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PALAEOMAGNETIC DATA FROM THE WESTERN MEDITERRANEAN: A REVIEW

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ABSTRACT

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A review is given of palaeomagnetic data that have become available during the last years. The accent of this review is on the palaeomagnetic results from the Italian peninsula, since most of the new data came from there. It is shown that the data from the Italian peninsula are consistent and define the movements of the Adriatic block. The Adriatic block moved together with Africa during post-Hercynian times until the Early Tertiary. In a post-Early Tertiary movement phase this block was detached from the African continent. The Tertiary rotation pole that describes this detachment is derived according to a new method for fitting apparent polar wander curves.

INTRODUCTION

In the last years a large number of palaeomagnetic studies from the Western Mediterranean area have been published. Most of these studies were on Mesozoic and Tertiary rocks from the Apennines and Alps. They all aimed at a better understanding of the megatectonic movements in the Western Mediterranean. However, readers not acquainted with such investigations easily get lost among the apparently conflicting results and interpretations put forward.

The confusion is caused mainly by the fact that some authors present their palaeomagnetic results either with respect to European palaeomagnetic data, to African data or to the geographic pole. Only the last method provides an objective reference; in the other cases the interpretation highly depends on the reliability of the European or African data as well. The palaeomagnetic results proper also attribute to this confusion, since two rotational phases (Late Cretaceous as well as Late Tertiary) seem to have caused the westward offset of the palaeomagnetic directions in the Apennine and Alpine realm. So it is necessary to distinguish the consequences of each of these rotational phases.

Another reason for confusion is that many areas studied are located within the Alpine orogene, where small-scale tectonics could have influenced the results. Only comparison of coeval results from several areas can solve this problem.

The present review is an attempt to end this confusion, and to give a coherent interpretation of all palaeomagnetic data relevant for further geotectonic studies in Alpine Europe.

EUROPEAN APPARENT POLAR WANDER CURVE

In table I a compilation of post-Hercynian palaeomagnetic poles from stable Western Europe is given. The scarcity of Mesozoic data is obvious, and hardly allows to draw a polar wander curve of stable Europe for that era. To overcome this problem the palaeomagnetic data from the U.S.S.R., including the most recent results (KHRAMOV, 1977) have been compiled (Table II) and mean values were computed. IRVING (1977) grouped all the palaeomagnetic data from the major continental blocks according to their absolute ages. Then starting with the oldest data he calculated running mean va-

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lues for overlapping 30 to 40 Ma intervals moving forward the interval limits 10 Ma at each step. In this way a smooth polar wander curve is obtained. For Eurasia IRVING (1977) included data from Western Europe and from the U.S.S.R. (Fig 1). Comparison of the mean poles from table II and this curve only shows minor differences, in particular for the Upper Cretaceous, which may be attributed to the fact that table II is based on a more recent compilation of Russian poles (KHRAMOV, 1977) and to the smoothing effect of the method applied by Irving. To leave no doubt that this mainly U.S.S.R. curve of IRVING (1977) is applicable for stable Western Europe, the mean values of Late Palaeozoic and Early Mesozoic data exclusively from Western Europe (Table I) have been plotted in figure 1 as well (open squares).

The proposed polar wander curve for Eurasia of IRVING (1977) and the palaeolatitudes of table II permit to deduce the following Mesozoic and Tertiary movements of stable Europe with respect to the pole: during the Triassic to Early/Middle Jurassic the European continent moved northward with a clockwise rotational component. Then during the Late Jurassic and Early Cretaceous the European continent remained stationary. The difference in palaeolatitude for the Upper Cretaceous and Lower Cretaceous in table II indicates a distinct southward movement in the mid-Cretaceous. During the latest Cretaceous and Early Tertiary a northward movement with a clockwise rotational component was performed.

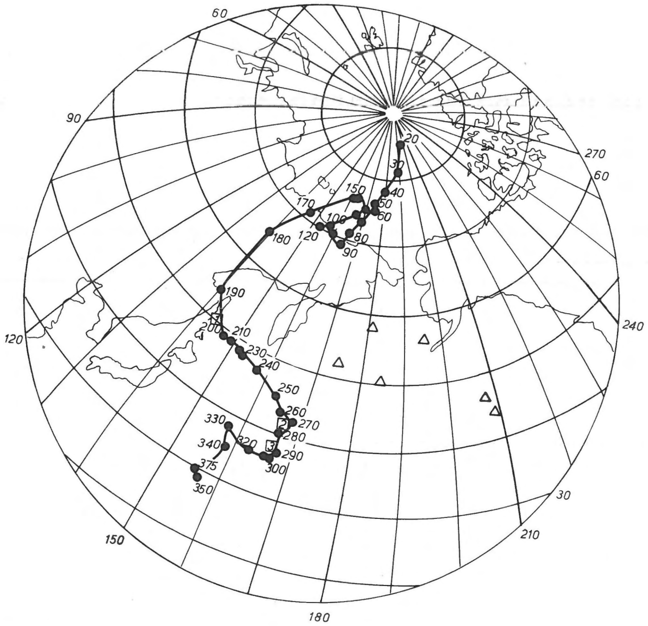

Fig. 1
Equal area projection of the apparent polar wander curve of Eurasia (Irving, 1977). Numbers indicate ages in millions of years of palaeomagnetic poles. Open triangles represent Permian palaeomagnetic poles from Corsica (Westphal et al., 1976; Nairn & Westphal, 1968). Open squares containing numbers indicate West European mean palaeomagnetic poles (1 = PU-TRL, 2 = P, 3 = CU-PL), which are compiled in table I.

Table I
Western European palaeomagnetic poles

NUMBER 1)	Plat.	Plong.	N	a_{95}	AGE
14-211(049)	70.9	125.8	1	10.3	KU
I (127)	65.0	125.0	1	5.0	JU
10-78 (026)	65.0	143.0	1	-	JL
10-79 (026)	62.0	114.0	1	-	TRU
1-64 (043)	43.0	131.0	1	-	TRU
14-292(038) 14-308 (400) II (184)	50.3	144.0	3	2.6	PU-TRL
5-36 (075) 14-315 (116) 7-35 (037) 14-316 (048) 5-37 (494) 14-324 (104) 9-90 (066) 14-325 (038)	41.6	167.0	8	7.1	P
14-338(045) 10-108 (033) 2-36 (102) 10-109 (048) 10-107(080) 12-119 (037)	37.8	167.8	6	7.3	CU-PL

1) NUMBER, refers to listings of McElhinny, 1968, 1969, 1970, 1972, 1977; number in brackets represents amount of samples.
N :Number of poles, giving unit weight to each pole for calculation of the mean value
I :Heller, 1977; recalculated from original since Kimmeridgian data have Tertiary magnetization (personal communication).
II:Van den Ende, 1977.

