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PALEOMAGNETISM AND THE CHANGING CONFIGURATION OF THE WESTERN MEDITERRANEAN AREA IN THE MESOZOIC AND EARLY CENOZOIC ERAS

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PALEOMAGNETISM AND THE CHANGING CONFIGURATION OF THE WESTERN MEDITERRANEAN AREA IN THE MESOZOIC AND EARLY CENOZOIC ERAS

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door

Jörgen van den Berg

geboren op 16 december 1947 te Willemstad (N.A.)

Promotor : Dr.E. ten Haaf

Co-referent : Dr.J.D.A. Zijderveld

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"eppur si muove!"

VOORWOORD

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SAMENVATTING

De Jelinek JR3 spinner magnetometer en de recente ontwikkeling van de ScT supergeleidende magnetometer hebben het mogelijk gemaakt dat zeer zwak magnetische gesteenten kunnen worden betrokken in paleomagnetisch onderzoek. Ook al zijn door deze magnetometers de meetgrenzen een faktor 10 à 20 verlegd ten opzichte van de conventionele astatische magnetometers en kunnen nu met name diepzee kalken worden gemeten, de euforie van het eerste uur is voorbij. Er is gebleken dat hoewel er nu uiterst zwakke remanente magnetisaties gemeten kunnen worden, deze zeker niet altijd overeenkomen met de primaire natuurlijke remanente magnetisatie, waar men toch over het algemeen naar op zoek is.

Behalve de grotere meetgevoeligheid, die deze magnetometers vertonen is ook de effectieve meetsnelheid enorm vergroot. Dit komt niet in de laatste plaats door de koppeling van computers aan deze moderne magnetometers.

Het onderzoekgebied en de resultaten in dit proefschrift vastgelegd zijn in zeer belagrijke mate door deze ontwikkeling beïnvloed.

Wetenschappelijk onderzoek is steeds minder een aangelegenheid van eenlingen en het voor U liggende proefschrift is er het bewijs van dat nauwe samenwerking met een andere discipline de onderzoeksmogelijkheden sterk uitbreidt. Dit blijkt duidelijk uit de gebundelde publikaties in deel III van dit proefschrift, waarin meestal meerdere auteurs participeerden.

Het paleomagnetisch onderzoek dat uiteindelijk leidde tot dit proefschrift heeft zich sinds 1974 toegespitst op gesteenten uit Italië en hoofdzakelijk op diepzee kalken. Het aantrekkelijke van deze gesteenten is dat zij in ruime mate voorhanden zijn en dat zij zeer nauwkeurig kunnen worden gedateerd met mikro-fossielen. Het belangrijkste resultaat van het onderzoek in de Zuidelijke Alpen en Noordelijke Apennijnen is dat het verloop van de paleomagnetische veldrichtingen in detail kon worden vastgelegd voor het geologische tijdvak van Jura tot vroeg Tertiair. Deklinatie veranderingen van de geregistreerde paleomagnetische veldrichtingen werden verklaard door bewegingen van het korst gedeelte waartoe het Italiaanse schiereiland behoort en wel door rotaties tegen de klok in, terwijl de veranderingen in de inklinatie werden geinterpreteerd als een beweging naar de pool toe of er vanaf. Tevens kon worden vastgesteld dat, integenstelling tot de gangbare opvatting, in het Boven Krijt en in het Midden Krijt omkeringen van het aardmagneetveld zijn opgetreden.

Door de paleomagnetische resultaten uit Italië te vergelijken met de bekende gegevens uit Europa en Afrika was het mogelijk aan te tonen dat Italië tenminste gedurende de Jura en het gehele Krijt een noordelijk deel van Afrika was, maar dat in het Tertiair Italië werd ontkoppeld van Afrika en een onafhankelijke ro-

tatie tegen de klok in uitvoerde. De overeenkomst in paleomagnetische gegevens uit zeer uiteenlopende gedeelten van het Italiaanse schiereiland en struktureel geologische overwegingen maken het aannemelijk dat deze resultaten gelden voor een samenhangend gebied rond de Adriatische Zee. Op basis van reeds bekende paleomagnetische gegevens van de omringende kontinenten en door middel van de bekende rekonstrukties van de Atlantische oceaanbodem kon de positie van het Italiaanse schiereiland (in casu het "Adriatische blok") worden vastgelegd in het verloop van de tijd. Deze rekonstrukties vormen een kader dat kan leiden tot een beter begrip van de Alpine gebergtevorming.

PALEOMAGNETISM AND THE CHANGING CONFIGURATION OF THE WESTERN MEDITERRANEAN AREA IN THE MESOZOIC AND EARLY CENOZOIC ERAS

PART I

PALEOMAGNETIC DATA FROM THE WESTERN MEDITERRANEAN : A REVIEW

ABSTRACT

A review is given of paleomagnetic data that have become available during the last years. The accent of this review is on the paleomagnetic 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 paleomagnetic studies from the Western Mediterranean area has been published. Most of these studies were on Mesozoic and Tertiary rocks from the Apennines and Alps. All researchers had in common that they wanted to contribute to 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 that were put forward.
The confusion is caused mainly by the fact that some authors compare their paleomagnetic results either with European data, or with African data or compare the results with respect 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 paleomagnetic results proper attribute to this confusion also, since two rotational phases (Late Cretaceous as well as Late Tertiary) seem to have caused the westward offset of the paleomagnetic directions in the Apennine and Alpine realm. So it is necessary to distinguish the consequences of each of these rotational phases.
An other reason for confusion is that many areas studied by paleomagnetic groups 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.

Table I

Western European paleomagnetic poles

NUMBER 1)	Plat.	Plong.	N	α_{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, ..fers 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.

The present review is an attempt to put an end to this confusion, as far as possible, and to give the reader a coherent interpretation of all paleomagnetic data relevant for further geotectonic studies in Alpine Europe.

Table II

Russian paleomagnetic 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) 4-13 (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.

EUROPEAN APPARENT POLAR WANDER CURVE

In Table I a compilation of post-Hercynian paleomagnetic 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 paleomagnetic 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 paleomagnetic data from the major continental blocks according to their absolute ages. Then starting with the oldest data he calculated running mean values for overlapping 30 to 40 Myr. intervals moving forward the interval limits 10 Myr. at each step. This way a smooth polar wan-

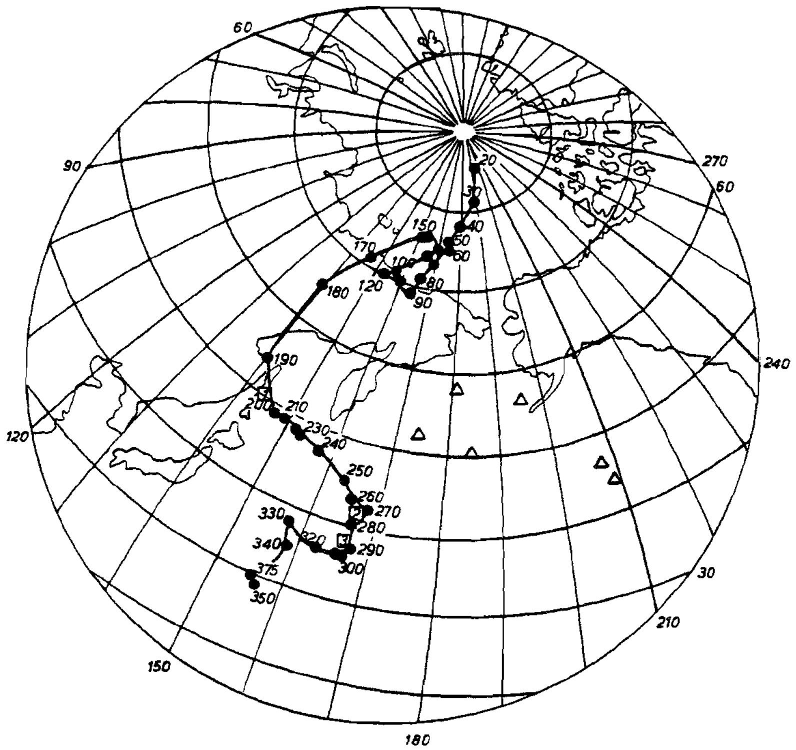

Figure 1. Equal area projection of the apparent polar wander curve of Eurasia (Irving, 1977). Numbers indicate ages in millions of years of paleomagnetic poles. Open triangles represent Permian paleomagnetic poles from Corsica (Westphal et al., 1976; Nairn and Westphal, 1968). Open squares containing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

der curve is obtained. For Eurasia Irving (1977) included data from Western Europe and as well 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 Paleozoic and Early Mesozoic data exclusively from Western Europe (Table I) have been plotted in Fig. 1 as well (open squares).
The proposed polar wander curve for Eurasia of Irving (1977) and the paleolatitudes 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 paleolatitude 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.

THE AFRICAN APPARENT POLAR WANDER CURVE

In Table III a compilation is given of the presently available paleomagnetic data from Africa; mean values were computed for different stages and plotted in Figure 2. Only a small number of paleomagnetic data of Mesozoic age have been published, some are based on a few samples only, others are 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 paleomagnetic 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 and French (1974) is plotted for comparison (full dots). Van der Voo and French (1974) calculated mean poles for time intervals ranging from Late Carboniferous to Early Eocene by averaging paleomagnetic poles of the Atlantic-bordering continents, with

Table III

African paleomagnetic 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.

respect to the paleopositions of these continents, as reconstructed from correlations of marine magnetic anomalies in the Atlantic Ocean (Pitman and 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 Paleozoic and Early Mesozoic paleomagnetic data from the continents that once formed Gondwanaland. The relative positions of these continents were reconstructed according to Smith and Hallam (1970). This polar wander curve is given in Figure 3. For the pre-Late Triassic data there exists a large discrepancy between the curves of Figure 2, derived from the "North Atlantic" continents, and the "Gondwana" curve of Figure 3. This discrepancy can be accounted for in different ways, such as by proposing an alternative fit (Van der Voo and French, 1974), see Figure 2, or by assuming a more or less continual motion in the Paleozoic of the major continents (Irving, 1977). Nevertheless the

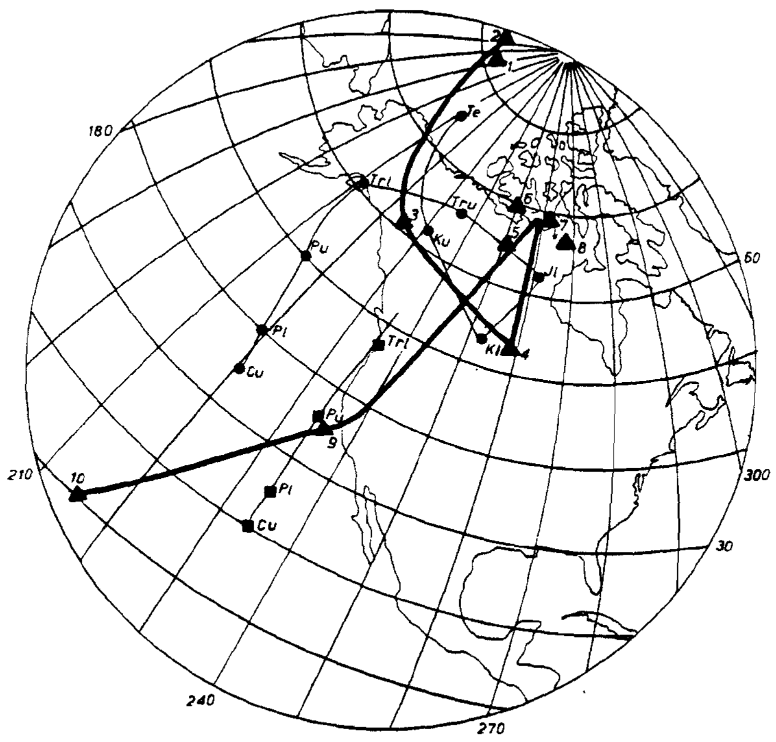

Figure 2. Equal area projection of the apparent polar wander curves for Africa. Heavy line is direct apparent polar wander curve connecting African observations (full triangles), which are compiled in Table III. Thin lines are indirectly obtained apparent polar wander curves, according to Van der Voo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

Middle and Late Mesozoic and Tertiary parts of these indirect polar wander curves are in good agreement with the observed African paleomagnetic 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 LePichon and Fox (1971), who determined the direction of early motion from the marginal fracture zones. In Figure 4 this indirect "African" polar wander curve is plotted. The applied initial fit of Africa and North America (LePichon and Fox, 1971) is only slightly different from the Bullard fit and therefore this "African" curve of Figure 4 is similar to the indirect polar wander curve of Van der Voo and French (1974), see Figure 2.

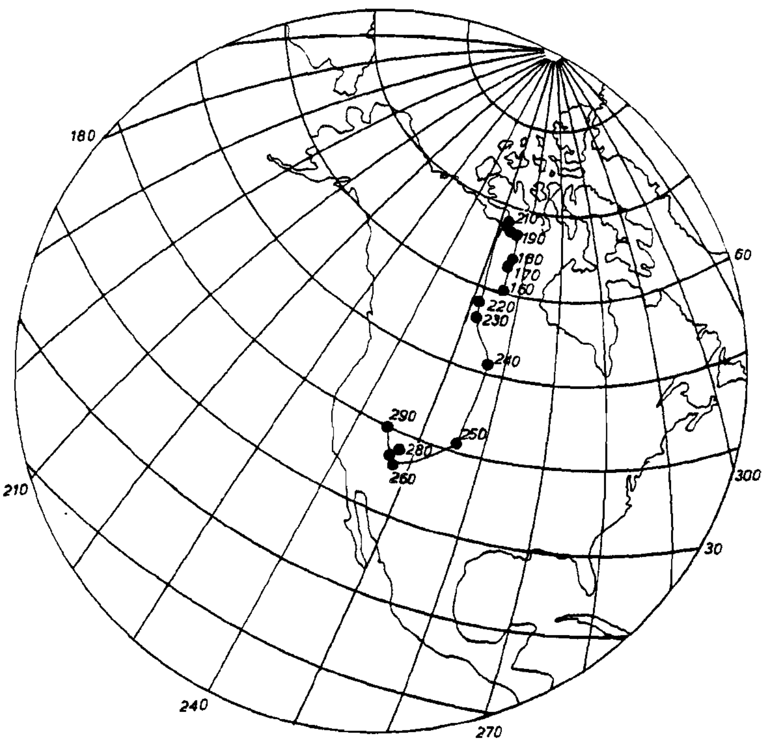

Figure 3. Equal area projection of apparent polar wander curve for Africa, as deduced from former Gondwana continents (Irving, 1977). Numbers indicate ages in millions of years.

The loop formed by the Mesozoic and Tertiary data is very conspicuous in Figure 2 as well as in Figure 4. The mean African paleomagnetic data of Table III for the Late Mesozoic and Early Tertiary coincide remarkably well with these indirectly derived Mesozoic and Tertiary loops of Figure 2 and Figure 4, not only in form but also in age. We may therefore conclude that although the scarcity and large scatter of the African Paleozoic 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 paleolatitudes in Table III :
Africa remained about stationary during the latest Triassic and Early Jurassic timespan. Paleomagnetic data that have absolute ages, ranging between 120-106 Myr. 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.

