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PALEOMAGNETIC RESULTS FROM ALBANIA AND THEIR SIGNIFICANCE FOR THE GEODYNAMIC EVOLUTION OF THE DINARIDES, ALBANIDES AND HELLENIDES

H. Mauritsch*, R. Scholger* and S. Bushati**

ABSTRACT

Mesozoic and Cenozoic rocks were studied throughout whole Albania, covering the major tectonic units beginning with the Albanian Alps in the North, the Ionian - Kruja- and Cucali Krasta zone as well as the Sazan zone in the South. Stable characteristic remanent magnetizations, proved by laboratory- and field-tests, are obtained for Upper Triassic up to Tortonian. These directions indicate a general clockwise rotation of post-Tortonian age, but also give rise for individual movements of the Ionian-, Kruja- and the Cukali-Krasta-zone, respectively. The transition of the counterclockwise rotation in the Dinarides and the clockwise rotation in the Albanides-Hellenides is concluded to be the result of block rotation between large transverse fault zones (Split-Sarajewo-Shkoder-Pec-line).

INTRODUCTION

Since the early seventies a number of investigators compiled paleomagnetic data from the Mediterranean in order to describe and discriminate areas with unique rotation senses (Channel et al., 1979; Lowrie, 1986; Lowrie and Alvarez, 1975; Marton, 1987; Mauritsch and Becke, 1987; Van den Berg et.al., 1978; Westphal et.al., 1986). These papers lead to a central realm of counterclockwise (CCW) rotations relative to present North, called the Adriatic plate. In the Eastern Alps and in the transition zone from the Dinarides into the Albanides - Hellenides abrupt changes of this regime were found. Whereas in the Dinarides CCW rotations are reported (Marton and Veljovic, 1983; Marton, 1987; E. Marton, pers. commun., 1993), clockwise (CW) rotations were found in the Hellenides (Laj et.al., 1982; Horner and Freeman, 1983; Kissel et.al., 1985; Marton et.al., 1990). In two investigations in Albania (Mauritsch et.al., 1991; Speranza et.al., 1992) the overall CW rotation of the Hellenides was demonstrated for the Albanides as well. The paleomagnetic directions are of Upper Cretaceous and Cenozoic age and belong to the Ionian zone, the Kruja zone (the equivalent to the Gavrovo-Tripolitza zone) and the Cukali - Krasta zone (the equivalent of the Pindos zone in Greece). The age of the rotation agrees with observations from Greece. The youngest CW rotation was found in the Inner Albanides in Upper Pliocene marls near Korca (Table 1). This CW rotation can be noticed throughout the Albanides and Hellenides, as well as the Circum Rhodope - and the Serbo-Macedonian massif (Kondopoulou, 1986; Pavlides et.al., 1988; Edel et.al., 1992). This general CW rotation is in good agreement with

* Geophysical Institute, Mining University, Franz-Josef-Str. 18, A-8700 Leoben (Austria)
** Geophysical Enterprise Tirane, Blloku „Vasil Shanto" L. 9, Tirane (Albania)

the sense and the age of rotations estimated from the geological reconstructions after Aubouin (1976) and Le Pichon and Angelier (1979).

Two phases of orogeny are reported in the Inner Albanides (Upper Jurassic and Upper Cretaceous), while in the Outer Albanides three phases are evident in Upper Liassic, Lower Miocene and Middle to Upper Miocene (Jacobshagen et.al., 1978; Melo and Aliaj, 1980; Pumo et.al., 1981; Thorbecke, 1987). The identification of these tectonic phases is the main target of this study.