Table II
Russian palaeomagnetic poles

NUMBER 1)	Plat.	Plong.	N	a_{95}	Palat.2)	AGE
1-45 (0180) 2-19 (0160) 2-57 (0563) 1-50 (0188) 2-32 (1200) 2-58 (0308) 1-48 (0219) 2-47 (0153) 2-59 (0232)	78.7	206.0	09	5.8	-29.9	TP-QP
2-22 (0269) 2-40 (1300) 2-42 (2500) 2-29 (1013) 2-41 (2400)	83.9	270.5	05	5.4	-38.7	TM-TP
2-64 (0696) 3-02 (0081) 3-17 (0177) 3-10 (0410) 3-11 (0035)	77.8	226.2	05	10.7	-29.8	TE-TO
3-15 (0059) 3-09 (0032) 3-16 (0504) 3-07 (0020) 3-14 (0196)	78.9	148.9	05	22.1	-31.3	TPA
4-18 (0075) 4-26 (0158) 4-33 (0127) 4-19A(0062) 4-30 (0121) 4-19C(0056) 4-32 (0404)	63.7	171.4	07	11.4	-14.7	KU
4-04 (0037) 4-10 (0031) 4-21 (0024) 4-06 (0421) 4-11 (0046) 4-25 (0110) 4-09 (0101) 4-12 (0080) 4-34 (0063)	73.6	157.9	09	7.5	-25.7	KL
4-37 (0118) 5-03 (0040) 5-22 (0030) 5-01 (0020) 5-21 (0045) 5-02 (0033)	70.5	134.6	06	8.9	-27.4	JU
5-04 (0034) 5-19 (0093) 5-20 (0120) 5-17 (0430) 5-23 (0081) 5-24 (0106)	68.4	144.3	06	13.6	-23.6	JL-JM
6-01 (0065) 6-02 (0029) 6-06 (0197) 6-04 (0032) 6-05 (0368) 6-07 (0384)	54.3	145.8	06	7.4	-11.6	TRM-TRU
6-09 (0052) 6-35 (0084) 6-48 (0235) 6-10 (0180) 6-36 (0060) 6-50 (0141) 6-19 (0111) 6-37 (0088) 6-53 (0040) 6-20 (0119) 6-38 (0151) 6-55 (0061) 6-21 (0271) 6-39 (0042) 6-56 (0075) 6-29 (0121) 6-43 (0226) 6-33 (0129) 6-47 (0375)	53.2	143.6	19	5.2	-11.4	TRL
7-01 (0136) 7-26 (0175) 7-36 (0082) 7-02 (0242) 7-27 (0626) 7-39 (0588) 7-06A(0260) 7-32 (0155) 7-15 (0150) 7-34 (0140)	47.7	166.9	10	4.4	-00.1	PU
7-22 (0055) 8-04 (0189) 8-33 (0408) 7-42 (0081) 8-32 (0164) 8-24 (0044)	39.7	159.7	06	19.2	+05.6	CM-PL
8-16 (0026) 8-41 (0122) 8-50 (0114) 8-17 (0037) 8-19 (0031) 8-39 (0028) 8-21 (0036)	27.5	139.8	08	16.0	+07.9	DU-CL

1) NUMBER, refers to list of Khramov (1977), in brackets the number of samples is given; only a.f. and/or thermal cleaned data were selected.
N :Number of poles, giving unit weight to each pole for calculation of the mean value.
2) Palat.= Paleolatitude calculated for 40.0 N 10.0 E.

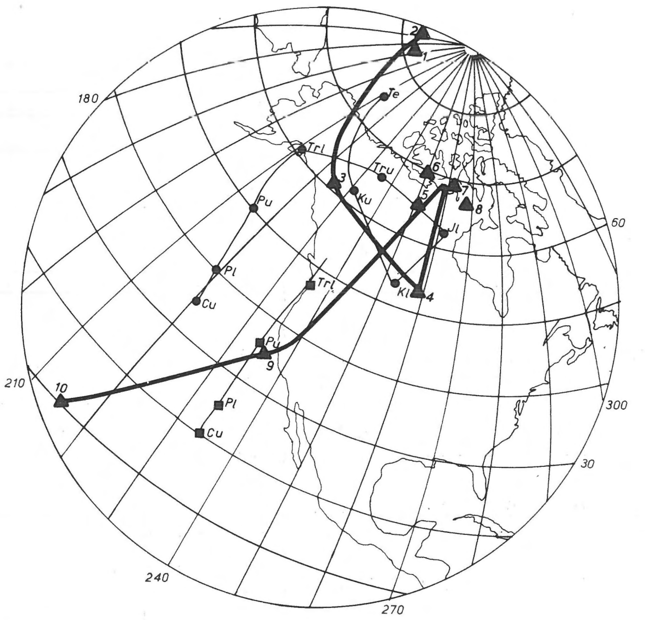

Fig. 2
Equal area projection of the apparent polar wander curves for Africa. Heavy line is direct apparent polar wander curve connecting African observations (full triangles), which are compiled in table III. Thin lines are indirectly obtained apparent polar wander curves, according to Van der Voo & French (1974); full dots and full squares for an alternative fit (Van der Voo & French, 1974).

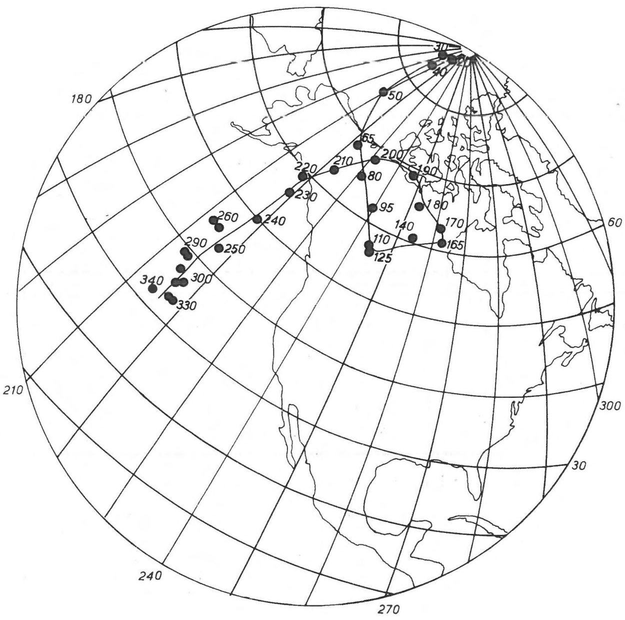

Fig. 3
Equal area projection of apparent polar wander curve for Africa, transferred from the North American A.P.W. curve according to Irving (1977), having applied the stage poles for the Atlantic opening according to Sclater et al. (1977). Numbers denote ages of the palaeomagnetic poles in millions of years.

THE AFRICAN APPARENT POLAR WANDER CURVE

In table III a compilation is given of the presently available palaeomagnetic data from Africa; mean values were computed for different stages and plotted in figure 2. Only a small number of palaeomagnetic data of Mesozoic age have been published, some based on a few samples, others poorly dated. An additional problem with the African data is that many of the more recent studies have been carried out on rocks from localities in or nearby the Atlas mountain chain.

Several authors recognizing these difficulties have tried to reconstruct the African polar wander curve indirectly by transferring palaeomagnetic data from other continents with the aid of reconstructions of continental drift. In figure 2 such an indirect African polar wander curve by VAN DER VOO & FRENCH (1974) is plotted for comparison (full dots). Van der Voo & French calculated mean poles for time intervals ranging from Late Carboniferous to Early Eocene by averaging palaeomagnetic poles of the Atlantic-bordering continents, with respect to the palaeopositions of these continents, as reconstructed from correlations of marine magnetic anomalies in the Atlantic Ocean (PITMAN & TALWANI, 1972) and from the fit of BULLARD ET AL. (1965).

