,beginning with those within in which reference poles and vertical vertical rotations are constrained. Numbered localities (1-19) correspond to those plotted in Figure 6. Ages of magnetization (asssumed to be primary) are taken as the central point between upper and lower rock age limits. Observed direction— inclination (I_O, and declination (D_O) of site mean paleomagnetic directionns with 95% confidence cirlce radius (α95), precision parameter (*k*), and the number of sites used to calculate mean direction (*n*). Inclination shallowing (ΔI) and vertical rotation (ΔD; positive indicates clockwise) are differences from expected directions calculated from a pole of reference. Latitude and longitutde are degrees E and N, respectively.

[1] From the compilation of Dupont-Nivet (2005) , [2] From the compilation of Márton et al. (1987), [3] from the compilation of Burtman (1986)

Figure 5.



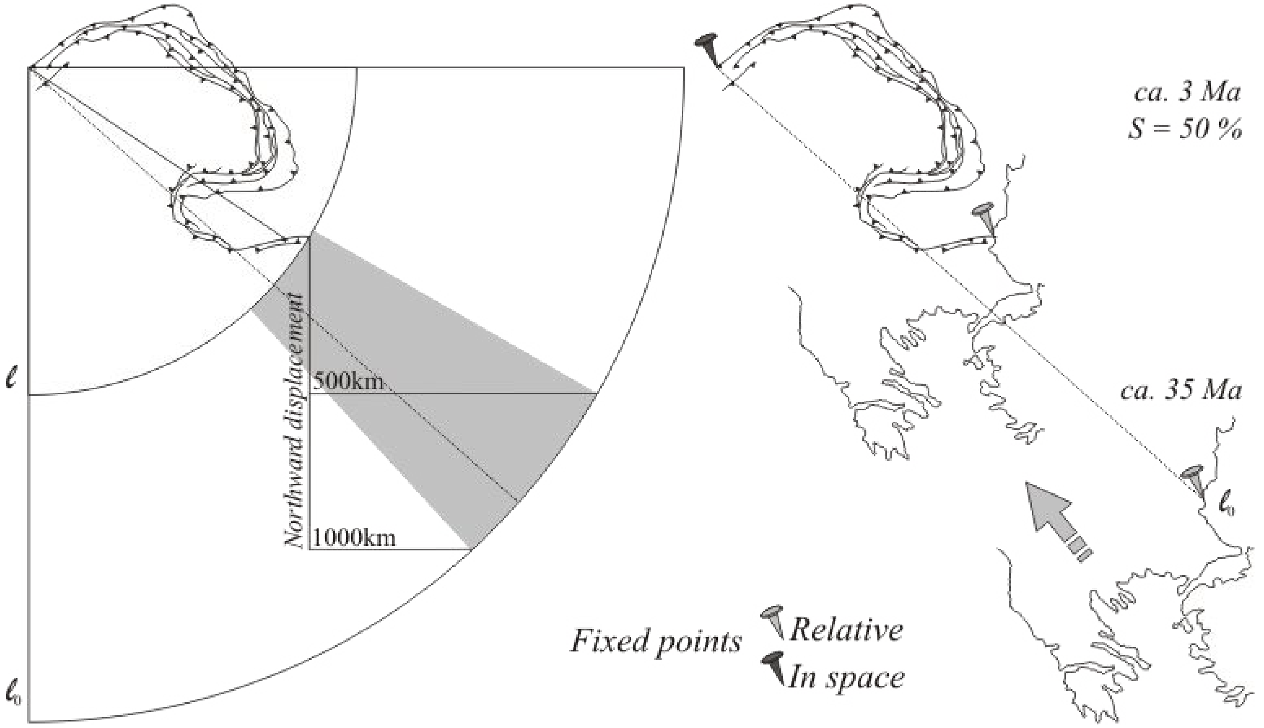
Vertical rotation data from the compilations of Dupont-Nivet *et al.* (2005) and van Hinsbergen (2008) show a general pattern of increasing rotation with increasing age. Site numbers correspond to those listed in Table 2. Note (1) sites with small rotations and small errors (5, 8, 12-14) and (2) error range is not plotted where not included or accurately inferable from data source (sites 17-19).