GEOLOGICAL SETTING AND SAMPLING

The area under investigation constitutes the three major tectonic units, the Ionian, Kruja and Cucali-Krasta zone. To the west, the Ionian zone is overthrusting the Preapulian foreland, whereas in the east it is overthrusted by the Kruja-zone and the Cukali-Krasta zone. The tectonic features and the lithofacies development support the Ionian-zone as being remnants of a miogeosynclinal area. Two major tectonic events, in the Lower Miocene and Middle to Upper Miocene transformed the geosynclinal development into an intensive folded zone. Mainly carbonatic rocks build up the Mesozoic overlying Permian-Lower Triassic evaporites. In the Oligocene the sedimentation of terrigenous flysch starts and continues up to Lower Miocene. These sediments are overlain by a molasse formation of the pre-Adriatic depression, comprising Middle and Upper Miocene. At the margins of the depression, the Tortonian rests with angular unconformity on older formations (Melo and Aliaj, 1980).

The objective of this study was to complete the information about the geodynamic evolution of Albania presented by Mauritsch et al. (1991), which was based on northern and middle Albanian paleomagnetic data of Mesozoic and Cenozoic rocks, sampled in 1989. In the southernmost part of Albania, different nappes of the Outer Albanides contain sediments from Permo-Triassic to Quarternary, predominantly in carbonaceous facies. A nappe- and fold structure with an overall north-northwest (NNW) strike enables the application of paleomagnetic fold tests within sites, as well as on a regional scale.

In order to identify possible individual rotations of the nappes, a few Lower and Upper Cretaceous sites were sampled in the Ionian tectonic zone near Saranda as well as a Paleogene locality in the upper tectonic unit near Selcke (Fig. 1.).

The sampling was carried out by drilling cores and orientation with standard paleomagnetic techniques, except of the three localities near Delvine, where a number of oriented hand samples were taken.

The bedding planes observed in the sites for tilt correction scatter around a 60 degree declination of azimuth with various inclinations, corresponding to the regional structures. The overall fold axis obtained from this planes by fabric analysis is subhorizontal with a NNW alignment, thus enabling the use of simple tilt correction for the paleomagnetic data.

ROCKMAGNETIC INVESTIGATIONS

Within each locality, two or more samples were chosen for either thermal or alternating field demagnetization, in order to study the stability of different components of the natural remanent magnetization (NRM). Additionally, the isothermal remanent magnetization (IRM) was observed before and after thermal treatment. All measurements were carried out in the paleomagnetic laboratory of the Mining University in Gams using a 2G three-axis cryogenic magnetometer.

The demagnetization paths of both thermal and alternating-field treatment show in most of the samples a single stable characteristic remanence vector after a few cleaning steps (Fig. 2.), whereas in some other samples a

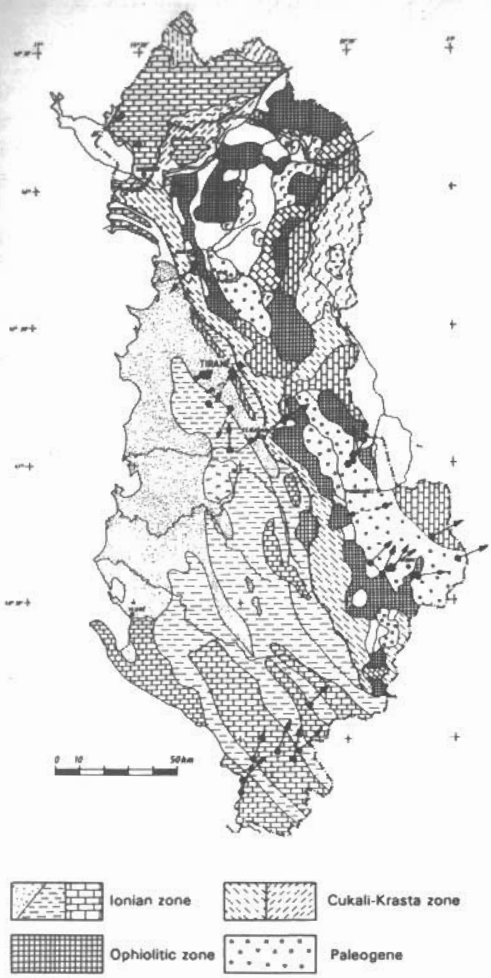


Fig.1: Generalized geological map of Albania showin the position and direction of the average paleomgagnetic directions.

demagnetization plane of two antipodal directions can be obtained (Fig. 2.a).