IRVING (1977) published an indirect polar wander curve for Africa, that was the result of the combination of Late Palaeozoic and Early Mesozoic palaeomagnetic data from the continents that once formed Gondwanaland. The relative positions of these continents were reconstructed according to SMITH & HALLAM (1970).

For the pre-Late Triassic data there exists a large discrepancy between the curve derived from the 'North Atlantic' continents, and the 'Gondwana' curve. This discrepancy can be accounted for in different ways, such as by proposing an alternative fit (VAN DER VOO & FRENCH, 1974), see figure 2, or by assuming a more or less continual motion in the Palaeozoic of the major continents (IRVING, 1977). Nevertheless the middle and late Mesozoic and Tertiary parts of these indirect polar wander curves are in good agreement with the observed African palaeomagnetic poles.

The apparent polar wander curve of North America is fairly well specified and therefore the reconstruction stage poles of SCLATER ET AL. (1977) were applied to the N. American polar wander curve of IRVING (1977). SCLATER ET AL. (1977) used the finite rotations for Africa with respect to North America according to FRANCHETEAU (1973) and LE PICHON & FOX (1971), who determined the direction of early motion from the marginal fracture zones. In figure 3 this indirect 'African' polar wander curve is plotted. The applied initial fit of Africa and North America (LE PICHON & FOX, 1971) is only slightly different from the Bullard fit and therefore this 'African' curve of figure 3 is similar to the indirect polar wander curve of VAN DER VOO & FRENCH (1974) in figure 2.

The loop formed by the Mesozoic and Tertiary data is very conspicuous in both figures. The mean African palaeomagnetic data of table III for the late Mesozoic and early Tertiary coincide remarkably well with these indirectly derived Mesozoic and Tertiary loops, not only in form but also in age. We may therefore conclude that although the scarcity and large scatter of the African Palaeozoic data leave enough room for doubt, the Mesozoic part of Africa's polar wander curve is defined within narrow limits. The following Mesozoic movements of Africa with respect to the pole can be deduced from these curves and the palaeolatitudes in table III: Africa remained about stationary during the latest Triassic and Early Jurassic timespan. Palaeomagnetic data that have absolute ages, ranging between 120-106 Ma reveal a southward movement in the Early Cretaceous. This southward movement is followed by a counterclockwise rotation (about 25°) during the Late Cretaceous. Late Cretaceous to Early Tertiary data indicate an additional northward movement during this period.

When we compare the African movement scheme with the European one, then we can generally remark that both continents moved southward in the Early Cretaceous; and later, in the Late Cretaceous and Early Tertiary, northwards. It is hazardous to draw any conclusions from the discrepancies in timing or magnitude of these movements based on the present data. The rotational movements are in opposite sense, clockwise for Europe and counterclockwise for Africa. The large counterclockwise rotation in the Late Cretaceous of the African continent caused the wide loop in the African polar wander curve, which is the most pronounced difference with the European polar wander curve.

Table III
African palaeomagnetic poles

NUMBER 1)	Plat.	Plong.	N	a_{95}	Palat.2)	AGE 3)
12-27 (0142) 14-84 (0031) 11-19 (0051) 14-65 (0125) 14-97 (0147) 12-31 (0119) 14-74 (0023) 14-98 (0057) 14-83 (0138) 14-99 (0024)	82.9	186.3	10	5.2	-32.9	TM-TP (1)
12-43 (0109) 14-125(0024) 12-46 (0052) 14-112(0092) 14-135(0218) 14-113(0026) 8-36 (0021)	83.0	164.2	07	4.6	-33.6	TE-TM (2)
14-193(0163) 14-221(0107) 14-197(0115) I (0057)	61.4	225.6	04	5.3	-15.4	KU (3)
7-21 (0061) 14-226(0118) 13-32 (0035) 14-225(0078) 9-40 (0008)	53.5	259.7	05	8.0	-21.0	KL (4)
8-63 (0036) 6-40 (0074) 14-250(0010) 8-59 (0067) 14-248(0243) 13-36 (0096)	65.4	251.1	06	6.0	-25.5	JL-JM (5)
10-77 (0068) 14-273(0160) 8-72 (0013) 8-67 (0032)	70.3	250.3	04	13.1	-28.5	TRU-JL (6)
14-288(0062) 14-290(0030) II (0054) 8-73 (0019) 14-303(0032)	68.9	262.7	05	4.9	-31.2	TRL-TRM (7)
8-73 (0019) 14-303(0032)	67.0	268.0	02	-	-31.9	PU-TRL (8)
II (0057) 8-92 (0034) III (0030)	35.0	235.4	03	22.8	+04.1	CU-PL (9)
9-117 (0029) 14-361(0038) III (0034)	10.6	215.5	03	34.0	+34.2	DU-CL (10)

1) NUMBER, refers to listings of McElhinny, 1968, 1969, 1970, 1972, 1977; number in brackets represents the amount of samples.
N :Number of poles, giving unit weight to each pole for calculation of the mean value.
2) Palat.= Paleolatitude calculated for 40.0 N 10.0 E.
3) Number in brackets refers to plot of these poles : Figure 2.
I :McFadden and Jones, 1977.
II :Daly and Pozzi, 1976.
III :Martin et al., 1978.