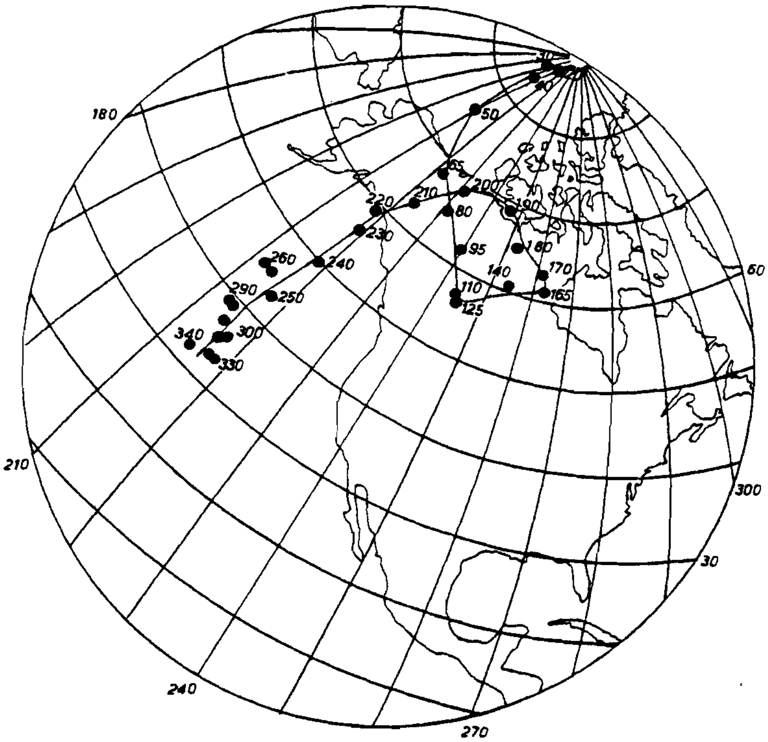

Figure 4. Equal area projection of apparent polar wander curve for Africa, transferred from the North American A.P.W. curve according to Irving (1977), having applied the stage poles for the Atlantic opening according to Sclater et al. (1977). Numbers denote ages of the paleomagnetic poles in millions of years.

When we compare the African movement scheme with the European one, than 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.

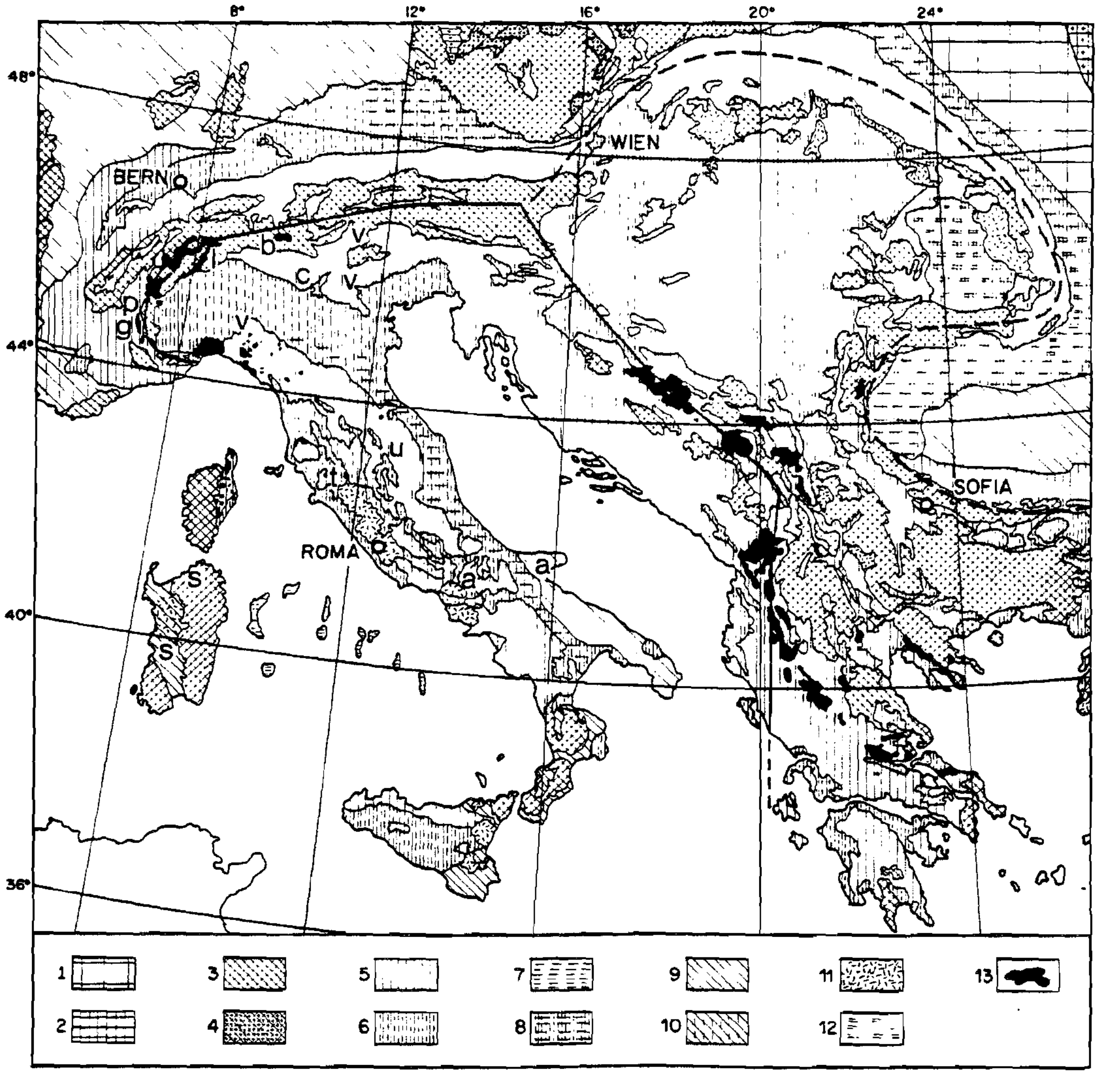

Figure 5. Geological map of the Alpine system around the Adriatic sea. Indicated are the locations of which paleomagnetic studies have been reported. Letters refer to Table IV and V.

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= Paleozoic platform, Alpine reactivated; 11= Volcanic complex; 12= Area of salt tectonics; 13= Ophiolites.

PALEOMAGNETIC DATA FROM THE ITALIAN PENINSULA, SARDINIA AND CORSICA

1) NORTHERN APENNINES (UMBRIA)

Many paleomagnetic workers have focused their attention on the Mesozoic of Umbria (Fig. 5) (Channell et al., 1978; Roggenthen and Napoleone, 1977; VandenBerg et al., 1978; and others). In Figure 6 is shown 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

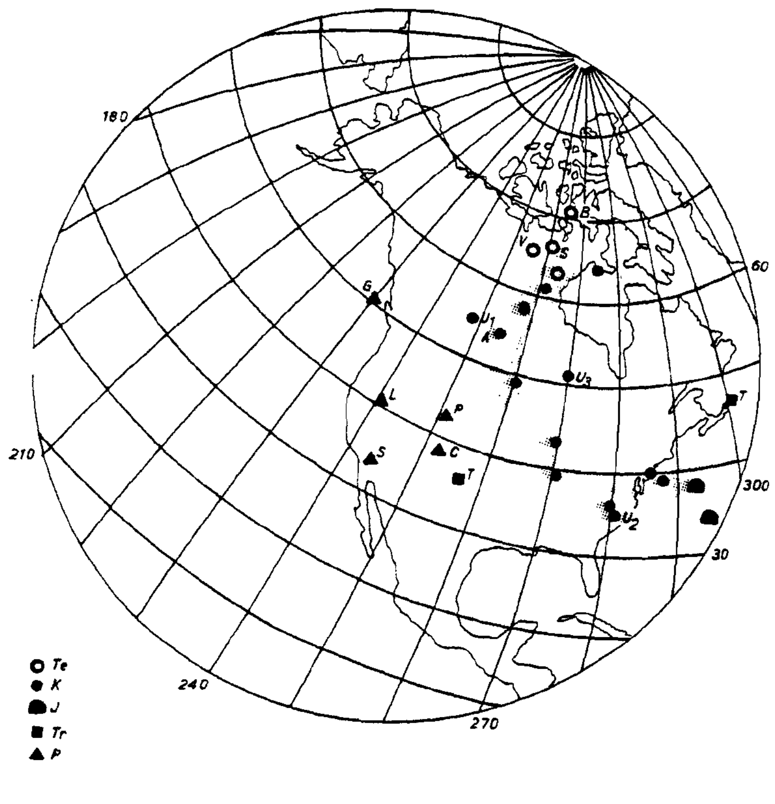

Figure 6. Equal area projection of apparent polar wander curve for the Adriatic continental block from Jurassic to Tertiary. Poles without label defining the stippled curve are according to VandenBerg et al. (1978). Triassic poles according to VandenBerg and Wonders (1976) and from VandenBerg (1979a). Other poles are identified by a letter to which is referred in the text and Table IV.

additionally in Figure 6. The mean results of Channell and Tarling (1975) are plotted, differenciated according to the assigned ages : poles "U_1" (KU-TL) and "U_2" (KL-KU). The mean result of Lowrie and Alvarez (1975) is represented by pole "U_3" (KL?-KU).
Paleomagnetic studies on geographically distributed sites in the southern part of Umbria show a difference in paleomagnetic direction with the outermost north western part (Gubbio and Moria/Cagli, Fig. 7) according to Channell et al. (1978). The bending of the Apennine trend and the more intense deformation in the southern part (see Fig. 7) can very well account for that.

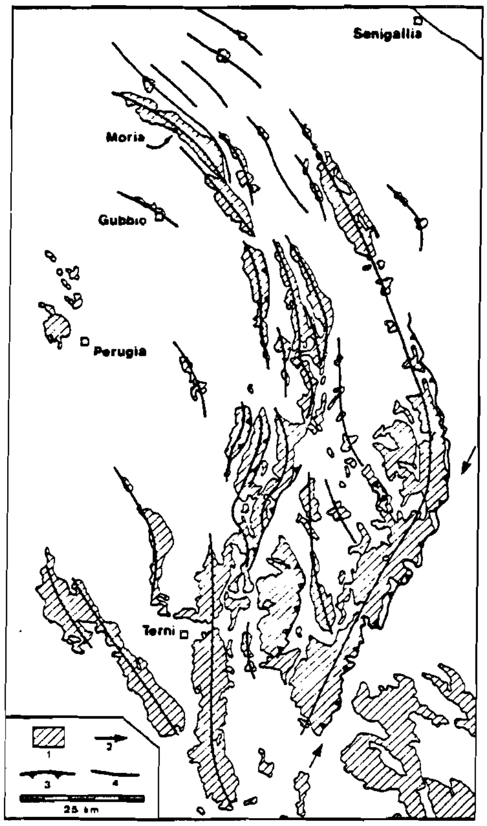

Figure 7. Structural outlines of the Umbrian Apennines, which show the change of the general (NW-SE) Apennine trend to locally NNE-SSW near the Anzio-Ancona line. Note the presence of thrusts or reverse faults in the Southern part. (1= major outcrops of the Upper Triassic to Lower Cretaceous of the sequence; 2= Anzio-Ancona line; 3= major reverse faults or thrusts; 4= anticlinal axes; after Channell et al., 1978).

When the Umbrian Mesozoic data in Figure 6 are examined than 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 merely depends on the age distribution of the studied sites.

2) CENTRAL APENNINES (TUSCANY)

Two paleomagnetic studies have been carried out in Tuscany (Fig. 5) on different lithostratigraphic units of the so-called Verrucano (VandenBerg and Wonders, 1976; VandenBerg, 1979a). The results have been plotted in Figure 6 as full squares. The ages that have been assigned to these units are Lower and Upper Triassic respectively, which is reflected in the different positions of the respective paleomagnetic poles. The study on the Lower Triassic rocks has revealed reversals, this in contrary to the Upper Triassic results which revealed only normal polarities. The paleomagnetic declinations of the Tuscan Triassic results are in agreement with the Jurassic paleomagnetic declinations from the Umbrian sequence (VandenBerg and Wonders, 1976; VandenBerg, 1979a).

3) SOUTHERN APENNINES (CAMPANIA AND GARGANO/APULIA)

Paleomagnetic studies in this area (Fig. 5) have been carried out on bauxites in Campania and Gargano (Channell and Tarling, 1975) and on platform limestones from the Gargano peninsula (Channell, 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 paleomagnetic results very similar to the bauxites (Channell, 1977).
The paleomagnetic results from the bauxites and from the platform limestones were combined and a mean pole was calculated. This mean result is slightly differing from Channell's result (1977), because only sites with an a_{95} smaller than or equal to 15^{o} were incorporated (VandenBerg and Wonders, 1979a). This Late Cretaceous result is plotted in Figure 6 and is represented by pole "A".

4) SARDINIA

Paleomagnetic data of Permian age (Westphal et al., 1976; Zijderveld et al., 1970) and of Oligocene/Early Miocene age (see review of Manzoni, 1974) are available from Sardinia. A mean pole has been calculated from all the Permian data (giving unit weight to each site), which is represented by pole "S" (full triangle) in Figure 6. The Oligocene/Early Miocene result, a mean value of all presently available data (Manzoni, 1974), is represented by pole "S" (open circle) in Figure 6.

5) NORTH WESTERN APENNINES

Early Tertiary paleomagnetic data were obtained from the outermost part of the North Western Apennines (Fig. 5) (VandenBerg, 1979b). A paleomagnetic study was carried out on Late Eocene to Early Oligocene sediments belonging to the base of the Piemonte Tertiary. 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 6 by pole "V" (open circle). Notice that its position is close to the Early Tertiary result from the Umbrian area (open circle without label).

6) SOUTHERN ALPS (WESTERN PART)

Several paleomagnetic studies have been carried out in this area (Fig. 5) on very different rock types. An Early Permian result has been reported by Zijderveld and de Jong (1969), obtained from the lower Collio and Auccia volcanics (Fig. 5). This result is plotted in Figure 6 as the Permian pole "C" (full triangle). In the Southern Tessin Alps, Van Hilten and Zijderveld (1966) have studied the Lugano porphyries (Fig. 5), also of Permian age. This result is represented in Figure 6 by the Permian pole "L" (full triangle). A paleomagnetic study on the Bergell granite (Fig. 5) by Heller (1973) has resulted in a paleomagnetic pole for this granite massif (30 Myr.) given as the Early Tertiary pole "B" in Figure 6 (open circle).