The pattern that emerges in the Carpathians is consistent with the arcuate geometry of the chain being the result of significant rotations about a vertical axis (some > 90°). In addition, the magnitudes of rotation increase with increasing magnetization age; 35+ Ma magnetizations yield the largest rotations while younger rocks yield smaller rotations. Sampling is biased toward the southern limb of the bend, for which exclusively clockwise rotations are recorded, consistent with the expected sense of rotation should the arcuate nature of the Carpathians have resulted from buckling of a previously linear orogen. In the Balkan region, data are sparse and assessments of data error are lacking. Reported rotations are small, variable, and do not provide a test of the origin of the Balkan segment of the orogen.

A Geometric model for eastern Mediterranean crustal displacement and oroclinal buckling in the Carpathian – Balkan belt

We have established that (1) the arcuate Carpathian – Balkan segment of the Alpine orogenic belt likely originated as a linear orogen which was subsequently buckled to yield a Z-shaped geometry oroclinal pair, (2) orocline formation probably occurred after 35 Ma, and (3) the EMIA is attributable to a minimum 500, but more likely 1000 km of northward translation of the Eastern Mediterranean region between 33 and 3 Ma. Hence, oroclinal bending of the Carpathian – Balkan orogen was coeval with northward translation of the eastern Mediterranean, suggesting that the two may be related. Here we provide a simple geometric test of a model in which buckling of the Carpathian – Balkan chain is explained as a result of northward translation of the Eastern Mediterranean region.

Figure 6.



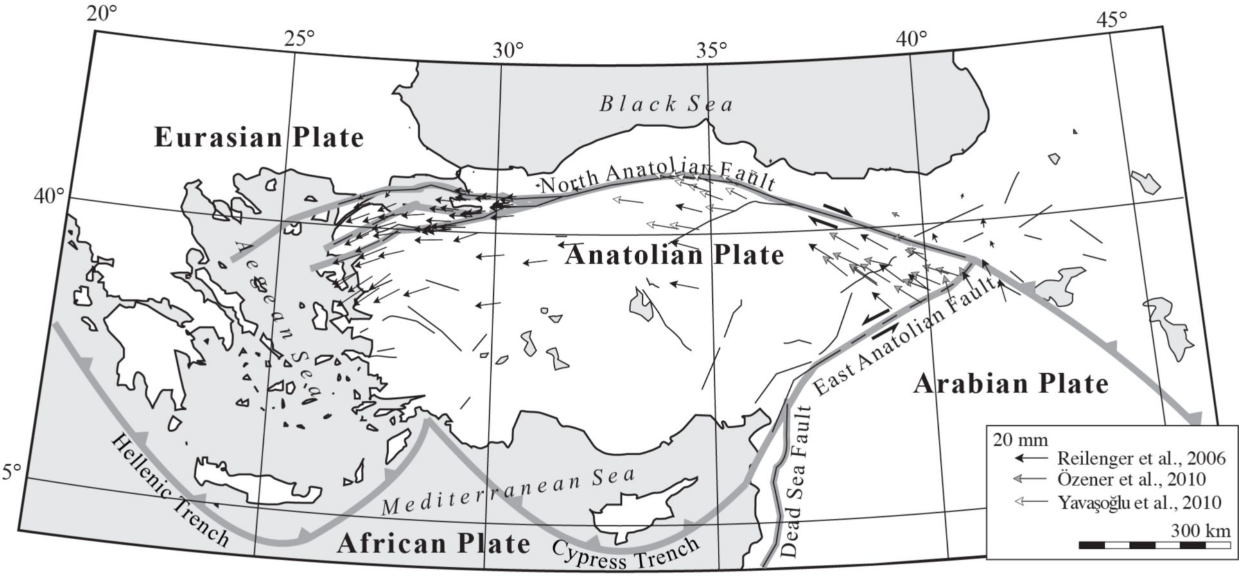
Geometric model showing 50% shortening of the Carpathian-Balkan orogen with a fixed northwest corner reveals the necessity for a component of latitudinal displacement of the Aegean. Length of originally linear orogen (l_0) = 2100 km; current length of orogen (l) measured linearly from northeast to southwest endpoint = 1050 km. The shaded region represents possible pathways of a point marking the southeastern end of the orogen starting along an arc of radius l_0 between 500 km and 1000 km vertical distance from its current location. The dashed line illustrates one potential geometry for the originally linear orogen.