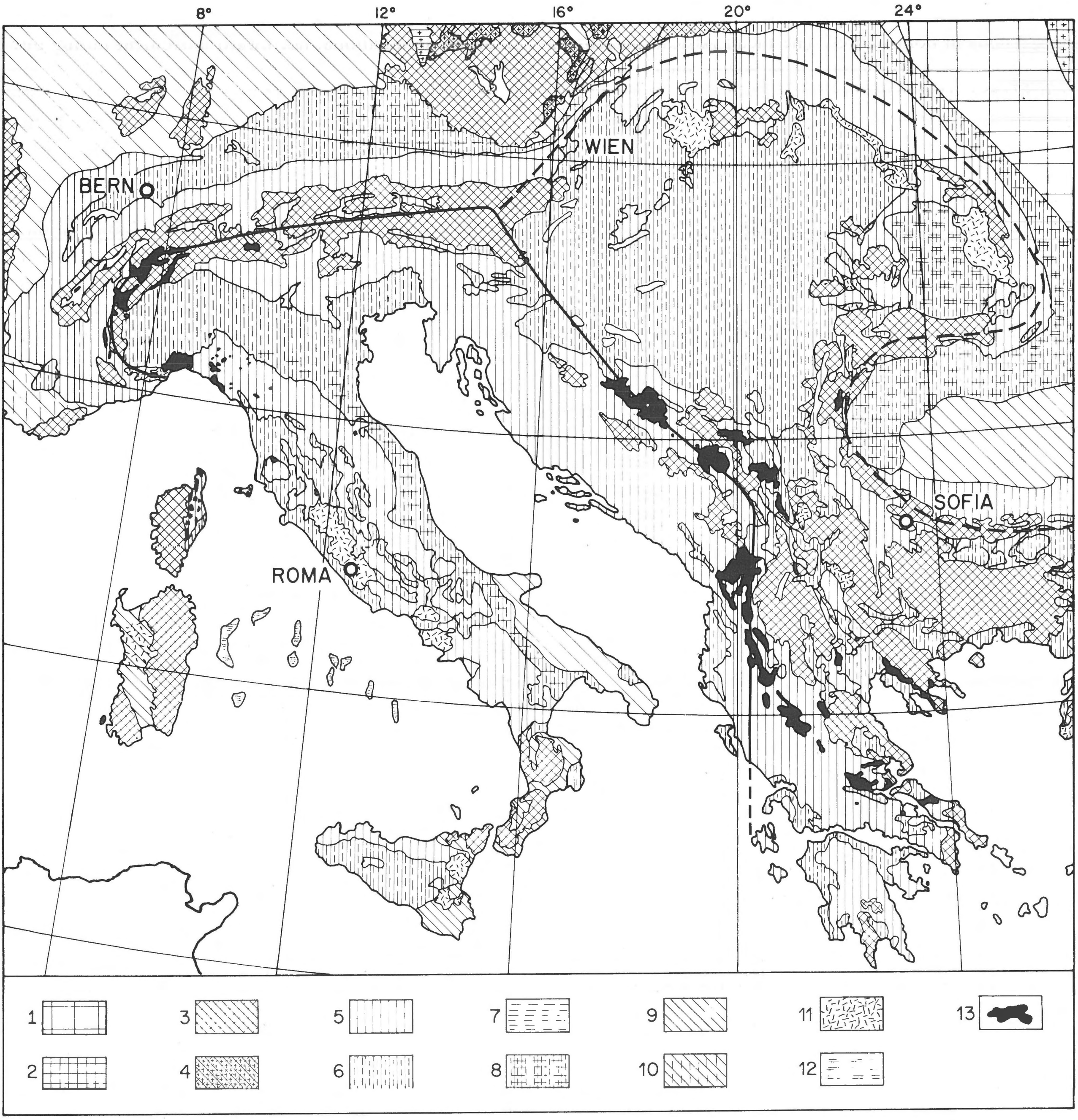

Fig. 4

Geological map of the Alpine system around the Adriatic Sea. Indicated are the locations of which palaeomagnetic studies have been reported. Letters refer to tables IV and V.

Legend: 1 = Russian shield, undifferentiated; 2 = Archaean shield; 3 = Hercynian, undifferentiated; 4 = Hercynian with Cadomian nuclei; 5 = Alpine fold belts; 6 = inner basins; 7 = Hercynian metamorphic basement (Selli, 1974); 8 = Alpine molasse; 9 = Mesozoic platforms; 10 = Palaeozoic platform, Alpine reactivated; 11 = volcanic complex; 12 = area of salt tectonics; 13 = ophiolites.

PALAEOMAGNETIC DATA FROM THE ITALIAN PENINSULA, SARDINIA AND CORSICA

Northern Apennines (Umbria)

Many palaeomagnetic workers have focused their attention on the Mesozoic of Umbria (Fig. 4) (CHANNELL ET AL., 1978; ROGGENTHEN & NAPOLEONE, 1977; VANDENBERG ET AL., 1978; and others). Figure 5 shows the Mesozoic pattern that was recognized for the north-western part of Umbria after VANDENBERG ET AL. (1978). CHANNELL ET AL. (1978) confirmed these results after studying the same area near Cagli, but noticed differences with the Gubbio section. Unfortunately their data were published in diagrams, so they could not be represented here. Only their mean results of earlier published studies can be reproduced and are plotted additionally in figure 5. The mean results of CHANNELL & TARLING (1975) are plotted, differentiated according to the assigned ages: poles U_1 (KU-TL) and U_2 (KL-KU). The mean result of LOWRIE & ALVAREZ (1975) is represented by pole U_3 (KL?-KU).

Palaeomagnetic studies on geographically distributed sites in the southern part of Umbria show a difference in palaeomagnetic direction with the outermost north-western part (Gubbio and Moria/Cagli) according to CHANNELL ET AL. (1978). The bending of the Apennine trend and the more intense deformation in the southern part can very well account for that. When the Umbrian Mesozoic data in figure 5 are examined we may conclude that these data are in mutual agreement, especially when we realize that, because of the curved shape of this A.P.W. path, the position of mean poles depends on the age distribution of the studied sites.

Central Apennines (Tuscany)

Two palaeomagnetic studies have been carried out in Tuscany (Fig. 4) on different lithostratigraphic units of the so-called Verrucano (VANDENBERG & WONDERS, 1976; VANDENBERG, 1979-a). The results appear in figure 5 as full squares. The ages assigned to these units are Lower and Upper Triassic respectively. This age difference is reflected in the different positions of the palaeomagnetic poles. The Lower Triassic rocks show palaeomagnetic reversals, in contrast with the Upper Triassic which reveals only normal polarities. The palaeomagnetic declinations of the Tuscan Triassic results are in agreement with the Jurassic palaeomagnetic declinations from the Umbrian sequence (VANDENBERG & WONDERS, 1976; VANDENBERG, 1979-a).

Southern Apennines (Campania and Gargano/Apulia)

Palaeomagnetic studies in this area (Fig. 4) have been carried out on bauxites in Campania and Gargano (CHANNELL & TARLING, 1975) and on platform limestones from the Gargano peninsula (CHANNEL, 1977). The age of the bauxites is bounded by the overlying Senonian limestones and the underlying Aptian/Albian calcilutites. However, the diagenesis of the bauxites and the presence of reversely magnetized samples point to an age not earlier than Campanian-Maastrichtian for the Natural Remanent Magnetization. The very weakly magnetized platform sediments of Cenomanian-lower Senonian age revealed palaeomagnetic results very similar to the bauxites (CHANNELL, 1977).

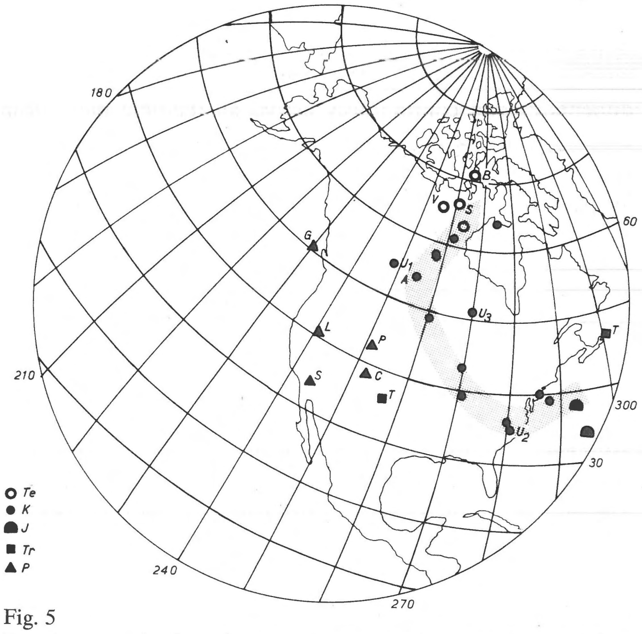

Fig. 5
Equal area projection of apparent polar wander curve for the Adriatic continental block from Jurassic to Tertiary. Poles without label defining the stippled curve are according to VandenBerg et al. (1978). Triassic poles according to VandenBerg & Wonders (1976) and from VandenBerg (1979-a). Other poles are identified by a letter to which is referred in the text and table IV.