This was also described by Speranza et al. (1992). After cleaning additional samples of the same site, a paleomagnetic direction can then be calculated as the intersection of the demagnetization planes, presented as great circles in an equal-area projection (Fig. 3). These calculated directions, as well as the stable end directions after the different demagnetization methods correspond for equivalent samples. An exception are the Triassic localities, where just stable end directions appear; in all other localities both behaviours occur.

Stepwise acquisition of IRM gives evidence for a magnetite-dominated magnetic phase in the majority of the samples (Fig. 4.b-d), while the presence of haematite is only significant in the Paleogene near Selcke (Fig. 4.a). Nevertheless, a small contribution of a higher coercive phase, probably haematite, can be observed in several sites (Fig. 4.c). IRM-acquisition experiments were carried out in the natural stage and after heating to 150°C in order to identify the presence of Ironhydroxide. In a large number of samples heating to 150°C or more causes a significantly different behaviour in the IRM acquisition, particular in the Triassic limestones (Fig. 4.d). This is most probably due to a change from goethite to magnetite by dehydration.

On a set of powdered samples, representing the different rock types, hysteresis experiments on a new balance system at the University of Munich were carried out by T. von Dobeneck. By analysing the hysteresis loop between -300 and +300 mT and using spectral analysis, pyroclastic magnetite was established in a mainly single domain particle size.

Measurements of low field susceptibility produced a weak, predominantly diamagnetic bulk susceptibility for the majority of the samples, indicating a limited „ferromagnetic" content in the mineral assemblage. This corresponds to the weak NRM intensities in the range of 2.10^{-4} A/m.

PALEOMAGNETIC RESULTS

All samples of Paleogene age were stepwise thermally demagnetized. The

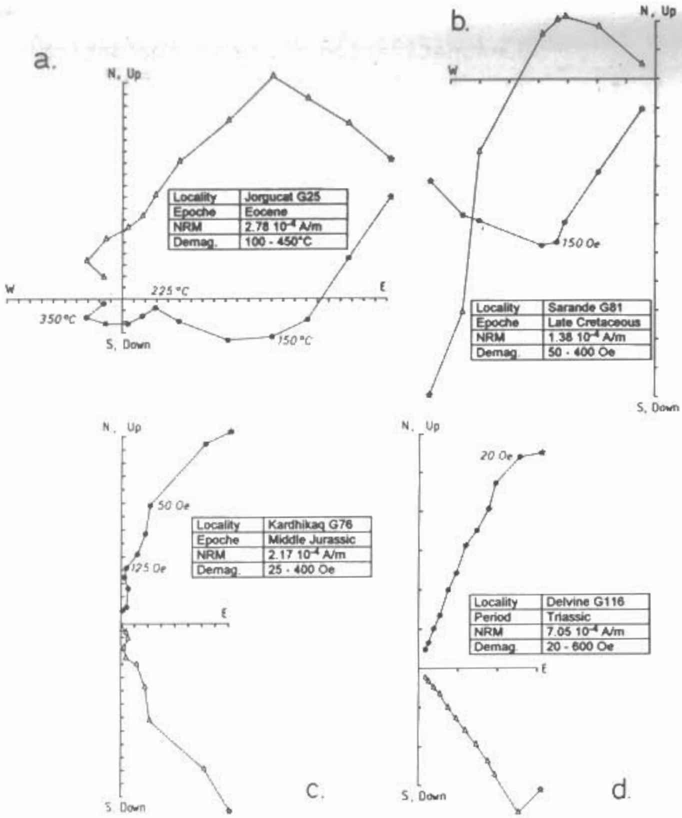


Fig.2: Thermal and alternating-field demagnetization diagrams in orthogonal projection. Tilt corrected. Circles and triangles represent projection on the horizontal and vertical planes (from Mauritsch et al. 1994)

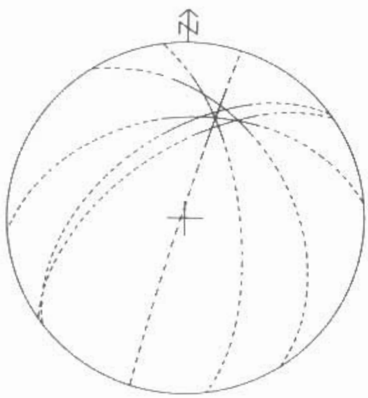


Fig.3: Demagnetization planes obtained from 6 Lower Jurassic samples. Equal-area projection.