7) WESTERN ALPS

Paleomagnetic studies on the andesitic and lamprophyric dikes (30-33 Myr.) of the Sesia-Lanzo Zone (Lanza, 1977; Heller and Schmidt, 1974) have revealed paleomagnetic data which are fully comparable with the Bergell result. The tectonic deformation of this area, however, makes it advisable to disregard them here.

Paleomagnetic data have been reported from the Belledonne and Pelvoux Massifs (Westphal, 1973) and from the Brianconnais Zone (Fig. 5) (Westphal, 1973; Vander Voo and Zijderveld, 1969; Roche and Westphal, 1969). The paleomagnetic results of different localities in the external massifs (Belledonne and Pelvoux) show counterclockwise rotated paleomagnetic 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 paleomagnetic 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 from all the concerned paleomagnetic data (Westphal, 1973; Van der Voo and Zijderveld, 1969; Roche and Westphal, 1969), and this mean result is indicated by pole "G" in Figure 6 (full triangle). Also the result from Ponsonnière (Westphal, 1973) has been plotted as the Permian pole "P" in Figure 6 (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 paleomagnetic data do perfectly fit together, as will be specified later, but the data presented so far (Table IV) reveal a coherent picture. At first VandenBerg et al. (1978) hesitated to conclude that the paleomagnetic 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 paleomagnetic data from Tuscany (VandenBerg and Wonders, 1976; VandenBerg, 1979a) of the supposed autochtonous 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.

Table IV

Paleomagnetic 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.

Important in this respect are also the paleomagnetic data from Campania and Gargano/Apulia (Channell and Tarling, 1975; Channell, 1977), particularly those from the Gargano/Apulia region, that has not suffered a Tertiary deformation and that is generally supposed to represent the autochtonous backbone of Italy. It can be observed that these data match perfectly with the Umbrian data, if general reliability criteria are applied (VandenBerg and Wonders, 1979a). Compare pole "A" from the southern Apennines with the Umbrian data in Figure 6, and as well with the pole "U_1" from the Umbrian area.
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. A conclusion that is sustained by the fact that also other areas in Italy revealed Eocene-Oligocene paleomagnetic data, which are rotated over the same angle, and counterclockwise with respect to the present North. This is very clearly shown in Figure 6 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 additio-

nal support.
The paleomagnetic poles (Fig. 6) from Sardinia (Early Tertiary and Permian, poles "S") are remarkably close to the paleomagnetic poles from the Apennines and Southern Alps. This indicates a very close relationship between Sardinia and the main Italian peninsula. Geological and geophysical evidence that support this will be discussed in part II of this study.
Provisionally it can be concluded that presently available paleomagnetic 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 : the "Adriatic continental block", as it will be referred to.

8) SOUTHERN ALPS (EASTERN PART)

Paleomagnetic research has been carried out on rocks from the Dolomites and Vicentinian Alps (Fig. 5) over more than a decade (see Zijderveld and Van der Voo, 1973). The paleomagnetic poles that were published through the years have been

Table V

Paleomagnetic 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.

plotted in Figure 8 (Table V). While in the beginning the paleomagnetic research was mainly concentrated on rocks of Permian and Triassic age, more recently the rocks of Cretaceous and Jurassic age have been studied. Channell and Tarling (1975) studied pelagic carbonates of Late Cretaceous to Early Tertiary age (pole "V_1", in Fig. 8) and Mid-Cretaceous age (pole "V_2", in Fig. 8). VandenBerg and Wonders (1976) studied Late Cretaceous pelagic carbonates and Late Jurassic sediments, and their results confirmed entirely Channell and Tarling's findings (1975). Comparison of Figure 5 and Figure 8 shows the different position but corresponding pattern of both polar wander curves. Moreover, VandenBerg and 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 research (VandenBerg and Wonders, 1979b). 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 paleomagnetic 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 paleomagnetic directions still reveal low inclination values, presumably due to local tectonics which could not be corrected for (see Fig. 8, Table V). Paleomagnetic 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 the tectonic position of the rocks in the Alpine orogene and the metamorphic events that affected them.
The presently available paleomagnetic data from the North Western 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. It seems very well possible that the Judicaria line and the Pusteria line could have played an important role during the Tertiary. This once more shows that a continental block closely situated to a collision zone should not be regarded as a rigid entity.

9) CORSICA

Paleomagnetic studies on rocks of Late Carboniferous to Late Permian age have

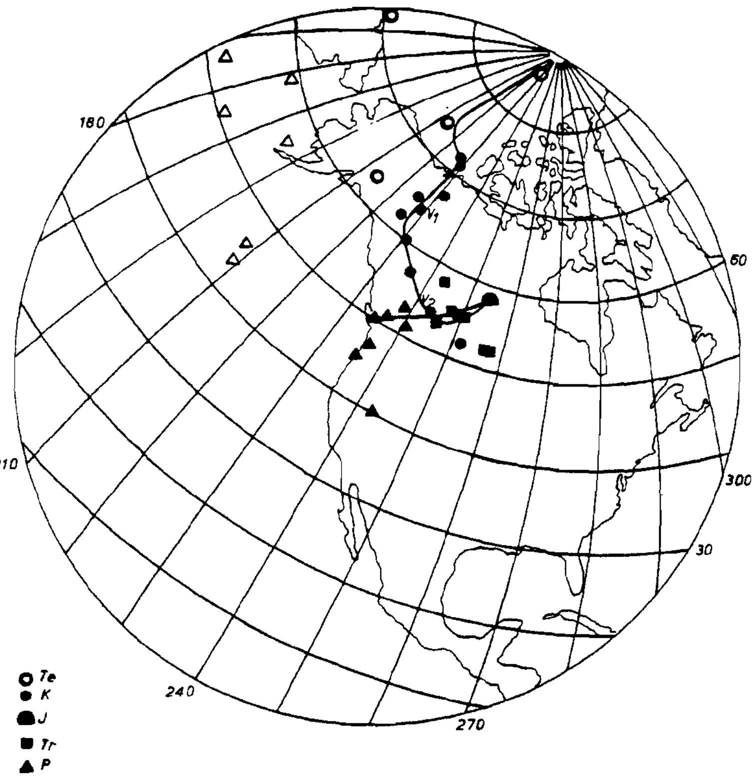

Figure 8. Equal area projection of the apparent polar wander curve for the Southern Alps (Eastern part), see Table V. Permian paleomagnetic poles (open triangles) from Corsica (Westphal et al., 1976; Nairn and Westphal, 1968).

been reported from Corsica (Nairn and Westphal, 1968; Westphal et al., 1976). These results have been plotted in Figure 1 and in Figure 8. Comparison of the Corsican data with the paleomagnetic data from the Southern Alps (Fig. 8) and with the data from the Adriatic block (Fig. 5) clearly shows that the Corsican data are not close to one of these A.P.W. curves. However, the Corsican data are close to the Iberian paleomagnetic data (see Fig. 1 and compare with Fig. 11), but the data are too few in number and all of about the same age, so no definite conclusions can be drawn from this fact. Nevertheless, those paleogeographic reconstructions that keep the Corsican block fixed to the Iberian peninsula are not in contradiction with the paleomagnetic data.

10) CALABRIA

Paleomagnetic data from Calabria (Manzoni, 1975) have been disregarded because of the tectonic position of the studied 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 6 with Figure 2 and Figure 4 clearly illustrates the identical U-shape of the Mesozoic polar wander pattern of Africa and of 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 the Late Cretaceous northward movement as specified by the Italian data (VandenBerg et al., 1978) is 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. 8) that is so characteristic for Africa's movement.
Therefore it can be concluded that paleomagnetic 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, and caused differential movements within this block.

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 paleomagnetic 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. Now the centres of gravity of both clusters are coinciding, but not necessarely 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.
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 counts, not the particular data on the curve. This is accomodating to the problem that many paleomagnetic 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, than all paleomagnetic data of intermediate ages can be used to establish the shape of the curve, and only paleomagnetic reliability criteria have to be applied.
The method is also very appropriate for fitting magnetic seafloor 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 : $15.15^{o}E$ $36.04^{o}N$ with an angle of rotation of -27^{o}. 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, see Figure 9. In the same figure the A.P.W. curves of Africa that have been derived earlier in this paper (Figs. 2 and 4) 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 10 all paleomagnetic data attributed to the Adriatic block are plotted, after having been rotated back.

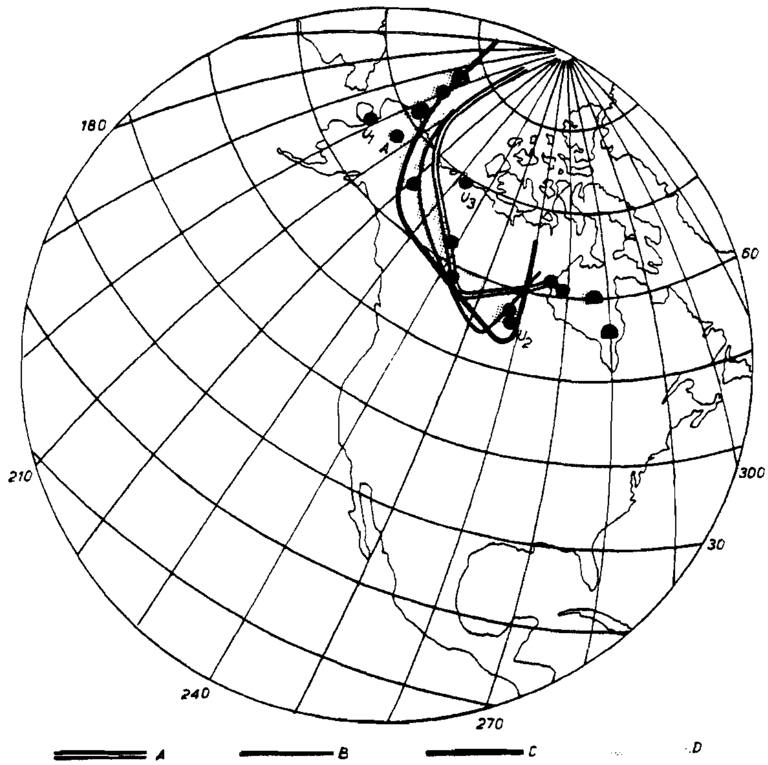

Figure 9. Equal area projection. Comparison of Mesozoic to Early Tertiary apparent polar wander curves from Africa (A= Fig. 4; B= Fig. 2) (Van der Voo and French, 1974);(C= Fig. 2 (Table III)). The A.P.W. curve for the Adriatic block is represented by the stippled curve (D= Fig. 6),rotated back to the African curves according to the Malta pole (see text). Letters refer to Table IV.

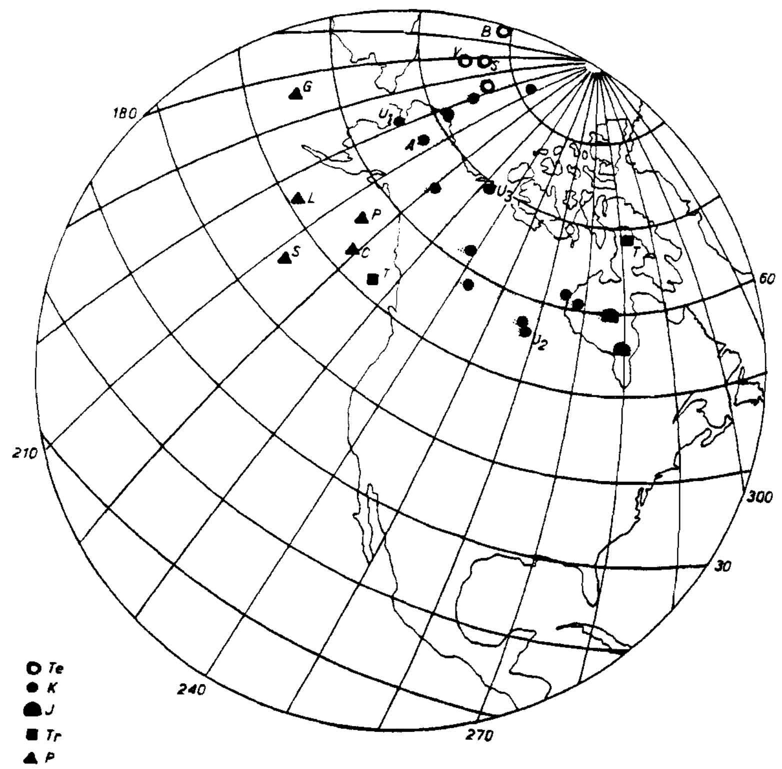

Figure 10. The apparent polar wander curve for the Adriatic block in equal area projection, after the independent Tertiary rotation has been nullified by an opposite rotation around the Malta pole. This curve can now be directly compared with Figures 2 and 4. Letters refer to Table IV.

Table VI

Paleomagnetic 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.

PALEOMAGNETIC DATA FROM THE IBERIAN PENINSULA

In Table VI a compilation is given of the presently available paleomagnetic data from Spain. In Figure 11 a comparison is given of these paleomagnetic poles with the A.P.W. curve of Europe from Irving (1977).
Zijderveld and Van der Voo (1973) argued that the counterclockwise rotation of Spain presumably occurred between Late Jurassic and latest Cretaceous. In Figure 11 it is clearly shown that the Late Cretaceous result (Van der Voo, 1967) is coinciding with the European A.P.W. curve. A latest Early Cretaceous paleomagnetic 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 Myr. (VandenBerg, 1979c).
Studies on the magnetic anomaly pattern of the Bay of Biscay have revealed addi-

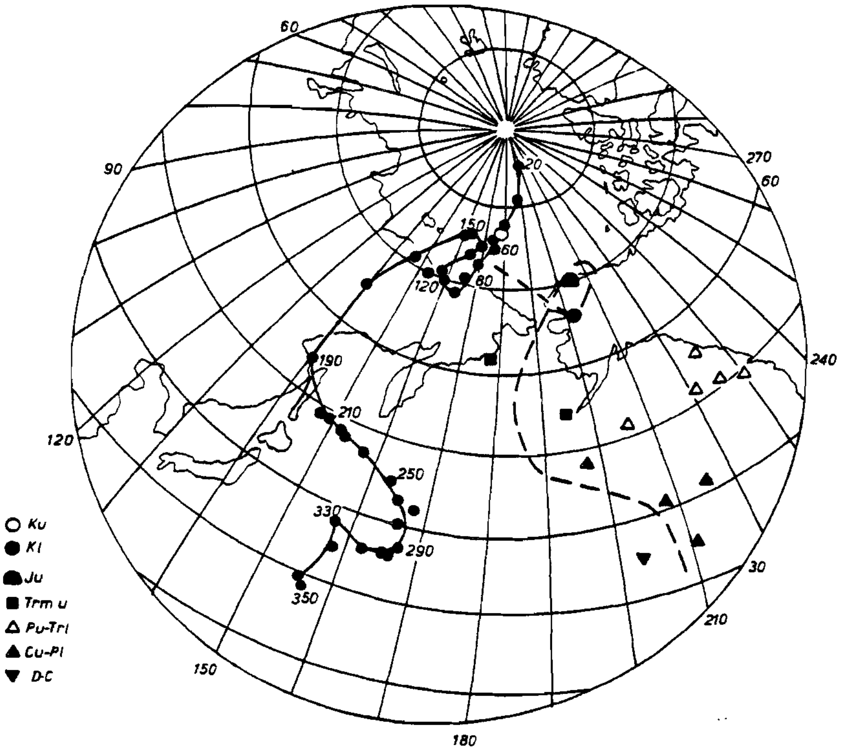

Figure 11. Equal area projection of the A.P.W. curve for Eurasia (Irving, 1977), and paleomagnetic poles from the Iberian peninsula (Table VI). Stippled line is the Eurasian curve transferred to the Iberian continent according to a rotation pole at 50.0 N 3.3 E and rotating over an angle of 25°. Numbers indicate ages in Millions of years.

tional 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 paleomagnetic 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 11 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

Paleomagnetic 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 belong therefore 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 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^{o}, around a pole situated close to the island of Malta.