The calculated mean pole of the palaeomagnetic results from the bauxites and the platform limestones slightly differs from Channell's result, because only sites with an a_{95} smaller than or equal to 15° were incorporated (VANDENBERG & WONDERS, 1979-a). This late Cretaceous result occurs as pole A in figure 5.

Sardinia

Palaeomagnetic data of Permian age (WESTPHAL ET AL., 1976; ZIJDERVELD ET AL., 1970) and of Oligocene/Early Miocene age (MANZONI, 1974) are available from Sardinia. The mean pole calculated from all the Permian data (giving unit weight to each site) is represented by the full triangle S in figure 5. The Oligocene/Early Miocene result, a mean value of all presently available data (MANZONI, 1974), is represented by the open circle S in figure 5.

Northwestern Apennines

Early Tertiary palaeomagnetic data were obtained from Late

Eocene to Early Oligocene sediments belonging to the base of the Piemonte Tertiary in the outermost part of the Northwestern Apennines (Fig. 4) (VANDENBERG, 1979-b). These sediments extend continuously across all tectonic units from the Voltri massif to the Antola slab (TEN HAAF, 1975). This Late Eocene-Early Oligocene result is indicated in figure 5 by pole V (open circle). Its position is close to the Early Tertiary pole from the Umbrian area (open circle without label).

Southern Alps (Western part)

Several palaeomagnetic studies have been carried out in this area (Fig. 4). An Early Permian result has been reported by ZIJDERVELD & DE JONG (1969) from the lower Collio and Auccia volcanics (Fig. 5, pole C full triangle). In the Southern Tessin Alps, VAN HILTEN & ZIJDERVELD (1966) reported a Permian pole from the Lugano porphyries (Fig. 5, pole L full triangle). A palaeomagnetic study on the Bergell granite (Fig. 4) by HELLER (1973) resulted in a palaeomagnetic pole for this granite massif (30 Ma) given as pole B in figure 5 (open circle).

Western Alps

Palaeomagnetic studies on the andesitic and lamprophyric dikes (30-33 Ma) of the Sesia-Lanzo Zone (LANZA, 1977; HELLER & SCHMIDT, 1974) have revealed palaeomagnetic data which are fully comparable with the Bergell result. The tectonic deformation of this area, however, makes it advisable to disregard them here.

Palaeomagnetic data have been reported from the Belledonne and Pelvoux Massifs and from the Brianconnais Zone (Fig. 4). The palaeomagnetic results of different localities in the external massifs (Belledonne and Pelvoux) show counterclockwise rotated palaeomagnetic declinations relative to the results from stable Europe (WESTPHAL, 1973). Even though their tectonic position is on the European side of the margin. Late Permian flows (rhyolites), attributed to the Brianconnais Zone, have been studied in the Guil and Ponsonnière valleys and revealed very similar westward deviating palaeomagnetic declinations. For the external massifs one may assume that a Tertiary rotational movement was imposed and that these massifs were not actively involved. A mean value has been calculated for the Guil flow (WESTPHAL,

Table IV
Palaeomagnetic poles from the Adriatic block

AGE	N	Plat.	Plong.	a_{95}	References 1)
TO (25-30 Myr.)	127	71.0	264.0	2.1	(B) Heller, 1973
TO (30-33 Myr.)	062	60.6	235.2	9.7	Lanza, 1977
TO-TM	600	66.0	261.0	-	(S) Manzoni, 1974
TE-TO	031	65.3	254.6	5.8	(V) VandenBerg, 1979b
TPA-TE	016	63.0	264.0	3.0	VandenBerg et al., 1978
KU-TPA	162	53.9	249.2	6.5	(U1) Channell and Tarling, 1975
KU (L.Camp./E.Maastr.)	016	61.9	261.1	3.7	VandenBerg et al., 1978
KU (M.-L. Camp.)	010	64.2	274.8	3.6	id.
KU (E.Camp.)	010	58.7	257.1	6.1	id.
KU (L.Sant.)	018	58.4	257.3	4.2	id.
KU (L.Con.-E.Sant.)	017	49.7	260.5	2.7	id.
KU (Con.)	009	39.5	270.9	6.1	id.
KU (E.Tur.)	010	43.3	269.4	5.4	id.
KU (L.Cen.)	010	36.9	279.1	4.3	id.
KL?-KU	204	51.1	270.5	6.1	(U3) Lowrie and Alvarez, 1975
KU-TPA	098	54.6	253.9	5.9	(A) Channell and Tarling, 1975;Channell, 1977
KL-KU	036	35.2	281.4	8.7	(U2) Channell and Tarling, 1975
KL (L.Apt.)	027	40.3	285.5	4.4	VandenBerg et al., 1978
KL (Neoc.)	010	39.4	287.1	7.0	id.
JU (Kim.)	013	34.4	294.6	8.0	id.
JM	013	38.0	292.3	6.4	id.
TRM-TRU	033	47.1	300.4	6.0	(T) VandenBerg and Wonders, 1976
TRL	051	36.3	256.6	10.6	(T) VandenBerg, 1979a
P	011	41.5	240.5	9.0	(L) Van Hilten and Zijderveld, 1966
P	025	43.7	251.0	30.0	(P) Westphal, 1973
P	057	51.0	230.0	10.0	(G) id.
PL	033	38.5	252.5	20.0	(C) Zijderveld and De Jong, 1969
PL	080	34.7	244.0	11.0	(S) Zijderveld et al., 1970a and Westphal et al., 1976 , combined result

N :Number of samples ; 1) :Letters in brackets refer to Figures 5, 6, 9 and 10.

1973; VAN DER VOO & ZIJDERVELD, 1969; ROCHE & WESTPHAL, 1969), and this mean result is indicated by pole G in figure 5 (full triangle). The result from Ponsonnière (WESTPHAL, 1973) has been plotted as the Permian pole P in figure 5 (full triangle).

Interpretation of the data so far presented

The detailed Mesozoic polar wander curve that was derived from pelagic sediments of the Umbrian sequence (VANDENBERG ET AL., 1978), begins to fit into a regional framework. Certainly not all palaeomagnetic data do perfectly fit together, as will be specified later, but the data presented so far (Table IV) reveal a coherent picture. All researchers active in Umbria hesitated to conclude that the palaeomagnetic data from Umbria were applicable to the whole Italian peninsula. This hesitation was not based on the data of the Umbrian sequence, but on the fact that a Tertiary rotational décollement of the whole sequence over its basement could have caused the present position of the Umbrian pattern. The matter therefore was to prove that the Umbrian pattern is valid for the basement and, moreover, for a larger area in Peninsular Italy. Therefore palaeomagnetic data from Tuscany (VANDENBERG & WONDERS, 1976; VANDENBERG, 1979-a) of the supposed autochthonous series (Permo-Triassic Verrucano) are crucial. The results from these studies showed the same total rotational amount for the Tuscan Triassic rocks as for the Umbrian Jurassic rocks.