Mesozoic samples were selected individually for thermal or alternating field treatment based on natural remanent intensity and mechanical condition (part of the micritic limestones exploded during heating at about 300°C). The characteristic remanent magnetization (ChRM) directions for single samples were calculated using principal component analyses (Kirschvink, 1980). Mean values for sites and localities were calculated following Fisher (1953).

Two fold tests were possible in the Paleogene of Selcke and one in the Maastrichtian of Grapsh. The a_{95} confidence cone of the mean direction is significantly smaller after unfolding by tilt correction (Fig. 5.a). All of them pass the statistical tests at a 95% significance level (McElhinny, 1964; McFadden and Jones, 1981; McFadden, 1990). Within localities of diverse bedding, the scatter of corresponding site mean directions also decreases significantly after tilt correction (Fig. 5., Table 1).

The Paleogene locality near Selcke shows several indicators for the reliabilty of the paleomagnetic data: Two positive fold tests, visualized in Fig. 5.a by a decrease of the confidence cones of the site mean directions, a distinct decrease of the overall confidence cone of the locality (a_{95} = 22.1° before and 8.6° after correction; Table 1.; Fig. 6.a) and the occurrence of a perfectly antipodal direction after tilt correction (Fig. 5.a). The effect of tilt correction is smaller in the Eocene locality of the second tectonic unit, because of uniform bedding pattern (Fig. 5.b). Here the reverse po-

Table 1: Compiled paleomagnetic data from Albania

Stratigraphic age	Age (My)	Rock unit	N	D/I_{ac}	a_{95}
Tortonian	7- 10	Outer Albanides	7	32/40	7.7
Tortonian	7- 10	Inner Albanides	3	40/38	10.9
Chattian	23- 29	Inner Albanides	11	40/44	8.6
Oligocene	23- 35	Outer Albanides	3	42/28	29.4
Paleogene	23- 65	Outer Albanides	5	39/34	8.6
Eocene	35- 56	Inner Albanides	5	57/43	19.5
Eocene	35- 56	Outer Albanides	10	43/38	5.5
Eocene	35- 56	Outer Albanides	11	43/39	4.0
Maastrichtian	65- 74	Outer Albanides	14	36/43	8.7
Maastrichtian	65- 74	Outer Albanides	3	34/33	26.2
Upper Cretaceous	65- 97	Outer Albanides	5	49/41	10.1
Upper Cretaceous	65- 97	Outer Albanides	3	37/28	7.4
Campanian	74- 83	Outer Albanides	5	39/30	6.5
Coniacian	87- 89	Outer Albanides	6	32/38	7.1
Cenomanian	90- 97	Inner Albanides	2	43/22	11.3
Lower Cretaceous	97-146	Albanian Alps	7	51/35	9.9
Lower Cretaceous	97-146	Outer Albanides	3	3/36	22.2
Tithonian	146-152	Inner Albanides	7	50/41	7.0
Tithonian	146-152	Outer Albanides	4	29/29	15.9
Middle Jurassic	157-178	Outer Albanides	7	6/46	8.9
Lower/Middle Jurassic Jurassic	178	Outer Albanides	4	18/37	2.9
Lower Jurassic	178-208	Outer Albanides	10	26/42	7.4
Upper Triassic	208-235	Outer Albanides	6	20/23	4.8

Ages taken from Harland et al. (1990), rounded. N: number of sites.
D/I_{ac}: characteristic remanence direction after tilt correction.
References are: (1) MAURITSCH (1993); (2) this paper; (3) SPERANZA et al. (1992).

larity is dominant, but antipodal normal polarity also occurs. The mean directions in both Paleogene localities of different tectonic units indicate a clockwise rotation of 39° or 43° respectively, relative to the recent magnetic north direction (Table 1., Fig. 6a). The overall mean for the two localities gives a paleomagnetic direction for the Paleogene age group of D= 42° and I= 37°, defined by 15 sites with an a_{95} = 4.4° (Table 1).