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

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PALEOMAGNETISM AND THE CHANGING CONFIGURATION OF THE WESTERN MEDITERRANEAN AREA IN THE MESOZOIC AND EARLY CENOZOIC ERAS

PART II

RECONSTRUCTIONS OF THE WESTERN MEDITERRANEAN AREA FOR THE MESOZOIC AND TERTIARY TIMESPAN

ABSTRACT

Based on seafloor data and paleomagnetic results, reconstructions are given for the Western Mediterranean area, for the period of 165 Myr. to 10 Myr. ago. Reconstructions for 13 episodes provide a framework that can be used to unravel the history of Alpine orogeny. Of crucial importance in these reconstructions is the Adriatic continental block, the movements of which determined to a large extent the location of Alpine foldbelts in the Western Mediterranean.

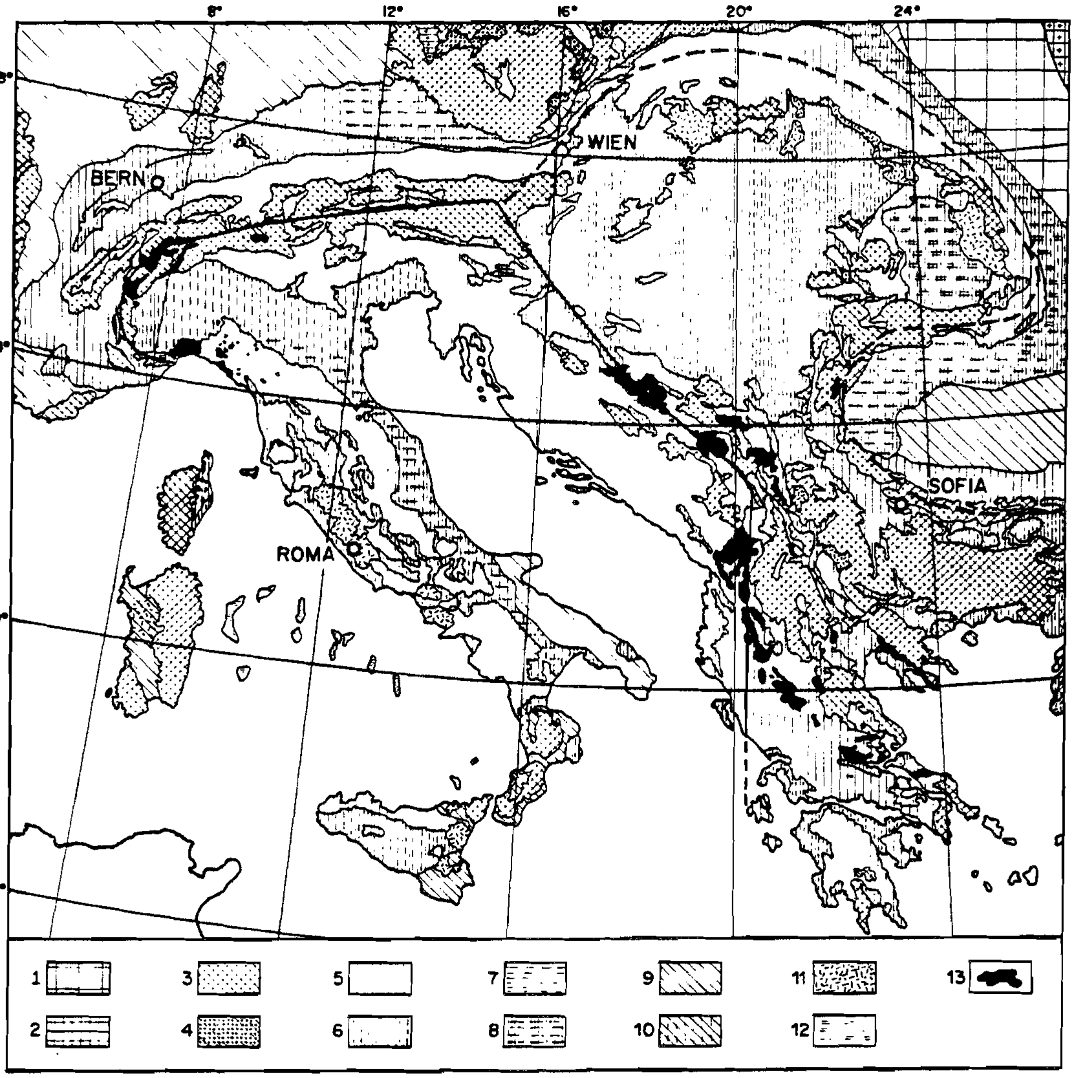


Figure 1. Geological map of the Alpine system around the Adriatic sea.
Legend : 1= Russian shield, undifferentiated; 2= Archaean shield; 3= Hercynian, undifferentiated; 4= Hercynian with Cadomian nuclei; 5= Alpine fold belts; 6= Inner basins; 7= Hercynian metamorphic basement (Selli, 1974); 8= Alpine molasse; 9= Mesozoic platforms; 10= Paleozoic platform, Alpine reactivated; 11= Volcanic complex; 12= Area of salt tectonics; 13= Ophiolites.
Heavy line is referred to in the text.

INTRODUCTION

Channell and Horvath (1976) advocated the "African/Adriatic Promontory", which is essentially the same as the Adriatic block of Part I, and assumed this promontory to have moved with Africa ever since the Early Mesozoic. They did not recognize the independent Tertiary movement of this block. Nevertheless, they showed that the concept of the Adriatic promontory provides a paleogeographic framework which fits the evolution of the Alpine system. The reconstructions of Biju-Duval et al. (1976), based on more recent seafloor data, differ from Channell and Horvath's approach (1976) by the assumption that the Adriatic block was an independent entity during all the Mesozoic and Tertiary, which also conflicts with the paleomagnetic data.
In Part I it has been argued that paleomagnetic data from various parts of the Italian peninsula and adjacent areas are consistent. These paleomagnetic data defined a crustal block that was called the Adriatic continental block. It was shown that this block was part of the African continent until Early Tertiary times, and a rotation pole, that describes the Tertiary decoupling, was derived mathematically. The Mesozoic apparent polar wander curves of Africa and the Adriatic block are in such agreement that large differential movements during Mesozoic times are very unlikely.
From these paleomagnetic results and from seafloor data, a series of palinspastic maps can be reconstructed, with implications that shall be discussed. In a general way a causal relationship between tectonic phenomena of widely separated areas is suggested. References cited are only indicative and by no way cover all the literature on the subject.

OUTLINES OF THE ADRIATIC CONTINENTAL BLOCK

In the following reconstructions an outline has been used for the Adriatic block (heavy line in Fig.1), which needs some explanation. It is fundamentally very difficult to delineate in an orogene the boundaries between blocks, because these variabled in time and are obscured by the latest tectonic phases. The margins of involved blocks probably changed during every movement phase and crustal fragments may have joined one or the other tectonic block for some time. Therefore the boundary of the Adriatic block in the Western and Eastern Alps has been taken arbitrarily.
The eastern margin of the Adriatic block is not sharply defined either. The Mesozoic sequences of the outer Dinarides show a close affinity to the Southern

Alpine sequences, but have been thrust towards the Adriatic sea (Aubouin, 1965). The ophiolitic suture is assumed to represent a fundamental boundary during Mesozoic times (Channell and Horvath, 1976), but during the Tertiary the boundary had most probably a more external position (closer to the Adriatic sea) represented by the Insubric fault system. The eastern boundary has been drawn southward across Albania, initially following the ophiolitic suture and then along the structural trends of the external Hellenides, west of the Gavrovo-Tripolitza zone. Support for the last part of the boundary is found in Biju-Duval et al.'s (1976) reconstructions, in the analysis of structural trends by Letouzey et al. (1976) and in the offshore continuation (Morelli et al., 1975a) of these trends.

Sardinia is assumed to have been part of the Adriatic block at least during post-Hercynian times, for the following reasons : 1) Paleomagnetic data clearly indicate so (Part I). 2) A continental Moho is indicated all over the traject Sardinia-Triëst at 35 km (Nolet et al., 1978). 3) The Tyrrhenian sea only became in the the Pliocene a deep sea (Selli, 1971; Morelli, 1970) and had essentially a continental crust, now melting up after its foundering. This is proved by the results of dredging (Fig. 1), which revealed Hercynian rocks over a vast area in the northern Tyrrhenian sea (Selli, 1974; Heezen et al., 1971). An almost continuous basement of Hercynian folded and metamorphic rocks is present in a region that comprises Western and Southern Tuscany, Sardinia and most of the Tyrrhenian sea. 4) Finally, Alpine elements in Northeastern Corsica do not continue southward and therefore do not separate Sardinia from the Italian mainland. There is no evidence why Sardinia should not be just simply part of the Adriatic continental block. Deep seismic reflection profiles reveal that in the Sardinia channel (Auzende, 1971) the continental Paleozoic basement is continuous between Sardinia and Africa, while the overlying unconsolidated sediments do not show any folding.
A stationary position relative to the European continental block is assumed for Corsica at least during the Tertiary. During the Mesozoic, Corsica is assumed to have moved with the Iberian peninsula, separated from Europe by an eastward branch of the Pyrenean fault zone, as proposed by Biju-Duval and Montadert (1976).

RECONSTRUCTION PARAMETERS

Reconstructions of the Western Mediterranean area were made for 13 episodes ranging in age from 165 Myr. to 10 Myr. (Figs. 2 and 3). The reconstruction

TABLE I

RECONSTRUCTION PARAMETERS FOR ADRIATIC BLOCK

	rel. to Africa			rel. to N. America 1)		
5 MA	36.04	15.15	0.0	70.50	341.30	- 1.35
10 MA	36.04	15.15	- 7.0	45.80	9.81	- 9.26
15 MA	36.04	15.15	-12.0	44.95	9.69	-15.49
21 MA	36.04	15.15	-18.0	44.09	9.55	-22.72
30 MA	36.04	15.15	-27.0	43.37	9.04	-33.66
38 MA	-	-	-	44.98	7.45	-35.75
53 MA	-	-	-	48.36	4.96	-41.23
65 MA	-	-	-	50.42	3.22	-45.71
80 MA	-	-	-	57.90	358.60	-53.05
95 MA	-	-	-	57.54	356.17	-60.22
110 MA	-	-	-	57.20	354.24	-67.39
125 MA	-	-	-	56.87	352.71	-74.52
140 MA	-	-	-	56.68	350.63	-81.60
165 MA	-	-	-	56.08	349.24	-98.25

1) Calculated from parameters according to Sclater et al., 1977.

parameters for these are essentially those that were proposed by Sclater et al. (1977). Sclater et al. (1977) ventured upon a renewed attempt, after Pitman and Talwani (1972), to reconstruct, by means of all seafloor data that came available since, the history of the Atlantic bordering continents. A major advantage is that they were able to incorporate the new data from the Bay of Biscay, which are of course crucial in any reconstruction of the Western Mediterranean. For a justification of the parameters the reader is referred to Sclater et al.'s original paper (1977).

The reconstruction parameters used for the Adriatic block are given in Table I. These were calculated, assuming the Tertiary rotation relative to Africa of the Adriatic block to have started later than 30 Myr.. A constant rotational movement for the Adriatic block around the pole 15.15^{o} E 36.04^{o}N and over an angle of 27^{o} was assumed during Late Oligocene and Miocene times, from 30 Myr. to 5 Myr.. The Adriatic block is kept fixed to Africa in all pre-21 Myr. reconstructions. The initial fit of the major continents (Fig. 3) is essentially that of LePichon et al. (1977), with a slight modification after Sclater et al. (1977).

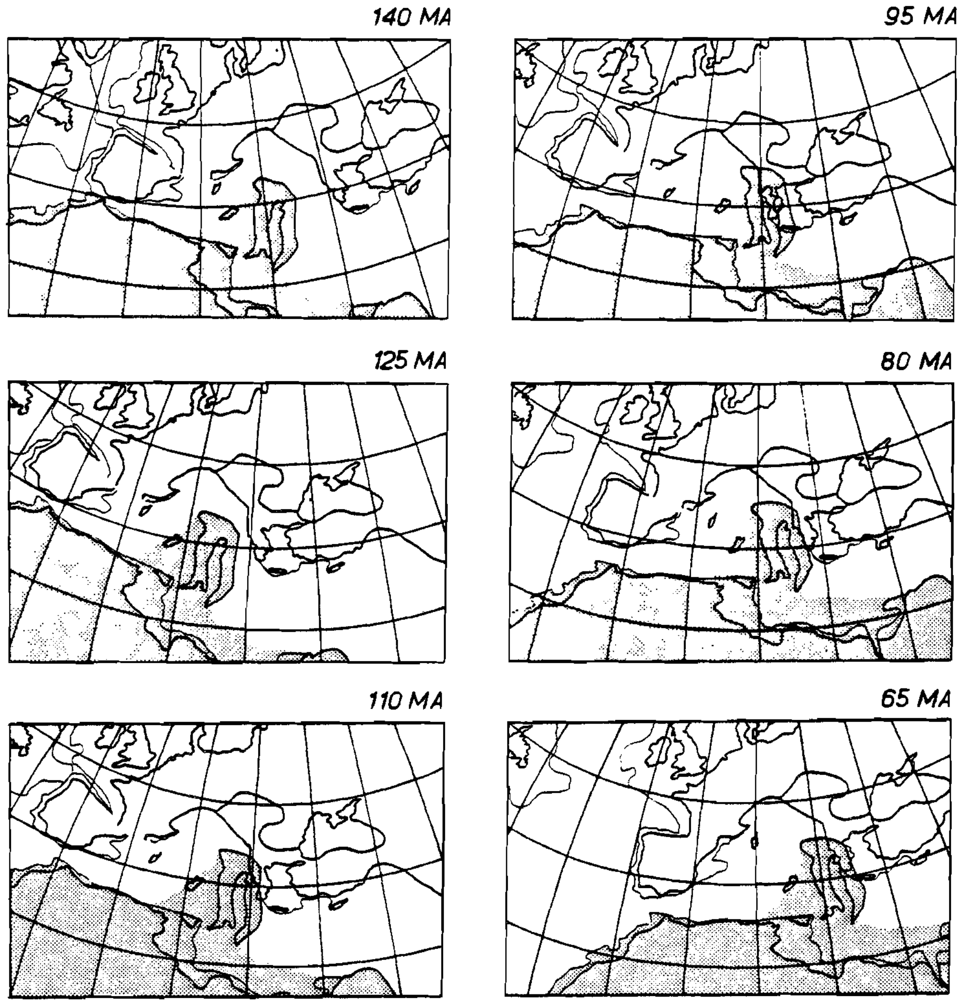


Figure 2A. Mesozoic reconstructions of the Western Mediterranean area. Stippled area represents the African continent and the Adriatic block. For parameters see Sclater et al. (1977) for the major continents and for the Adriatic block see Table I. Gridnet is kept fixed to N. America.