Important in this respect are the palaeomagnetic data from Campania and Gargano/Apulia (CHANNELL & TARLING, 1975; CHANNELL, 1977), particularly those from the Gargano/Apulia region, that has not suffered Tertiary deformation and that is generally supposed to represent the autochthonous backbone of Italy. These data match perfectly with the Umbrian data, if general reliability criteria are applied (VANDENBERG & WONDERS, 1979-a). Compare pole A from the southern Apennines with the Umbrian data in figure 5. The conclusion is therefore justified that if a décollement of the Umbrian sequence has occurred, this movement was not rotational with respect to the Tuscan basement or to the Gargano/Apulia region. This conclusion is sustained by the fact that other areas in Italy also revealed Eocene-Oligocene palaeomagnetic data, which indicate a rotation over the same angle, and counterclockwise with respect to the present North. This is expressed in figure 5 by the Early Tertiary data from the North Western Apennines (pole V) and from the Bergell granite (pole B). The proximity of the Permian data from Lugano (pole L) and from Collio (pole C) to the Early Triassic result from Tuscany is of additional support.

The palaeomagnetic poles (Fig. 5) from Sardinia (Early Tertiary *and* Permian, poles S) are remarkably close to the palaeomagnetic poles from the Apennines and Southern Alps. This indicates a very close relationship between Sardinia and the main Italian peninsula. Supporting geological and geophysical evidence will be discussed elsewhere in this issue.

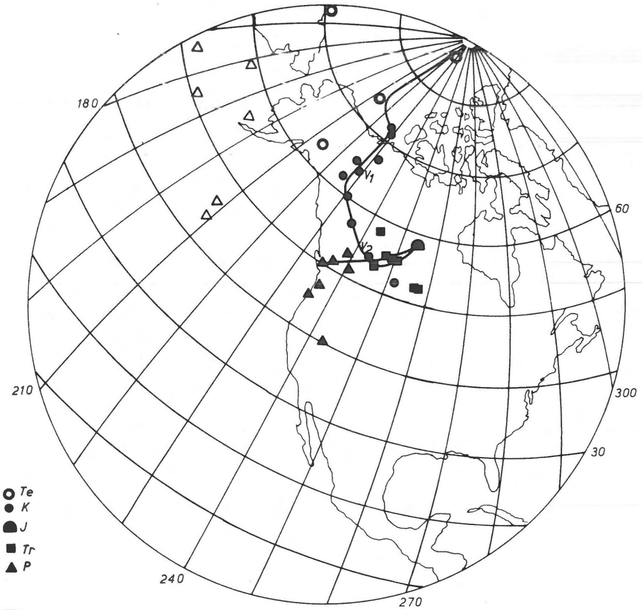

Fig. 6
Equal area projection of the apparent polar wander curve for the Southern Alps (Eastern part), see table V. Permian palaeomagnetic poles (open triangles) from Corsica (Westphal et al., 1976; Nairn & Westphal, 1968).

Provisionally it can be concluded that presently available palaeomagnetic data from N.W. Umbria, Tuscany, Campania, Gargano/Apulia, the Northern Apennines, Sardinia and from the Southern Alps (western part) are consistent. This implies that all these areas belonged to a single crustal block here referred to as the ‘Adriatic continental block’.

Southern Alps (Eastern part)

Palaeomagnetic research has been carried out on rocks from the Dolomites and Vicentinian Alps (Fig. 4) over more than a decade (see ZIJDERVELD & VAN DER VOO, 1973). The palaeomagnetic poles that were published through the years have been plotted in figure 6 (Table V). While in the beginning the palaeomagnetic research was mainly concentrated on rocks of Permian and Triassic age, more recently the rocks of Cretaceous and Jurassic age have been studied. CHANNELL & TARLING (1975) studied pelagic carbonates of Late Cretaceous to Early Tertiary age (pole V_1, in Fig. 6) and mid-Cretaceous age (pole V_2, in Fig. 6). VANDENBERG & WONDERS (1976) studied Late Cretaceous pelagic carbonates and Late Jurassic sediments, and their results agree with Channell and Tarling. Comparison of figure 5 and figure 6 shows the different position but corresponding pattern of both polar wander curves. Moreover, VANDENBERG & WONDERS (1976) showed that, although the timing and sense of the movements for the Apennines and the Southern Alps was essentially the same, the amounts of rotation in the Late Cretaceous and Tertiary were different. This was confirmed by further re-

Table V
Palaeomagnetic poles from Dolomites and Vicentinian Alps

AGE	N	Plat.	Plong.	a95	References 1)
TO	150	71.0	164.8	9.6	Soffel, in press
TE	160	63.7	213.1	8.0	id.
TO	010	87.0	330.0	-	De Boer, 1963, 1965
TE	029	74.0	214.0	-	id.
KU-TPA	072	64.1	229.2	7.5	(V1)Channell and Tarling, 1975
KU (E.Camp.)	011	72.0	228.7	-	VandenBerg and Wonders, 1979b
KU (Sant.)	017	71.0	230.0	8.3	id.
KU (L.Con.)	016	67.0	232.6	8.4	id.
KU (L.Tur.-E.Con.)	050	65.7	226.7	7.4	id.
KU (M.Tur.)	066	62.9	226.6	5.5	id.
KU (E.Tur.)	050	60.4	231.4	9.5	id.
KU (M.-L.Cen.)	044	57.6	236.7	4.6	id.
KL (L.Alb.)	048	52.9	252.3	5.4	id.
KL-KU	018	54.8	244.6	14.9	(V2)Channell and Tarling, 1975
JU	010	58.5	255.3	3.0	VandenBerg and Wonders, 1976
TRM-TRU	030	44.0	237.0	12.0	Manzoni, 1970
TRM-TRU	017	55.0	248.0	18.0	id.
TRM	009	50.0	238.0	-	id.
TRM	007	62.0	258.0	-	De Boer, 1963, 1965
TRM	009	62.5	257.0	-	id.
TRL-TRM	014	55.5	251.0	-	id.
TRL	005	58.5	244.0	-	id.
TRL	010	55.5	249.0	-	id.
TRL	004	53.5	246.0	-	id.
PM-PU	008	41.0	237.0	18.0	Manzoni, 1970
PM-PU	010	50.0	235.0	-	Guicherit, 1964
PU	017	53.0	239.0	-	De Boer, 1963, 1965
PM-PU	005	47.3	237.5	-	id.
PL	152	45.5	236.0	5.0	Zijderveld et al., 1970b
PL	033	51.5	241.5	7.0	Van Hilten, 1960, 1962

1):In brackets special annotation refers to Figure 8.
N :Number of samples.

search (VANDENBERG & WONDERS, 1979-b). This implies that the Southern Alpine continental block to which the Dolomites and the Vicentinian Alps belong, was essentially part of the Adriatic block, although it did not follow completely the rotational movements.

The palaeomagnetic data from the Late Eocene and Oligocene volcanics of the Colli Euganei and Monti Lessini (SOFFEL, 1974, 1975), have been updated (CHANNELL ET AL., in press; SOFFEL, in press) and are in better accordance now with the other data from the Southern Alps, although the Eocene palaeomagnetic directions still reveal low inclination values, presumably due to local tectonics which could not be corrected for (see Fig. 6, Table V). Palaeomagnetic data from rocks north of the Insubrian line also reveal westward deviating declinations (FÖRSTER ET AL., 1975) but these data have been disregarded because of their tectonic position.