The Upper Cretaceous localities 3 to 5 on the eastern flank of the Mali i Gjere structure produce undistinguishable results between Maastrichtian, Campanian and Coniacian paleomagnetic directions, with evidence for clockwise rotation too (Fig 5.c). The data are supported by a positive fold test in the Maastrichtian. These localities can be combined with the Upper Cretaceous in the southernmost tectonic unit near Sarande (locality 16) to a clearly positive fold test at a regional scale (Fig. 6.b). Consequently, we comprise the time span from Maastrichtian to Coniacian, leading to a paleomagnetic direction for the Upper Cretaceous of D = 35° and I = 33°, based on 17 sites with a_{95} = 4.4° (Table 1). Following the data presented above, no significiant rotations took place between Upper Cretaceous and Paleogene.

Lower Cretaceous data differ substantially from those presented above. The Neocomian samples which were collected at the Muzine pass in a strongly tectonized site, displayed well defined remagnetization circles. Their subparallel orientation does not allow the computation of a statistically significant

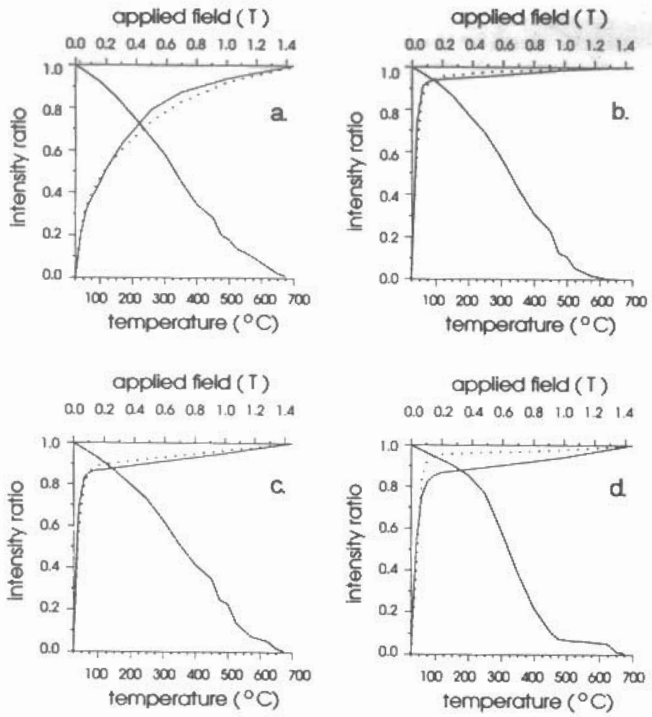


Fig.4: Stepwise accquisition of isothermal remanent magnetization (IRM) and subsequent thermal demagnetization of IRM for samples of different age. (a) Paleogene, (b) Coniacian, (c) Tithonian, (d) Triassic, Dotted curves represent IRM after thermal treatment at 150°C or more.

direction but defines an average plane. By combination of principal component analysis with the remagnetization planes, the site mean of 6 samples with an a_{95} = 13.0° was obtained. In contrast to this, the Lower Cretaceous of Cuke (locality 17) contained mainly stable characteristic magnetization components (Fig. 3.d), but produced comparably scattered directions, resulting in an a_{95} confidence cone of 22.2° for the locality mean (Table 2). While this direction (D =3°; I = 36°) fits better into the general view, the Neocomian of Muzine appears to be influenced by local tectonics.

The Jurassic data are of different quality, but homogeneous in their paleomagnetic setting. The majority of the observed directions are in normal polarity, only in the Tithonian sites both normal and reverse polarities are seen (Fig. 5.d).