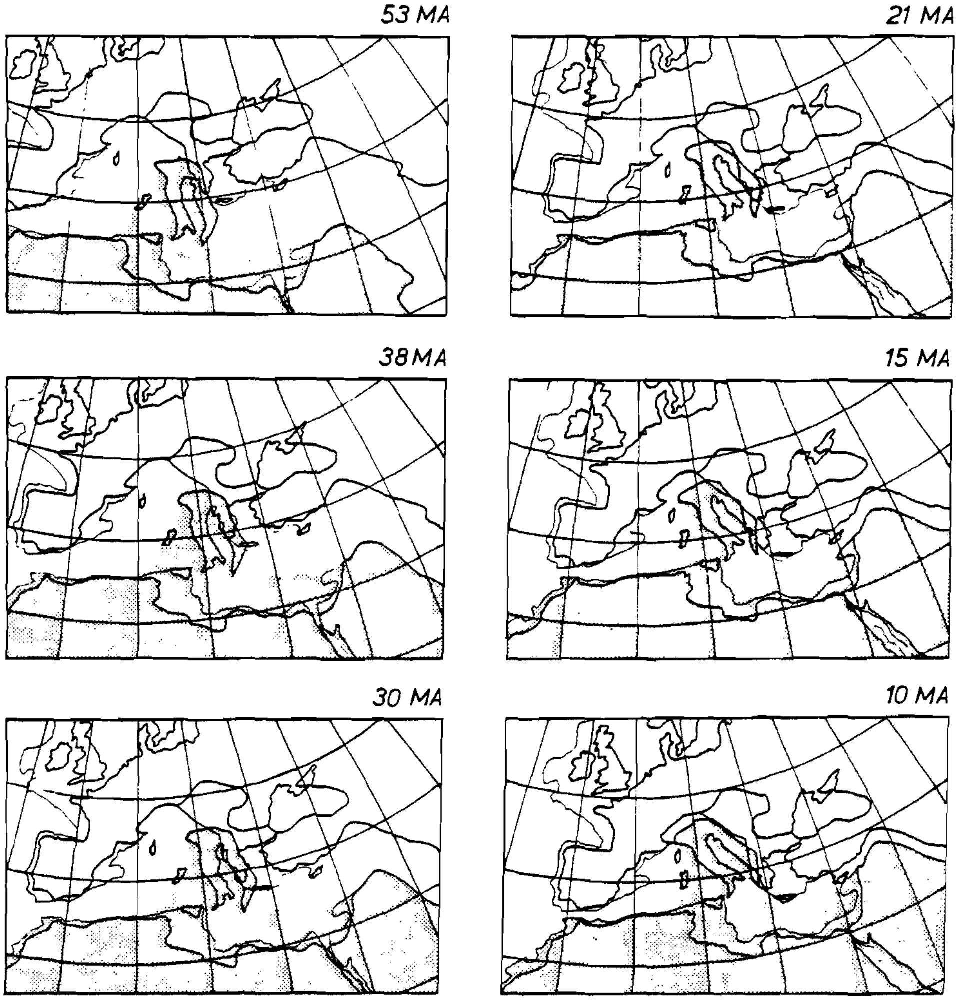


Figure 2B. Tertiary reconstructions of the Western Mediterranean area. For parameters see Sclater et al. (1977) and Table I for the Adriatic block. Simple application of these parameters result in an overlap in the Dinarides/ Hellenides region. Gridnet is kept fixed to N. America.

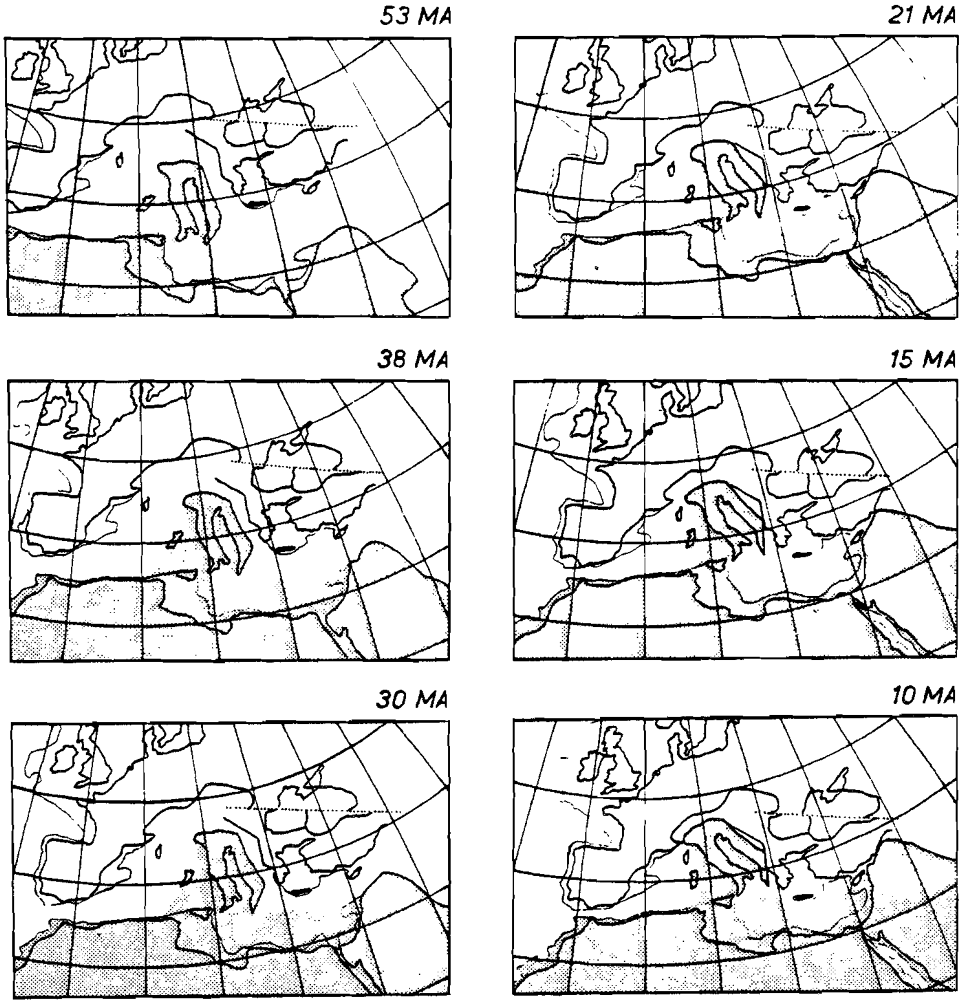


Figure 2C. Tertiary reconstructions of the Western Mediterranean. To avoid continental overlaps the Balkan-Rhodope-Turkey block has been shifted eastward relative to Eurasia, and is gradually shifted back in the 21 MA to 10 MA reconstructions. Gridnet is kept fixed to N. America.

DRIVING FORCES OF THE COUNTERCLOCKWISE TERTIARY ROTATION

Inspection of the 65 MA to 10 MA reconstructions (Fig. 2B) shows that during the Tertiary, differential movements between Africa and Europe were very small. Spreading rates in the North and Central Atlantic appear to have been about equally fast, so no important shear movement, that could have caused the counterclockwise Tertiary rotation of the Adriatic block, was therefore present. The 110 Ma to 10 MA reconstructions (Fig. 2A, 2B) suggest a major overlap of continental crust in the Dinarides and Western Hellenides, which is of course very unlikely. In Figure 2C the Tertiary reconstructions have been redrawn, to eliminate this overlap. This can only be accomplished by shifting eastward the Balkan-Rhodope-Turkey continental block. The new 21 MA to 10 MA reconstructions (Fig. 2C) demand a gradually westward shift of this Balkan-Rhodope-Turkey block to avoid an overlap of the Balkan-Rhodope-Turkey block and the Arabian block. This Late Tertiary to recently active movement of the Balkan-Rhodope-Turkey block is a well-known phenomenon (McKenzie, 1972, 1976) and is inferred to be caused by the northward movement of the Arabian (African) block relative to the European continent. The continent to continent contact in the Western Hellenides and Dinarides does not allow the movement of the Balkan-Rhodope-Turkey block to be absorbed by large scale crustal shortening. And therefore this movement was passed on to the Adriatic continental block. Together with the relative northward movement of the African continent a stress field was created in which the Adriatic block was constrained to rotate counterclockwise and to separate from the African continent.

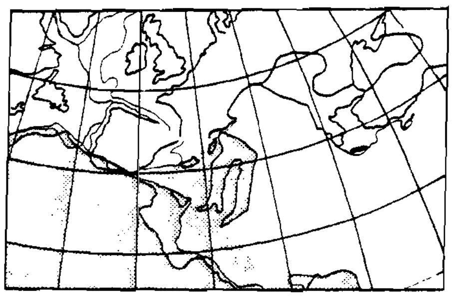


Figure 3. Reconstruction of the major continental blocks for 165 Myr. and before. Continents around the Atlantic in a best fit position. For parameters see Sclater et al. (1977) and Table I for the Adriatic block. The African continent and the Adriatic block are stippled. Gridnet is kept fixed to N. America.

MESOZOIC RECONSTRUCTIONS

The 165 MA reconstruction (Fig. 3) shows a familiar picture, since it has been produced before by various authors, following very different lines of reasoning (Smith, 1971; Bosellini and Hsü, 1973; Dewey et al., 1973). Corsica, Sardinia and the Balearic islands constituted an arc in a very similar way as has been proposed by Alvarez et al. (1974). If we suppose that the Great and Little Kabylian Massifs were originally located close to the Balearic islands, then the Western Mediterranean was completely closed by pre-Hercynian continental crust.

During the period of 165 Myr. to 110 Myr. the opening of the Central Atlantic caused the creation of new oceanic crust and extension of the former continental crust in the Western Mediterranean and Alpine region. Sardinia and the Kabylian Massifs formed the western continental margin of the Adriatic block (Fig. 2A). The extensional regime lost most of its effect in the Western Mediterranean after the Iberian peninsula started to separate from North America at about 110 Myr. and the formation of new crust ceased. In the Alpine region this happened slightly later after the European continent separated from Greenland and North America at about 95 Myr. (Fig. 2A). Early deformation phases in the Alps resulted from differences in spreading rate between the Central and North Atlantic. From 65 Myr. on the spreading rates in the Central and North Atlantic became almost equal.

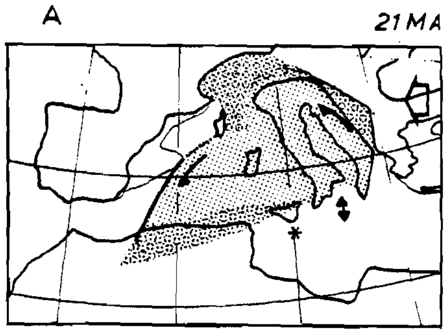
While in the Western Mediterranean and Alpine region an extensional regime dominated during the Late Jurassic and Early Cretaceous, in the Hellenides and Dinarides crustal shortening occurred during that time (Aubouin, 1965; Blanchet, 1976; and others). This can only be connected in a qualitative way with these reconstructions (Fig. 2A), since it is not known to what extend the Balkan-Rhodope-Turkey block was actively involved. The continental overlap in the Hellenides and Dinarides, as shown in the 110 Ma to 65 Ma reconstructions (Fig. 2A) only shows <u>that</u> the Balkan-Rhodope-Turkey block had to be situated in a more easterly position relative to Europe but it does not show how long this had been so. An eastward movement of this block during the Early Mesozoic as a result of spreading in the Eastern Mediterranean has been suggested (Dewey et al., 1973; Laubscher and Bernouilli, 1976; and others) to explain the ophiolite occurrences in Greece, Cyprus and Turkey.

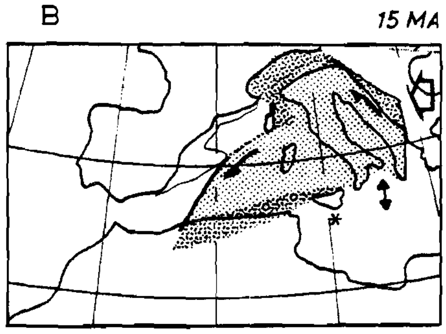
TERTIARY RECONSTRUCTIONS

From the 53 MA to 10 MA reconstructions of Figure 2C it appears likely that the relative northward movement of the African continent and the independent counterclockwise rotation of the Adriatic block caused the Alpine and N.W. Apennine fold belts. The new crust that had been formed in the Jurassic and Early Cretaceous was mostly destroyed during the Tertiary. The Western Alpine and Apennine belts were essentially created during the main orogenic phase in the Late Oligocene and Miocene, when the Adriatic block performed its counterclockwise rotation (Fig. 2C). This rotation could have generated the extensive Insubric and peri-Adriatic strike-slip fault system (compare the 30 MA to 10 MA reconstructions of Fig. 2C). The different structural evolution of the N.W. Apennines and the Southern Apennines was the logical consequence of the protruding position of Corsica. Crustal shortening occurred in the Alpine region and the N.W. Apennines, while the position of Corsica, east of the external Massifs in the Western Alps, caused the present offset between the N.W. Apennines and Western Alps. Laubscher (1971) has pointed this out before. The present reconstructions (Fig. 2C) clearly show that a Tertiary rotation of Corsica (Alvarez et al., 1974; Boccaletti and Guazzone, 1972; and many others) is not necessary at all to explain the evolution of the Western Alps and the N.W. Apennines, although it is not unlikely that as a reaction to the stress field the position of Corsica was adjusted.

The presented Mesozoic and Tertiary reconstructions (Figs. 2A, 2C) provide the space necessary for a palinspastic reassembly of the sedimentary basins of the Alps and N.W. Apennines (Laubscher, 1971). Notice that without a Tertiary rotation of the Adriatic block (Channell and Horvath, 1976) this reassembly should be problematic, since the differential movement between the European and African continent had been very small in the Tertiary, and a relative small northward movement of the African continent can hardly have resulted in east-west directed movements and compression in the Western Alps during the Miocene.