The presently available palaeomagnetic data from the Northwestern Apennines, from the Western Alps and from the Western part of the Southern Alps indicate a larger rotation amount for the Tertiary than can be deduced for the Eastern part of the Southern Alps.

Corsica

Palaeomagnetic studies on rocks of Late Carboniferous to Late Permian age from Corsica (NAIRN & WESTPHAL, 1968; WESTPHAL ET AL., 1976) have been plotted in figures 1 and 6. Comparison of the Corsican data with the palaeomagnetic data from the Southern Alps (Fig. 6) and from the Adriatic block (Fig. 5) clearly shows that the Corsican data are not close to one of these A.P.W. curves. The Corsican data are close to the Iberian palaeomagnetic data (see Fig. 1 and compare with Fig. 9), but they are too few (and all of about the same age) to allow definite conclusions to be drawn. Nevertheless, those palaeogeographic reconstructions that keep the Corsican block fixed to the Iberian peninsula are not in contradiction with the palaeomagnetic data.

Calabria

Palaeomagnetic data from Calabria (MANZONI, 1975) have been disregarded because of the tectonic position of the rocks in a pile of nappes and since the age of the Natural

Remanent Magnetization is very uncertain due to a Tertiary metamorphic event.

THE RELATIONSHIP WITH AFRICA

The movement scheme of Umbria during the Mesozoic timespan was identical to that of the African continent and a post-Early Tertiary rotation relative to Africa has caused the present offset of the Umbrian pattern (VANDENBERG ET AL., 1978). Comparison of figure 2 with figures 5 and 6 clearly illustrates the identical U-shape of the Mesozoic polar wander pattern of Africa and Italy. In the European A.P.W. curve this wide Mesozoic loop is not present (see Fig. 1). The southward movement in the late Early Cretaceous and northward movement in the Late Cretaceous as specified by the Italian data (VANDENBERG ET AL., 1978) are present in the African A.P.W. curve as well as in the European curve. Although distinct differences between the A.P.W. curves from the Southern Alps and from the Apennines exist, the Southern Alpine A.P.W. curve shows the Late Cretaceous counterclockwise rotation (Fig. 6) that is so characteristic for Africa's movement.

Therefore it can be concluded that palaeomagnetic data from the Italian peninsula and the Southern Alps very clearly indicate that the Adriatic continental block was part of the African continent during its post-Hercynian history until the Early Tertiary. In a post-Early Tertiary period the Adriatic continental block became detached from the African continent, during an independent counterclockwise rotation. Interaction with the European continental block can very well account for the fact that the most Northern extension of the Adriatic block (the Southern Alps) did not completely follow this rotation.

THE TERTIARY ROTATION POLE OF THE ADRIATIC CONTINENTAL BLOCK

The congruent Mesozoic polar wander curves for the Adriatic continental block and Africa were once coincident, but a Tertiary rotation of the Adriatic block has caused the present offset. The Eulerian rotation pole that describes this rotation can be found, by making the A.P.W. curves coincide again. However, an other method for fitting polar wander curves than by trial and error has not been reported so far as known.

Especially for this case a purely mathematical approach of the problem was developed. A smooth curve, fitting in a best possible way the palaeomagnetic poles of both polar wander curves (ranging from Jurassic to Early Tertiary) was approximated by about 35 points for each curve. These points are considered as the end points of vectors from the earth's centre and thus form two vector clusters: VCOLD for the African curve and VCNEW for the Italian curve. For both vector clusters the eigenvalues and eigenvectors were determined, by means of matrices containing the elements of the sum of the cross products and using the method of Jacobi. The three eigenvectors (I, II, III) are arranged in order of diminishing length. The largest eigenvector (I) points to the centre of gravity of the vector cluster, and the eigenvectors II and III point in the direction of the long and short axes of the vector cluster respectively. The eigenvector I of VCNEW is brought into coincidence with eigenvector I of VCOLD through a rotation over the smallest angle between both vectors. The centres of gravity of both clusters now coincide, but not necessarily so the long and short axes of the clusters. A second rotation bringing into coincidence eigenvector II of VCNEW with eigenvector II of VCOLD is needed. Both rotations are then combined into one single rotation around an Eulerian rotation pole, that now brings into coincidence both A.P.W. curves.

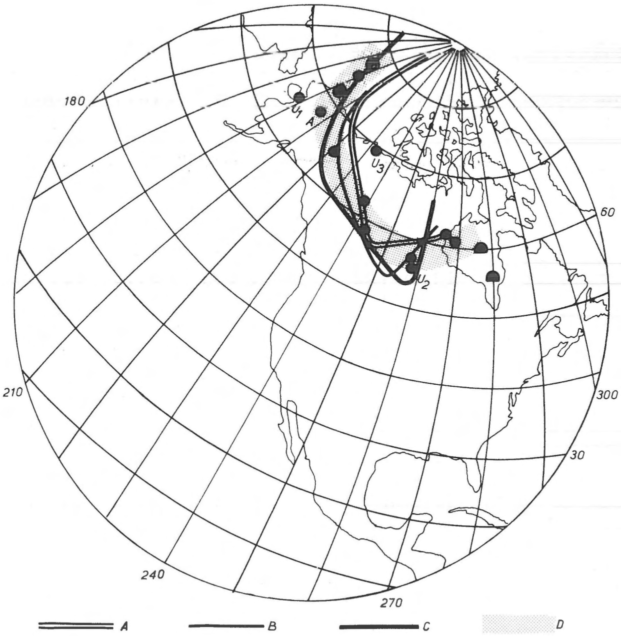

Fig. 7
Equal area projection. Comparison of Mesozoic to Early Tertiary apparent polar wander curves from Africa (A = Fig. 4; B = Fig. 2) (Van der Voo & French, 1974); (C = Fig. 2 (Table III)). The A.P.W. curve for the Adriatic block is represented by the stippled curve (D = Fig. 6), rotated back to the African curves according to the Malta pole (see text). Letters refer to table IV.

Like the trial and error method, our method can be applied only if the vector clusters (A.P.W. curves) have a distinct shape, preferable elongated instead of circular. An attractive feature of the method is that only the shape of the A.P.W. curve is of importance and not the particular data on the curve. This is accommodating to the problem that many palaeomagnetic poles, although of excellent quality, are not precisely dated. If the starting and end points of the considered A.P.W. curves are fairly well dated, then all palaeomagnetic data of intermediate ages can be used to es-

Table VI
Palaeomagnetic poles from the Iberian Peninsula

AGE	N	Plat.	Plong.	a_{95}	References
TE	008	73.0	175.5	-	Van der Voo, 1967, 1969
TE	176	72.5	196.0	3.0	Van der Voo and Zijderveld, 1971
KU (80 Myr.)	008	76.5	174.0	8.0	Van der Voo, 1967, 1969
KL (Bar.-Apt.)	045	66.5	201.7	1.0	VandenBerg, 1979c
JU (Kim.)	047	70.4	203.7	4.0	id.
TRM-TRU	039	63.0	177.5	-	Van der Voo, 1967, 1969
TRM-TRU	084	54.5	196.0	-	id
PU-TRL	030	52.9	221.9	5.8	VandenBerg, 1979c
PU-TRL	012	55.7	225.7	9.5	id.
PU-TRL	008	49.4	230.0	25.5	id.
PU-TRL	014	51.0	227.0	-	Schwarz, 1963
PU-TRL	011	52.0	206.0	-	Van der Lingen, 1960
CU-PL	014	41.0	208.0	13.0	Van der Voo, 1967, 1969
CU-PL	008	42.5	216.0	6.0	id.
CU-PL	017	35.5	211.5	7.0	id.
CU-PL	041	48.5	197.0	6.0	Van Dongen, 1967
D-C	033	35.5	203.0	12.0	Van der Voo, 1967, 1969
SU	010	21.0	228.0	-	id.