The locality mean directions show a slight discrimination throughout the Jurassic epochs (Table 2; Fig. 6.c). Besides the above mentioned Tithonian, a

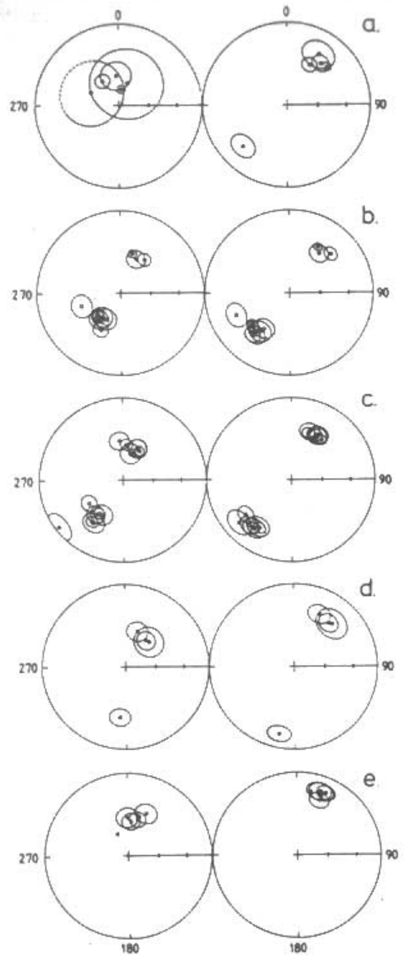
Table 2: Age group mean directions

Age group	N	D/I_{bc}	a_{95}	K	D/I_{ac}	a_{95}	K	Pole Lat°N/ Long°E
Paleogene	15	33/61	8.5	21.3	42/37	4.4	77.3	49/126
Upper Cretaceous	17	33/43	10.1	13.6	35/33	4.4	66.6	53/136
Middle Jurassic	7	346/50	9.5	41.3	6/46	8.9	47.0	76/177
Lower/Middle Jurassic	4	13/48	4.2	336.5	18/37	2.9	678.4	65/156
Lower Jurassic	10	4/55	10.8	20.9	26/42	7.4	43.4	63/138
Upper Triassic	6	8/54	10.0	46.2	20/23	4.8	198.9	57/162

N (S): number of sites (samples). nor/rev: number of sites in normal / reverse polarity.

D/I_{bc} : characteristic remanence direction before tilt correction.

D/I_{ac} : after tilt correction.



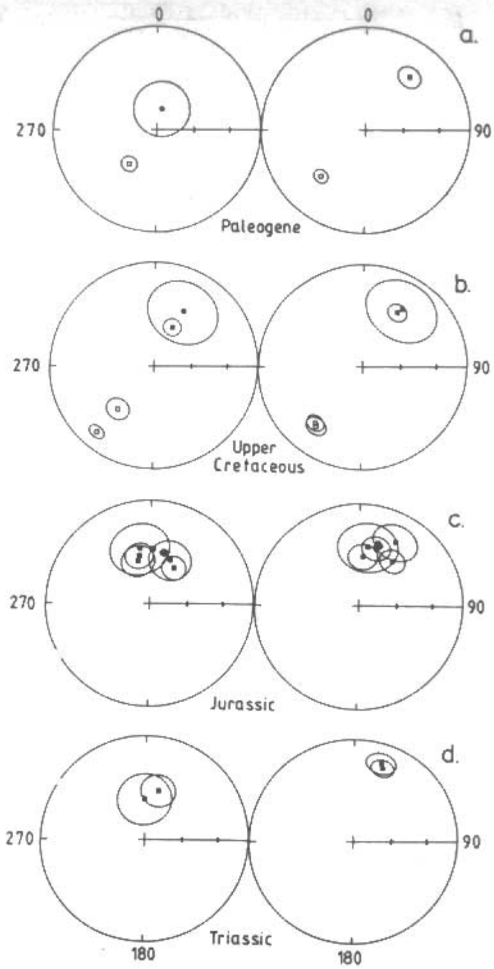


Fig.5: Site mean directions with α_{95} confidence circles before (left) and after (right) tilt correction. Equal-area projection with full symbols for lower hemisphere and open symbols for upper hemisphere. (a) site group 1 (Paleogene) including two fold tests. (b) site group 2 (Eocene). (c) site groups 3-5 (Maastrichtian, Campanian, Coniacian) including a fold test. (d) site group 7 (Tithonian). (e) site groups 14-15 (Upper Triassic).