In Figures 4A and 4B two enlargements are given of the 21 MA and 15 MA reconstructions (Fig. 2C). It was assumed that the Tyrrhenian sea floor consisted of continental crust and formed, together with Sardinia, part of the Adriatic block, which mainly during the Mesozoic had been enlarged westward with newly formed oceanic crust. A Tertiary rotation of the Adriatic block would then imply crustal shortening in the area of the Tell Atlas and strike slip movements along the Baudot escarpment (East of Majorca) and its supposed north eastward continuation as illustrated in Figures 4A and B. These movements have been recognized by se-





Figures 4A, 4B. Enlargements of the Tertiary reconstructions of 21 MA and 15 MA (Fig. 2C). The Adriatic continental block is stippled, and the areas of crustal shortening are shaded. Arrows indicate relative movements. Asterisk indicates location of Malta rotation pole (see text).

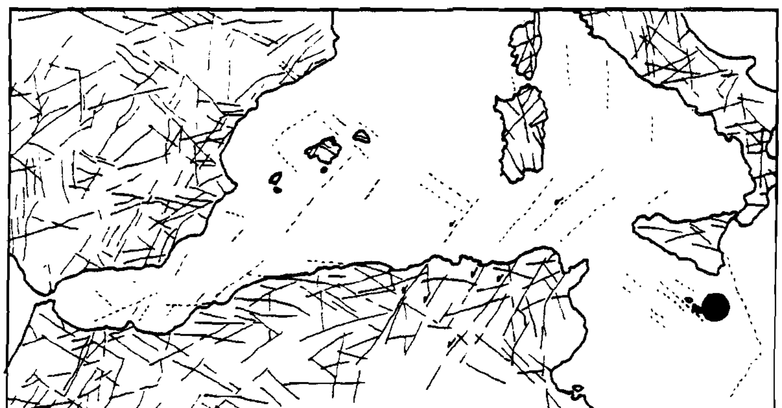


Figure 5. Major structural lineaments in the Western Mediterranean area, onshore after Letouzey et al. (1976) and offshore according to Auzende et al. (1973, 1974). Dot indicates the location of the Malta rotation pole (see text).

veral authors (Auzende et al., 1973; Auzende et al., 1974; Caire, 1973). Additional support is found in the directions of major onshore and offshore structural lineaments, which are lying more or less on small curcles of the Malta rotation pole, (Fig. 5) and are evidently related with the structural evolution of the Tunisian and Algerian fold belts.

It is very likely that the Balearic block joined temporarily the Tertiary movement, and that at least a part of the movement was passed on to continental areas west of the Baudot fault zone. The opening of the Gulf of Valencia and the foundering of the Provencal basin (Morelli et al.,1975b) can very well be associated with this Tertiary movement (Fig. 4). In any case these phenomena were synchronous.

The Tertiary movement of the Adriatic block implied for the area of the Ionian sea an extensional regime during the Late Oligocene and Miocene (Figs. 2C and 4). This is fully supported by the observations. The crust of the Ionian basin is continental, although presently involved in a process of oceanization (Morelli et al.,1975c). The Moho below the abyssal plain of the Ionian sea is only at a depth of 17 to 19 km (Weigel, 1974). This Moho deepens towards Calabria, the Peloponnesus, the Eastern Mediterranean and towards the Malta shelf (Makris, 1977; Weigel, 1974).

Foundering of the continental crust was already active in Early Miocene times (Finetti and Morelli, 1972; Hinz, 1974), and continued until Quaternary times.

CONCLUSIONS

Reconstructions of the Western Mediterranean area that are based on seafloor data and paleomagnetic results (Part I) reveal a coherent picture and can be used as a framework for the Alpine orogeny.

The Tertiary independent counterclockwise rotation of the Adriatic block is an essential part of this framework and it brings into a causal relationship very different fold belts and the foundering of the Ionian sea.

The driving forces of this Tertiary rotation were generated by the westward movement of the Balkan-Rhodope-Turkey block and the Northward movement of the African continent.

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PALEOMAGNETISM AND THE CHANGING CONFIGURATION OF THE WESTERN MEDITERRANEAN AREA IN THE MESOZOIC AND EARLY CENOZOIC ERAS

PART III

SUPPORTING PAPERS

TOELICHTING

Toegevoegd op verzoek van de promotor Dr.E. ten Haaf.

In verband met het feit dat het hier een promotie betreft op publikaties, waarbij de promovendus in een aantal gevallen niet de enige auteur is, lijkt het wenselijk het aandeel van de medeauteurs toe te lichten.

Drs.A.A.H. Wonders heeft zijn vakkundige bijdragen geleverd, waar het de determinatie van planktonische foraminiferen in Onder en Boven Krijt monsters betrof, en was behulpzaam bij het verzamelen van gesteente monsters in Spanje.

Dr.C.T. Klootwijk , die als eerste de bruikbaarheid ontdekte voor paleomagnetisch onderzoek van pelagische kalken uit Umbrië (Italië), was aktief betrokken bij het verzamelen van monsters in de omgeving van Cagli (Umbrië) en zijn bij eerder onderzoek opgedane ervaring was van groot nut voor de promovendus.

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LATE MESOZOIC AND CENOZOIC MOVEMENTS OF THE ITALIAN PENINSULA : FURTHER PALEOMAGNETIC DATA FROM THE UMBRIAN SEQUENCE

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ABSTRACT

About 210 samples of rocks of late Early Jurassic to early Tertiary age from 37 sites in the Umbrian carbonate sequence in the Northern Apennines were investigated paleomagnetically. Special attention was paid to the Scaglia Formation of Cenomanian to middle Eocene age, and three well-correlated sections were studied in detail. Accurate relative ages were determined from the well-preserved planktonic foraminiferal faunas.

Paleomagnetic directions of Toarcian-Aalenian to Late Aptian sites group fairly well, which implies the absence of major rotational and latitudinal movements of the sampling area during that interval. An only minor phase of movement at about Tithonian time resulted in a counterclockwise rotation over approximately 10°. Late Aptian to late Cenomanian directions indicate a southward movement over 10° of latitude; this was followed by a 30° counterclockwise rotation during Turonian, Coniacian, and Santonian time, and in addition, a northward movement over 10° of latitude during Santonian and Campanian time. Maastrichtian to early Eocene data group reasonably well but also deviate from the present local field direction; this indicates a further 25° counterclockwise rotation and an additional northward movement over more than 10° post-early Eocene time.

We suggest that the data presented here from the Northern Apennines are representative for the general pattern of movements of the Italian Peninsula. These paleomagnetically deduced movements conform during at least late Early Jurassic to early Tertiary time with the movements of the African plate as established from sea-floor spreading and paleomagnetic data. At the same time, however, the paleomagnetic results indicate that this coupled motion of the Italian Peninsula and the African continent did not persist until the present : a post-early Eocene 25° counterclockwise rotation of the Italian Peninsula must have occurred relative to Africa.
Our data are compared with available paleomagnetic data from the western Mediterranean area. Their relation to the structural evolution of the areas concerned is discussed.

INTRODUCTION

The quantity of paleomagnetic data from the Mediterranean area is rapidly incrasing because many groups have focused their research on this complex area. Paleomagnetic investigations are relatively important, since magnetic anomaly patterns in the Mediterranean are not well developed and give little or no information about megatectonic history. Recently proposed models for the structural evolution of the Mediterranean, like those of McKenzie (1970) and Dewey and others (1973), imply a complex pattern of plates and microplates moving relative to each other. The postulated movements of these plates can be tested by establishing standard paleomagnetic directional sequences in autochthonous elements on the plates.
Conclusions on the megatectonic history of the Mediterranean have been drawn mainly from well-established magnetic anomaly patterns in the North Atlantic (Smith, 1971; Phillips and Forsyth, 1972; Pitman and Talwani, 1972; Dewey and others, 1973). These analyses of the movements of the African plate and Europe, based on the successive opening phases of the Atlantic, give little information on the movements of minor plates in the enclosed Mediterranean area. Delineation of these minor plates and determination of their relative movements are problems yet to be solved. Paleomagnetic data are crucial in this respect.
Zijderveld and Van der Voo (1973) postulated that major parts of Mediterranean Europe formed part of the African plate during its post-Hercynian history. Their hypothesis was mainly based on the following observations: (1) The then available pole positions from the Iberian Peninsula and the Southern Alps conform with the

apparent polar wander path of Africa. (2) Well-established paleomagnetic data from some major units of Mediterranean Europe indicate similar rotations of comparable magnitude. (3) A synchronism in rotation of the Iberian Peninsula (between Late Jurassic and Eocene time) and Southern Alps (between Middle Triassic and Eocene time) with the rotation of the African plate (between Early Cretaceous and Eocene time) seems probable. Schult (1973) put forward a similar conclusion for Sicily. However, evidence obtained by Soffel (1972, 1974, 1975b) for a late Eocene to early Oligocene rotation, as shown in volcanic rocks from the northern Po Plain area, and Sardinia's Oligocene to early Miocene rotation (De Jong and others, 1973; Coulon and others, 1974) suggest that Zijderveld and Van der Voo's basically simple hypothesis needs further testing and elaboration.

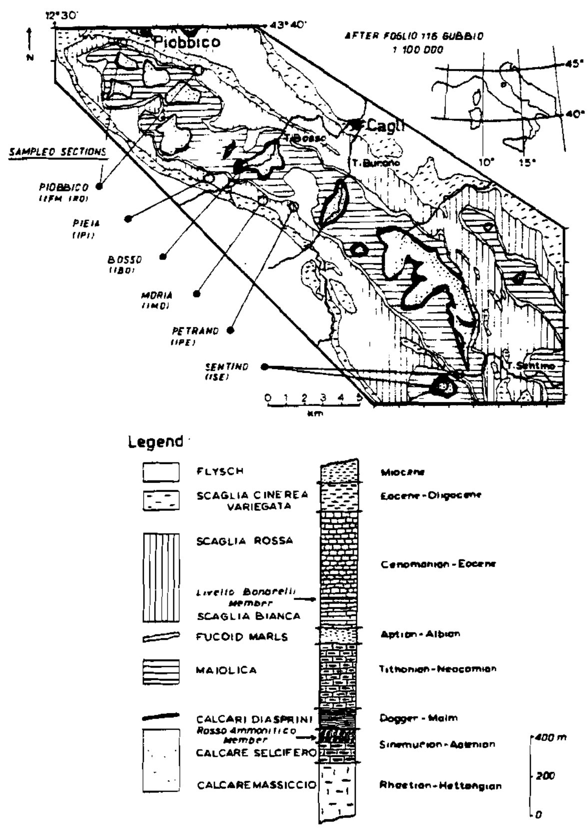


Figure 1 - Idealized stratigraphic column of the Umbrian sequence (Bortolotti and others, 1970, p. 354) and map of the Cagli area, Umbria, with sampling localities indicated.

GEOLOGIC SETTING, SAMPLING, AND DATA ANALYSIS

The paleomagnetic investigations were focused on the Mesozoic Umbrian carbonate sequence. In contrast to the adjacent Liguride and Tuscan sequences, developed largely in nappe structures (allochthonous), the Umbrian sequence is generally supposed to be autochthonous.

Outcrops of the Umbrian carbonate sequence are located in the southeastern part of the Northern Apennines and form a regularly curved belt about 200 km long and 60 km wide at its greatest width. This belt (Fig. 1) stretches southward from the Cagli area (lat 43°33'N, long 12°41'E), near the classical stratigraphic section of the Bottaccione gorge at Gubbio, near Rieti (lat 42°25'N, long 12° 52'E); the belt is truncated to the southeast by the Anzio-Ancona line.

We mainly directed our attention to the Cagli area, where the Umbrian sequence occurs in a wide northwest-trending anticline with a slight northwest plunge. The moderately dipping southwestern limb proved to be particularly attractive for paleomagnetic sampling. The steeply dipping, and locally overturned, northeastern limb is of complex structure; therefore, we restricted the sampling here to an application of the fold test only.

The Umbrian sequence is generally considered to be of miogeosynclinal nature and its lithology, as represented in the idealized stratigraphic column (Fig. 1), was desçribed in detail by Bortolotti and other, (1970).

In the sampling area, the outcropping rocks grade from a basal (Upper Triassic to Lower Cretaceous) sequence of limestones with some marly and siliceous intercalations (that is, the Calcare Massiccio, Calcare Selcifero (including the Rosso Ammonitico Member), Calcari Diasprini, and Maiolica) into the middle Cretaceous Fucoid Marls, which form the base of huge escarpments. The overlying limestones and marly limestones of the Scaglia Formation, which is informally subdivided into a lower "Scaglia Bianca" and an upper Scaglia Rossa unit, are well exposed in these escarpments. The lithologic boundaries between the units of the Scaglia Formation are quite irregular and probably not isochronous. A remarkable lithologic marker in the Scaglia Bianca is the bituminous Livello Bonarelli Member, a black shale with radiolaria and as much as 20% organic matter. The Scaglia Rossa, the youngest unit sampled for this study, ranges into the middle Eocene part of the section.

Preliminary sampling (10 sites, 43 samples) in the summer of 1973 appeared to be successful (Klootwijk and VandenBerg, 1975), and further detailed sampling was carried out in the summer of 1974 (37 sites, 210 samples). Especially in the Scaglia Formation, the sites were located in continuous sections (rather than being geographically distributed) in order to detail the sequential order of paleomagnetic direction changes. Red Scaglia limestones were sampled in three sections of about 10 sites each in fresh road cuts in the southern limb of the anticlinal structure - namely along the Pianello-Pieia road, the Moria-Monte Petrano road and the Monte Petrano-Ponte d'Azzo road (Fig. 1). In addition, shorter sections and some separate sites were sampled in the Rosso Ammonitico, in a siliceous red limestone bed in the Calcari Diasprini, in the basal Maiolica beds, in the Fucoid Marls, and, again, in the Scaglia Formation. The additional samples from the Fucoid Marls and Scaglia Formation were collected from the plunging nose and the northern limb of the anticline for an accurate application of the fold test. At each site, and in more detail, throughout the sections, special samples were collected for micropaleontologic studies. The rich and well-preserved planktonic foraminiferal faunas of the Umbrian sequence were promising for the construction of a rather continuous and well-dated paleontologic record of successive movements of the Northern Apennines.

MAGNETIC PROPERTIES

In the laboratory, core specimens (2.2 cm height, 2.5 cm diameter) were drilled from the hand samples. All measurements were done at the Paleomagnetic Laboratory of the State University of Utrecht by means of the Czechoslovakian JR-3 spinner (Jelinek, 1966).

The specimens were subjected to standard alternating field (AF) demagnetization, and for a few sites, to thermal demagnetization as well. At least one pilot specimen from each site was progressively demagnetized in 10 to 15 steps up to the maximum obtainable peak value of 3,100 Oe or up to 700°C. Following these pilot demagnetizations, at least five other specimens from each site were partially progressively demagnetized in 6 to 10 steps in the appropriate alternating field or thermal range.