We assume (1) an originally linear Carpathian – Balkan orogen with a northeastern end point fixed to autochthonous Europe just east of Vienna, Austria, and a southeastern endpoint fixed to the Eastern Mediterranean crustal block where the Balkans meet the western limit of the Black Sea, and (2) that a rigidly behaving Eastern Mediterranean crustal block originated between 500 and 1000 km south of its present-day location. The strike-parallel line length of the Carpathian – Balkan chain, measured from pinning point to pinning point (l_0) is 2100 km, contrasting with the 1050 km linear distance between the two points measured today (l_f); 50% shortening is therefore required in order to explain the bends as a product of an originally linear orogen. Our model demonstrates that 500 to 1000 km northward displacement of the eastern Mediterranean can be accommodated by 50% shortening of an originally Carpathian – Balkan orogen if (1) the orogen had an initial northwest-southeast strike (310-330°)

and (2) northward displacement of the eastern Mediterranean was coupled with a westward component of latitudinal displacement (Fig. 6).

Net displacement of the eastern Mediterranean is equivalent to the 1050 km line length difference between the initial linear and final buckled Carpathian – Balkan belt. Assuming the same 30 My time window for displacement, a recalculated required rate of translation remains a reasonable 3.5 cm·yr^{-1}. The perfect linearity of an unbuckled Carpathian – Balkan orogen depicted in this idealized model presents an end-member extreme. A gentle curvature inherent in the belt may have facilitated oroclinal buckling and enabled its achievement through a lesser extent of total displacement within the orogen and of the impeding Eastern Mediterranean region. Younging of the youngest deformation toward the SE in the Outer Carpathians (e.g Sperner *et al.*, 2002; Zattin *et al.*, 2011) may indicate that oroclinal buckling originated to the northwest and progressed to the southeast. As with most documented oroclines, there is little evidence for regional strain associated with buckling within the Carpathian – Balkan system, suggesting that buckling must have been accommodated along existing planes of weakness (Johnston, 2001, Weil *et al.*, 2000, Weil & Sussman, 2004, Shaw *et al.*, 2012).

Figure 7.



Tectonic setting for the Turkey and surrounding regions. GPS vector data along the North Anatolian fault zone show current westward motion (with a component of anticlockwise rotation) of the Anatolian plate. Thin black lines are active faults; thick grey lines are plate boundaries. Redrawn from Tartar *et al.* (2012) figures 1 and 2.

A latitude-parallel component of eastern Mediterranean displacement would not be visible in the paleomagnetic record, but is consistent with observed and ongoing westward displacement of the Anatolian block (Turkey). Westward directed tectonic escape of the Anatolian block out of the Arabian – Eurasian collision zone likely began in the mid-Miocene (Atzemoglou *et al.*, 1994), and continues into the present day at an average rate of 2 cm·yr^{-1} (Fig. 7) (Tartar *et al.*, 2012). Our model thus suggests that the Z-shaped geometry of the Carpathian – Balkan belt is explained as a result of westward tectonic escape of the Aegean – Anatolian region out of the Arabian – Eurasian collision zone coupled with a component of northward translation. Palinspastic restoration of the Carpathian – Balkan oroclines therefore restores Anatolia 500 to 1000 km to the east, and confirms that westward tectonic escape of Anatolia has been ongoing since at least the mid-Miocene, as suggested by Atzemoglou (1994). As the Arabian – Eurasian collision and related tectonic escape is ongoing, further study of the Carpathian – Balkan belt in the context of an oroclinal model may aid in determining how such large-scale features are accommodated within the surrounding lithosphere and at depth.

Conclusions

Interpretation of the Z-shaped bend geometry of the Carpathian – Balkan orogenic belt as being oroclinal in origin is supported by 1) the continuity of accreted terranes about both bends, 2) variance in structural vergence as a function of change in orogenic strike, and 3) space constraints imposed by issues associated with palinspastic restoration of orogenic shortening with the belt in its current geometry. A classic paleomagnetic orocline test cannot be applied to the Carpathian – Balkan belt given the currently available paleomagnetic data. However, available declination data show that large age progressive vertical rotations in the southern limb of the Carpathian bend 1) are consistent with it having originally been linear and 2) demonstrate that rotation was coeval with significant Late Eocene to Pliocene northward displacement of the Eastern Mediterranean region. A simple geometric model establishes that just over 1000 km northwestward displacement of the eastern Mediterranean at a modest rate of 3.5 cm·yr^{-1} can be accommodated by an equivalent amount of shortening through oroclinal buckling of an originally linear northwest-southeast striking Carpathian – Balkan orogen. The latitudinal component of eastern Mediterranean displacement is explained by ongoing westward tectonic escape of the Aegean – Anatolian block out of the Arabian – Eurasian collision zone, suggesting that that Carpathian – Balkan oroclines provide a record crustal scale deformation associated with continental escape out of an active collision zone.

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