N :Number of samples.

tablish the shape of the curve, and only palaeomagnetic reliability criteria have to be applied.

The method is also very appropriate for fitting magnetic sea-floor stripes of corresponding age, if no information on the rotation pole is available from fracture zones or when the course of fracture zones is to be tested.

For the Late Mesozoic to Early Tertiary A.P.W. curves of Africa and Italy, this method resulted in a rotation pole situated close to the island of Malta: 15.15°E 36.04°N with an angle of rotation of −27°. This rotation pole, that describes the independent rotation of the Adriatic block relative to Africa, has been used to rotate back the A.P.W. curve of the Adriatic block (Fig. 7). In the same figure the A.P.W. curves of Africa that have been derived earlier (Figs. 2 and 3) are shown for comparison. The loops coincide almost perfectly and show that the rotation pole as well as the amount of rotation are correct. In figure 8 all palaeomagnetic data attributed to the Adriatic block are plotted, after having been rotated back.

PALAEOMAGNETIC DATA FROM THE IBERIAN PENINSULA

In table VI a compilation is given of the presently available palaeomagnetic data from Spain. In figure 9 a comparison is given of these palaeomagnetic poles with the A.P.W. curve of Europe from IRVING (1977).

ZIJDERVELD & VAN DER VOO (1973) argued that the counterclockwise rotation of Spain presumably occurred between Late Jurassic and latest Cretaceous. In figure 9 it is clearly shown that the Late Cretaceous result (VAN DER VOO, 1967) coincides with the European A.P.W. curve. A latest Early Cretaceous palaeomagnetic pole, however, is still differing from the corresponding European pole and therefore the timespan of the rotation can be further specified as between 110 and 80 Ma (VANDENBERG, 1979-c).

Studies on the magnetic anomaly pattern of the Bay of Biscay have revealed additional information, since anomalies 34-31 have been recognized. This implies that spreading was still active in Campanian to Maastrichtian times (WILLIAMS, 1975). If constant spreading is assumed, the onset of the rotational opening of the Bay of Biscay can be extrapolated to Mid-Cretaceous. The palaeomagnetic data confirm this entirely, and we may therefore conclude that the Iberian peninsula rotated mainly during the Late Cretaceous, the period in which Africa and Italy also performed a major counterclockwise rotation.

It can be observed in figure 9 that the Late Permian-Early Triassic data from Spain have a deviating position relative to the transferred European A.P.W. curve. This could signify that the Iberian Peninsula was an independent block by that time and not yet attached to the European continent.

CONCLUSIONS

Palaeomagnetic data from the Southern Alps, Northern Apennines, Southern Apennines and Sardinia are in mutual agreement, despite the very different ages of these data, which range from Permian to Early Tertiary. These areas therefore belong to one single continental block: the Adriatic continental block. The Southern Alps have followed only partly its rotational movements.

The Adriatic block was part of the African continent during its post-Hercynian history, and only during a post-Early

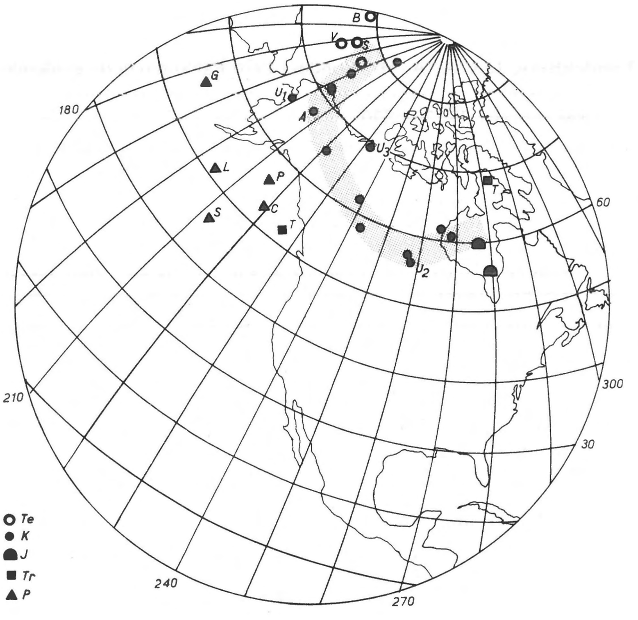

Fig. 8
The apparent polar wander curve for the Adriatic block in equal area projection, after the independent Tertiary rotation has been nullified by an opposite rotation around the Malta pole. This curve can now be directly compared with figures 2 and 4. Letters refer to table IV.

Tertiary rotational phase it was decoupled from the African continent. The post-Early Tertiary decoupling of the Adriatic block with respect to Africa can be described by a single counterclockwise rotation over an angle of 27°, around a pole situated close to the island of Malta.

Palaeomagnetic data from the Iberian peninsula indicate that this continental block rotated mainly during the Late Cretaceous.

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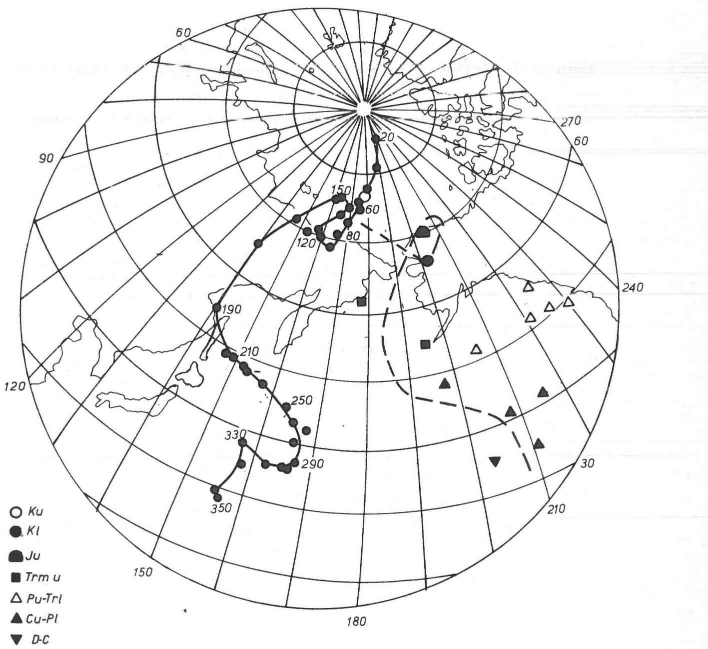

Fig. 9
Equal area projection of the A.P.W. curve for Eurasia (Irving, 1977), and palaeomagnetic poles from the Iberian peninsula (Table VI). Stippled line is the Eurasian curve transferred to the Iberian continent according to a rotation pole at 50.0 N 3.3 E and rotating over an angle of 25°. Numbers indicate ages in millions of years.

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