Through analysis of orthogonal projections (Zijderveld, 1967, 1975), showing sequential changes of the magnetization vector upon demagnetization, the characteristic and secondary magnetization components could be separated and their directions determined. For computation of mean directions, Fisherian statistics were used.

The intensity of initial remanent magnetization of the samples was very weak, generally ranging from 10^{-5} to 10^{-7} Gauss. Initial specimen directions from all sites were distributed mainly in the lower hemisphere (Fig. 2A), with a clear tendency for concentration toward the northern quadrants. This is largely due to an appreciable secondary component related to the present local field (D=359°, I=+59°).

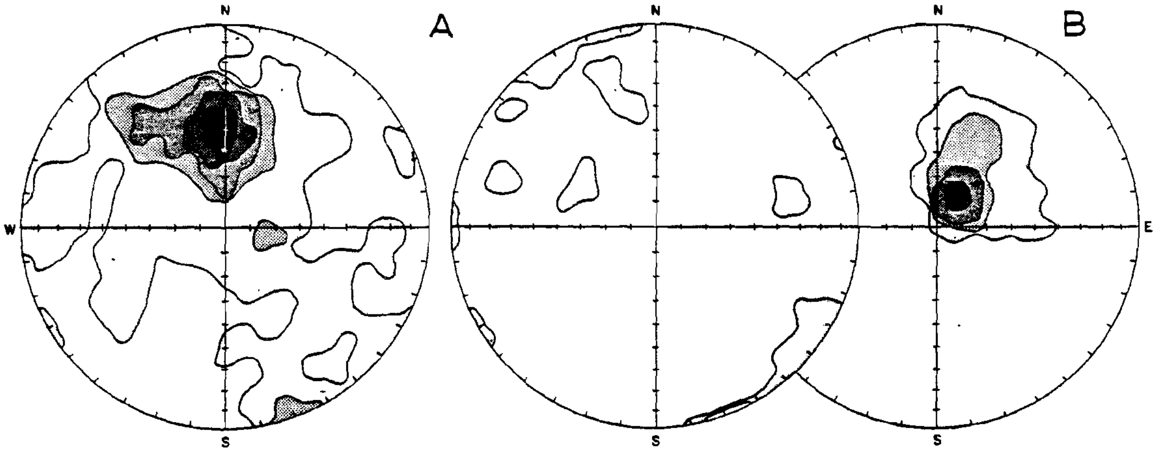


Figure 2 - Density distribution of remanent magnetization directions in equal-area projection, top view. The asterisk (white on black) denotes the present local field in the sampling area. (A) Initial remanent magnetization directions, lower-hemisphere (left) and upper-hemisphere projections (right). (B) Soft secondary magnetization components in lower-hemisphere projection.

In total, three vectorial components could be distinguished in the progressive demagnetizations. A soft secondary magnetization component of large intensity and aligned according to the direction of the present local field or, in case of the Scaglia samples with a somewhat more northeasterly declination (Fig. 2B), was generally removed upon AF demagnetization at 100-Oe to sometimes 200-Oe peak value. From 100 to 200 Oe onward up to 500 to 700 Oe for the Scaglia samples and up to much higher peak values for the samples of other formations, the characteristic magnetization component was eliminated. In the Scaglia samples, another hard secondary magnetization component was found, also aligned to the present-day local field. This hard secondary magnetization could be generally removed between 500 and 3,000 Oe-peak value. This removal occurred sometimes separately from, sometimes simultaneously with, a remaining part of the characteristic magnetization; thus the directions of these very hard secondary magnetizations were sometimes difficult to determine accurately.

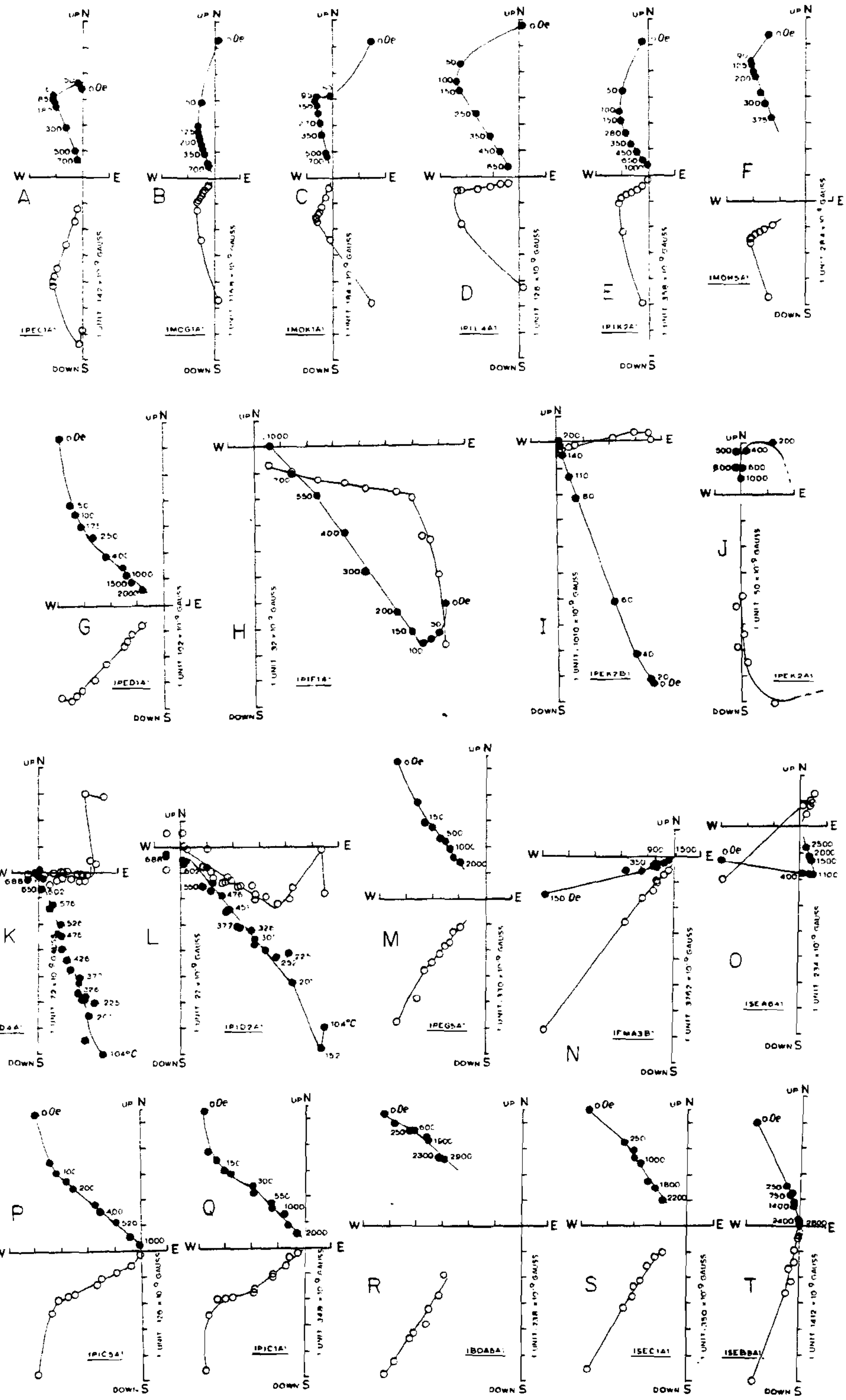


Figure 3. Orthogonal projections diagrams of the vector path of the total remanent magnetization vector during AF cleaning (A through J, M through T) or thermal cleaning (K, L). Circles are projections on the vertical east-west plane; dots are projections on the horizontal plane. Numbers denote peak values of the applied alternating fields (in oersteds) or values of the applied temperatures (in degrees Celsius). Underlined specimen code given in each diagram. Diagram J represents projections on an enlarged scale of diagram I, for the final demagnetization steps only. Note that 1 gauss = 10^3 A/m; 1 Oe = 10^{-4} T (tesla).

Scaglia Rossa and Bianca

The characteristic remanent magnetizations of the Scaglia samples are mainly of normal polarity, but reversed polarity directions were noted in its upper part (sites IMOO, IPID, IMOM, IPIF, IPEK, ISEA, IBOC, Table 1). In all Scaglia samples (Figs. 3A through 3H) a mainly northeast to north directed, steeply downward dipping secondary component of appreciable intensity - that is, 25% to 75% of the initial intensity (Fig. 3, 4A) - was removed upon AF demagnetization at about 100- to sometimes 200-Oe peak value. This soft secondary component, resembling the present local field direction, was present in both the samples of normal polarity (Figs. 3A through 3G) and of reversed polarity (Fig. 3H). In Figure 3I and 3J, we show a special case in which a very small soft secondary component is present in a reversed polarity sample. Well-concentrated characteristic directions were removed in general between 100-Oe and 700-Oe peak values (Figs. 3A through 3D, 3H), with a slight part of the characteristic component residing in domains with higher coercive forces (Figs. 3E, 3G). Sometimes a third magnetization component was removed upon demagnetization above 700 Oe. This component was identified before (Klootwijk and VandenBerg, 1975) as another "present local field" component residing in domains with higher coercive forces. Although good AF demagnetization results were obtained for a number of sites (Figs. 3H through 3J), thermal demagnetization was the preferred technique for site IPID as shown in Figures 3K and 3L. Upon thermal demagnetization of the samples from this site, the present local field component was removed around 100 to 150°C. The direction of the characteristic magnetization component could be determined accurately upon progressive demagnetization between 250 and almost 600°C (Fig. 3L) or higher (Fig. 3K). After thermal demagnetization up to the Curie temperature of magnetite (about 580°C), the small remaining magnetization (Fig. 4B), with a Curie temperature of about 650°C, indicated hematite to be present as well. As shown in Figure 3K, this small hematite magnetization component has a direction similar to the characteristic magnetization residing in the magnetite. A similar observation was noted also by Lowrie and Alvarez (1975).

Three sites in the upper part of the Scaglia Rossa in the northwest-plunging nose of the anticlinal structure yielded dispersed and uninterpretable results. These are probably due to the effect of drag folds, which are at places extensively developed in the Scaglia Formation (Fazzini, 1973).

The fold test, applied to samples from both the gently dipping southern limb and the subvertical northern limb of the anticlinal structure (Fig. 5), clearly indicates the characteristic magnetization component to be of pretectonic, that

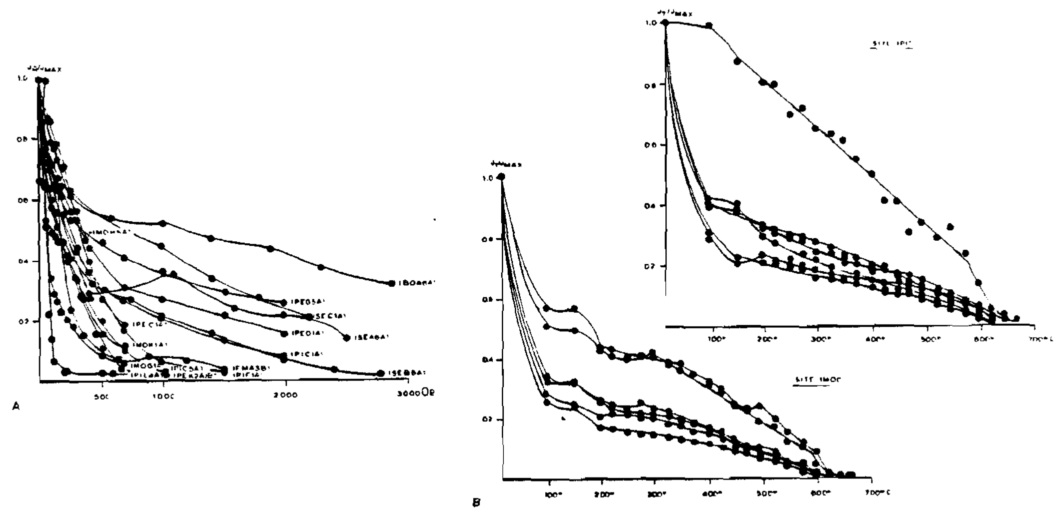


Figure 4 - Normalized curves, showing the decrease of total remanent magnetization during AF cleaning (A) and thermal cleaning (B). J_H/J_{max} and J_T/J_{max} are normalized intensities of the natural remanent magnetization during alternating field and thermal cleaning, respectively.

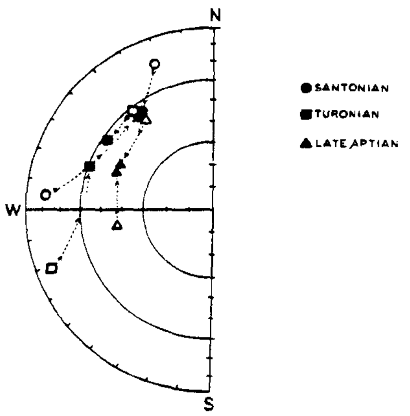


Figure 5 - Unfolding test applied to some site-mean directions (Table 1) from the Scaglia Rossa (circles - sites IPEB, IROC) and Scaglia Bianca limestones (squares - IPED, IROD) and from the Fucoid Marls (triangles - IPEG, IFMA). All symbols denote downward-pointing directions, open symbols before and solid symbols after correction for the strata dip.

is, pre-Pliocene, origin. As concluded earlier (Klootwijk and VandenBerg, 1975), we interpret this characteristic magnetization component as the primary magnetization. A similar conclusion was reached by Lowrie and Alvarez (1975) from detailed analysis of the magnetic mineralogy of Scaglia Roassa samples.

Fucoid Marls

In the Fucoid Marls (Figs. 3M, 3N) a present local field component of about 40% of the initial intensity was removed at about 150 Oe. Well-grouped characteristic magnetization directions, mainly of normal polarity, were removed above 250 Oe. Apart from the upper Scaglia Rossa samples, reversed polarity directions were observed only in the samples from site ISEA (Fig. 30), taken in the basal part of the Fucoid Marls in the Sentino gorge. In these samples a secondary magnetization component of great intensity, that is, 70% of initial intensity, with downward inclination and of uninterpretable westward declination, was removed at about 1,100-Oe peak value. From 1,100 Oe onward, well-determined characteristic directions of reversed polarity were removed. Samples from both the gently dipping southwestern limb and from the gently dipping nose of the anticlinal structure convincingly show this characteristic magnetization to be of pretectonic origin (Fig. 5).

Basal Miaolica Beds

In the basal Maiolica beds, a present local field component of about 25% to 50% of the initial intensity was removed at about 150-Oe peak value, with the characteristic magnetization component being removed between 150- to 300-Oe and 2,000-Oe peak value (Figs. 3P, 3Q, 4A). Some samples also seemed to show a second present local field component, although simultaneous removal with the remaining part of the characteristic magnetization prevented a clear interpretation.

Calcari Diasprini

In the Calcari Diapsrini samples, a northwest-trending, downward-directed secondary magnetization component of about 30% of initial intensity was removed at 250-Oe peak value (Figs. 3R, 4A). The characteristic magnetization appeared to be of very hard character and was only partly removed at the obtainable peak value of AF demagnetization. Some samples had to be rejected since they contained only secondary magnetization components.