Fig.6: Locality mean directions with α_{95} confidence circles before (left) and after (right) tilt correction. Equal-area projection with full symbols for lower hemisphere and open symbols for upper hemisphere. (a), (b) and (d) show concentration within the Paleogene, Upper Cretaceous and Triassic age group, respectively. (c) Jurassic.

Middle Jurassic mean direction of D = 6° and I = 46°, a Lower/Middle Jurassic boundary direction of D = 18° and I = 37°, and finally a Lower Jurassic direction of D = 26° and I = 42° can be subdivided, representing

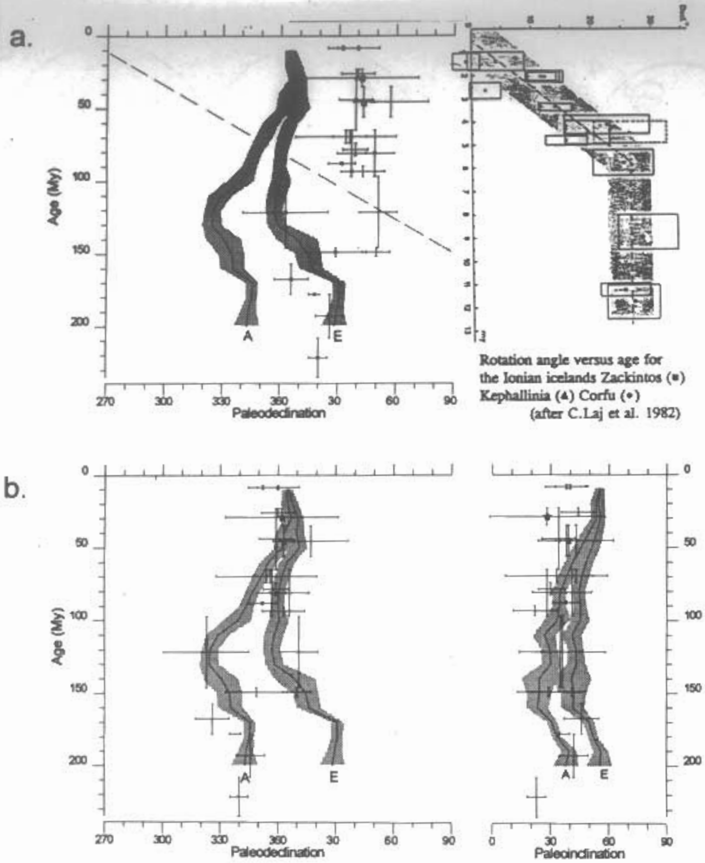


Fig.7: Compiled paleomagnetic data from Albania and predicted paleodirections for Africa (A) and Eurasia (E), calculated from *Master apparent polar wander paths* (BESSE & COURTILLOT, 1991) for a location 40°N, 20°E with their associated 95% confidence limits (shaded) as well as paleogene results after Laj et al. 1982. (a) Albanian data as listed in Table 3. (b) Albanian data after 40° counterclockwise rotation. Stars represent data taken from Speranza et al. (1992).

data from two localities each (Table 2). This gives evidence for another CW rotational movement during the Lower and Middle Jurassic and a subsequent CCW rotation between Middle Jurassic and Upper Cretaceous (Fig. 7). Based on the available data set, a more precise dating of the beginning of the CCW rotation is not possible.

Triassic samples are characterized by simple demagnetization paths and well defined remanence directions within both localities (Fig. 5.e).The scatter of the mean directions decreases significantly after tilt correction (Fig. 6.d). The Upper Triassic paleomagnetic mean direction from two site groups, containig 6 site-means is D = 20° and I = 23° with a_{95} = 4.8° (Table 2).

CONCLUSION

The paleomagnetic data presented above represent pre-folding magnetization directions, proved by successful laboratory experiments and field tests. At several sites fold tests were carried out, antipodal directions were found and equivalent results from three different tectonic units were found to be comparable.

For the geodynamic interpretation the data set from Albania covers a continuous time span from Upper Triassic to Tortonian (Table 1). Reference directions are the predicted values for the *present geographic position of* Albania (Latitude 40° N; Longitude 20° E), calculated from African and Eurasian *master apparent polar wander paths* (200 My - 10 My) after Besse and Courtillot (1991). The comparison demonstrates clearly a clockwise rotation of the Outer and Inner Albanides, which must be dated younger than Tortonian (Fig 7.a).

Elimination of this tectonic movement by back-rotating the whole data set 40° counterclockwise, produces a close correlation with the derived curves (Fig. 7.b). In particular, a strong affinity with the African curve is evident for Upper Triassic up to Lower Cretaceous results. A Neocomian result from the Albanian Alps, i.e. north of the Shkoder-Pec-line, shows affinity to Eurasian directions, which seems to be due to local tectonics in consequence of transversal movements along this line.

In general, for the whole data set of results (Table 1) one can notice a certain additional clockwise rotation for the Kruja- and the Cukali-Krasta-zone compared with the one of the Ionian zone. This rotation is not statistically significant, but in the trend consistent throughout the whole sequence.

For the Upper Cretaceous and the Tertiary a sufficient fit can be noticed, except a slight shallowing in the inclinations above Eocene (Fig. 8.b). Such shallow inclinations were found in the whole Thetian mobile belt by several authors. So far no satisfying explanation was found, since there is no space in this time for a southward shift of this extent. As discussed by Westphal (1993) just an alternative poleposition could solve this problem. The albanian data don't really support this model, since the shallowing start at about 60 Ma and last until recent. On the other hand, there are just a few African data available for the Neogene. The results from the Tortonian of the Inner as well as the Outer Albanides show some additional deviation, which could be due to the angular unconformity at the base of the Tortonian.

The Albanian paleodirections presented above fit perfectly to the results from the island of Corfu (Laj et al., 1982). This gives rise to the possibility to combine both studies to a continuous paleomagnetic information from the Upper Triassic to recent. In doing so, we date the overall clockwise rotational movement from 5 million years to recent. This clockwise rotation can be found on the island of Corfu (Laj et al. 1982), in the Inner and Outer Albanides (Mauritsch et al., 1991; Speranza et al., 1992; this paper), Inner and Outer Hellenides (Horner, 1983; Horner and Freeman, 1983; Marton et al., 1990), Chalkidiki ophiolites (Edel et al., 1990) and the Serbo-Macedonian massif (Pavlides et al., 1988). In the south and southeast of the Hellenic arc, no rotation was identified (Laj et al., 1982).

In contrast to this, the Dinarides, as far as they were investigated, show counterclockwise rotation in agreement with the Adriatic realm (Marton and Mauritsch, 1990; E. Marton, pers. commun. 1993).

Combining all available results, one can point out that the Shkoder-Pec-line seems not to be the transition zone of the senses of rotation. Since the southernmost result of the Dinarides from the island of Vis (west of the Split-line) shows a clear dominance of counterclockwise rotation and the northernmost result of Albania (north of the Shkoder-Pec-line) still shows clockwise rotation, the solution for the diverging rotation senses could be found in block rotations between the Split-Sarajewo-Shkoder-Pec-line. This would fit the scheme of transverse structures in the External and Internal zones of the Dinarides and Hellenides (Aubouin, 1976). The clockwise rotation is in good accordance to the reconstruction of Le Pichon and Angelier (1979). In addition, this model has to be slightly modified in the westernmost edge, as the results show a uniform clockwise rotation at least up to north of the Shkoder-Pec-line.

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