Ammonitico Rosso

In the Ammonitico Rosso samples a northwest-trending, downward-directed secondary magnetization component of about 35% to 50% of initial intensity and probably of present local field origin could be removed at 250 Oe (Figs. 3S, 3T, 4A). Upon progressive demagnetization above 250 Oe in both marl and limestone samples, well-determined characteristic directions were obtained.

PALEONTOLOGIC DATA

Micritic carbonates of marine pelagic origin prevail throughout the Umbrian sequence, and marine pelagic fossils are abundantly present in the carbonates as well as in the few intercalations of deposits of more terrigenous clastic character. The Umbrian sequence, and the Scaglia Formation in particular, is a classic deposit in Cretaceous planktonic biostratigraphy. In the Gubbio area, which is near the region we sampled around Cagli, the Scaglia Formation is developed in its most complete and undisturbed pelagic facies, comparable to that of recent planktonic foraminiferal oozes. It was in the Bottaccione section near Gubbio that the first subdivision of the Upper Cretaceous Series by means of planktonic foraminifera was made by Renz (1936). His four biozones of the Upper Cretaceous Series, based on thin sections only, have been shown to be reliable throughout the Tethyan realm.

Study of isolated planktonic foraminifera established many more zones, all of which can be recognized in the Umbrian Scaglia Formation (Luterbacher and Premoli Silva, 1962, 1964). This continuous fossil record of the sampled Scaglia sections allowed accurate dating of the paleomagnetic observations. Thin sections were prepared from the same hand samples from which core specimens for paleomagnetic analysis were taken, in order to make errors as small as possible. The washing residues of some additional samples were studied in order to check the determinations based on thin sections. In order to make our results reproducible, the species (Figs. 6A, 6B, 6C) were taken in the broadest taxonomic sense. The relative age determinations were based on the zonations of Moullade (1966) for the Albian and Aptian rocks, and those of Postuma (1971) for the Upper Cretaceous and lower Tertiary rocks.

The results reveal a regular age versus deposition curve (Fig. 7). Only three samples yielding Paleocene and Eocene faunas are in a relatively low stratigraphic position when compared to the roughly linear relationship during the Cretaceous Period.

This is possibly due to the suspected hiatus at the Cretaceous-Tertiary boundary (Luterbacher and others, 1964), though a drastic reduction in a sedimentation rate cannot be excluded (Premoli Silva and others, 1974).
The taxa shown in the distribution charts (Fig. 6) are listed below with short comments. A rather wide species concept had to be applied, as nearly all determinations are based on thin sections. The names given stand for morphologic groups in which several species would probably be recognized if they could have been studied in washing residues.

Hedbergella trocoidea (Gandolfi)

Anomalina lorneiana var trocoidea Gandolfi (1942, p. 134, Pl. 2, fig. 1 a-c). Abundant in the lower part of the Fucoid Marls. Determination was confirmed by washing residues.

Globigerinelloides algerianus Cushman and Ten Dam

Globigerinelloides algerianus Cushman and Ten Dam (1948, p. 43, Pl. 8, figs. 4-6). This species was found both in washed samples and in thin sections. Some individuals may belong to the group of *Planomalina cheniourensis* Sigal (Sigal, 1966). We unite all nonkeeled forms in the group of *G. algerianus*.

Planomalina cheniourensis Sigal

Planomalina cheniourensis Sigal (1966, p. 24, Pl. 3, figs. 5,8,9,11). Only keeled forms are considered to belong to this species.

Rotalipora appenninica (O. Renz)

Globotruncana appenninica O. Renz (1936, p. 14, Fig. 2).
We include all relatively flat, biconvex *Rotalipora* under this name. A washed sampled (IPEO) yielded great numbers of typical forms.

Rotalipora greenhornensis (Morrow)

Globorotalia greenhornensis Morrow (1934, p. 199, Pl. 31, fig. 1).
This species was found to be associated with *R. cushmani*. We use the specific name in a broad sense; forms resembling *R. brotzeni* (Sigal) may be included.

Rotalipora cushmani (Morrow)

Globorotalia cushmani Morrow (1934, p. 199, Pl. 31, figs. 2 a-b, 4 a-b).
The strongly inflated chambers on both sides of the test are characteristic.

Praeglobotruncana stephani (Gandolfi) s.l.

Globotruncana stephani Gandolfi (1942, p. 130, Pl. 3, fig. 4).
On the basis of as few individuals as were present in two or three thin sections, it was impossible to distinguish the main species or subspecies of this group, which therefore also comprises *P.delrioensis* (Plummer) and *P.turbinata* (Reichel).

Praeglobotruncana helvetica (Bolli)

Globotruncana helvetica Bolli (1945, p. 226, Pl. 9, fig. 6).

Globotruncana renzi Gandolfi

Globotruncana renzi Gandolfi (1942, p. 124, Text-Fig. 45, Pl. 3, fig. 1 a-c).
In thin sections, this species generally appears as biconvex forms with closely spaced keels. At the younger chambers, the keel may be single or even lacking. From a current study (A.A.H. Wonders, in prep.), we know that forms transitional to both *G. sigali* and *G. coronata* may be found. Together with the latter two species, *G. renzi* determines the general aspect of the extensive zone with large, flat *Globotruncana*, which can be subdivided by means of representatives of the *G. concavata* group.

Globotruncana sigali Reichel

Globotruncana (Globotruncana) sigali Reichel (1950, p. 610, Pl. 16, fig. 7).
See remarks on *G. renzi*.

Globotruncana coronata Bolli

Globotruncana lapparenti coronata Bolli (1945, p. 233, Fig. 1, nos. 21, 22, Pl. 9, figs. 14, 15).
See remarks on *G. renzi*.

Globotruncana primitiva Dalbiez

Globotruncana (Globotruncana) ventricosa primitiva Dalbiez (1955, p. 168, Text-Fig. 6).

It is possible to distinguish the three members of the *G. concavata* group in thin sections. *G. primitiva* is characterized by moderately inflated chambers, a nearly flat spiral side, and a low convex central side of the test. The keels are very close to each other, as in all representatives of the group.

Globotruncana concavata (Brotzen)

Rotalia concavata Brotzen (1934, p. 66, Pl. 3, fig. b).
The typical, highly inflated chambers at the ventral side make this species easily recognizable. See also remarks on *G. primitiva*.

Globotruncana carinata Dalbiez

Globotruncana (Globotruncana) ventricosa carinata Dalbiez (1955, p. 168, Text-Fig. 8).
The chambers are strongly inflated at the ventral side and subangular in outline. Periumbilical ridges are present. See also remarks on *G. primitiva*.

Globotruncana linneiana (d'Orbigny) s.l.

Rosalina linneiana d'Orbigny (1839, p. 101, Pl. 5, figs. 10-12).
Under this name, we include all biplanar forms with widely spaced keels.

Globotruncana elevata (Brotzen) s.l.

Rotalia elevata Brotzen (1934, p. 66, Pl. 3, fig. c).
This name stands for all ventroconvex single-keeled forms, which may belong to *G. elevata*, *G. stuartiformis* Dalbiez, or *G. stuarti* (de Lapparent).

Globotruncana fornicata Plummer

Globotruncana fornicata Plummer (1931, p. 198, Pl. 13, figs. 4-6).
The large group of *G. fornicata* has been subdivided into several species. Here, we only distinguish three species : *G. renzi* (biconvex), *G. fornicata* (moderately dorsoconvex), and *G. contusa* (Cushman). *G. contusa* is an extremely high dorsoconvex species and was not found in our material.

Globotruncana rosetta (Carsey) s.l.

Globigerina rosetta Carsey (1926, p. 44, Pl. 5, fig. 3).
The taxonomic position of this group is uncertain. In our concept, it comprises

forms of variable convexity with a weakly developed second keel, and - often not visible - an extensive and very high tegillar structure.

Globotruncana arca (Cushman)

Pulvinulina arca Cushman (1926, p. 23, Pl. 3, fig. 1).
Distinctly dorsoconvex forms with widely spaced keels are united under this name.

Globotruncana ventricosa (White)

Globotruncana canaliculata var. *ventricosa* White (1928, p. 284, Pl. 38, figs. 5 a-c).
This species is easily recognized by its high ventroconvex outline and relatively widely spaced keels.

Heterohelicidae

Representatives of this family were determined only at the generic level (*Heterohelix*, *Planoglobulina*, *Pseudotextularia*). They were not used for age determinations.

Globorotalia velascoensis (Cushman)

Pulvinulina velascoensis Cushman (1925, p. 19, Pl. 3, fig. 5 a-c).
The angular, strongly ventroconvex outline and heavy periumbilical ridges are characteristic features.

Globorotalia aequa Cushman and Renz

Globorotalia crassata var. *aequa* Cushman and Renz (1942, p. 12, Pl. 3 a-c).
Strongly ventroconvex forms with slightly inflated, little ornamented chambers and a narrow umbilicus.

Globorotalia formosa Bolli

Globorotalia formosa formosa Bolli (1957, p. 76, Pl. 18, figs. 1-3).
This species differs from *G. velascoensis* by the narrower umbilicus and the absence of strong periumbilical ridges.

Globorotalia aragonensis Nutall

Globorotalia aragonensis Nutall (1930, p. 288, Pl. 24, figs. 6-8, 10-11).
In thin sections, G. aragonensis appears very similar to *G. formosa*, from which it differs by a still narrower umbilicus.

Large Acarinids

These strongly ornamented, but nonkeeled forms were found in sample IMOO. They could not be determined at the specific level.

PALEOMAGNETIC RESULTS IN STRATIGRAPHIC ORDER

The paleomagnetic site-mean directions as obtained from the three sections and additional sites, combined with their maximum age ranges and foraminiferal content are shown in Figures 6 and 7. The Petrano section (Fig. 6A), the Pieia section (Fig. 6B), and, less evidently, the Moria section (Fig. 6C) show gradual changes in the directional pattern through the sections.
In our view it would be incorrect to draw conclusions from minor variations in the changes observed in each section. By combining all the data into one master section (Fig. 7), we obtain the best time-averaging of the data. Figure 7, therefore, represents our view of the best overall interpretation of the results displayed stratigraphically.
The main changes in paleomagnetic directions occurred in the Fucoid Marls and the Scaglia Formation. Fortunately, this is the interval with the best-known and most useful planktonic microfaunas, which thus allows accurate dating of the recorded changes.
Figure 7 clearly shows that from at least the Toarcian-Aalenian (upper Lower Jurassic) level - that is, the lower limit of our paleomagnetic coverage - up to the upper Aptian level, no major change in declination and inclination occurred. A minor phase of movement at about Tithonian time may be interpreted from the data shown in Figures 7 and 8. An about 10^{o} clockwise rotation follows from a declination increase from about 290^{o} to about 300^{o}. Considering the inclination curve, it is clear that between the upper Aptian and upper Cenomanian levels, the inclination values decrease by 15^{o} to a 35^{o} value. This means inclination value characterizes the upper Cenomanian, Turonian, and Coniacian rocks. In the Santonian and Campanian rocks, the mean inclination increases again to 50^{o}. This 50^{o} mean inclination remains characteristic for the interval from the Maastrichtian to at least the lower Eocene strata, that is, the present upper limit of

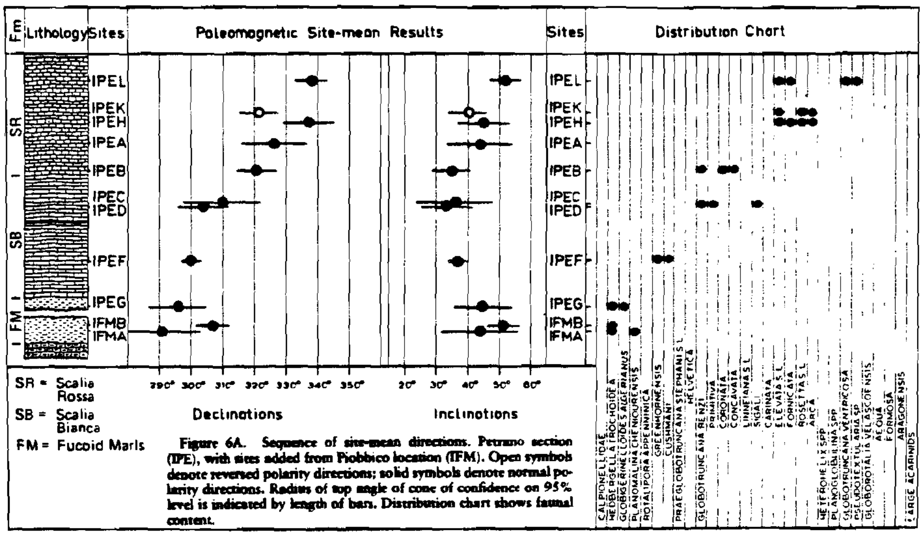


Figure 6A. Sequence of site-mean directions. Petrano section (IPE), with sites added from Piobbico location (IFM). Open symbols denote reversed polarity directions; solid symbols denote normal polarity directions. Radius of top angle of cone of confidence on 95% level is indicated by length of bars. Distribution chart shows faunal content.

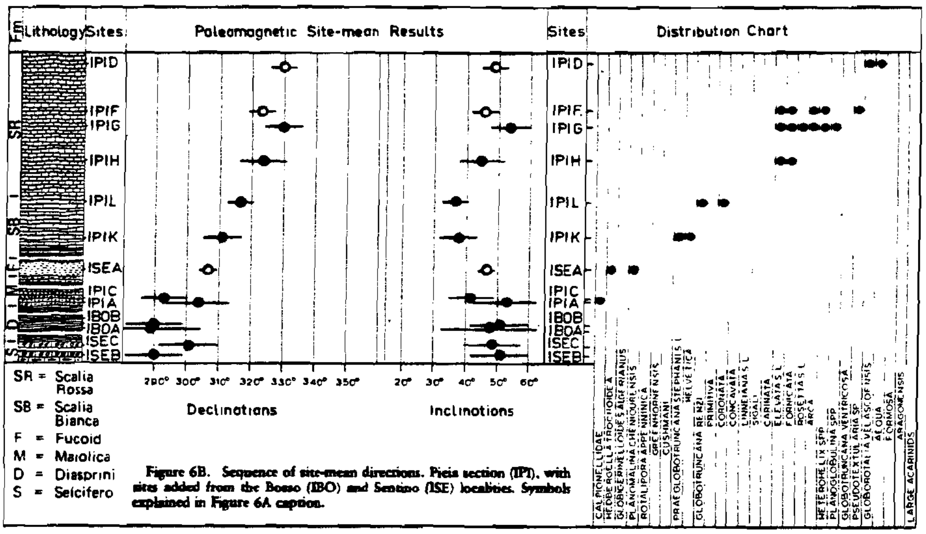


Figure 6B. Sequence of site-mean directions. Pieia section (IPI), with sites added from the Bosso (IBO) and Sentino (ISE) localities. Symbols explained in Figure 6A caption.

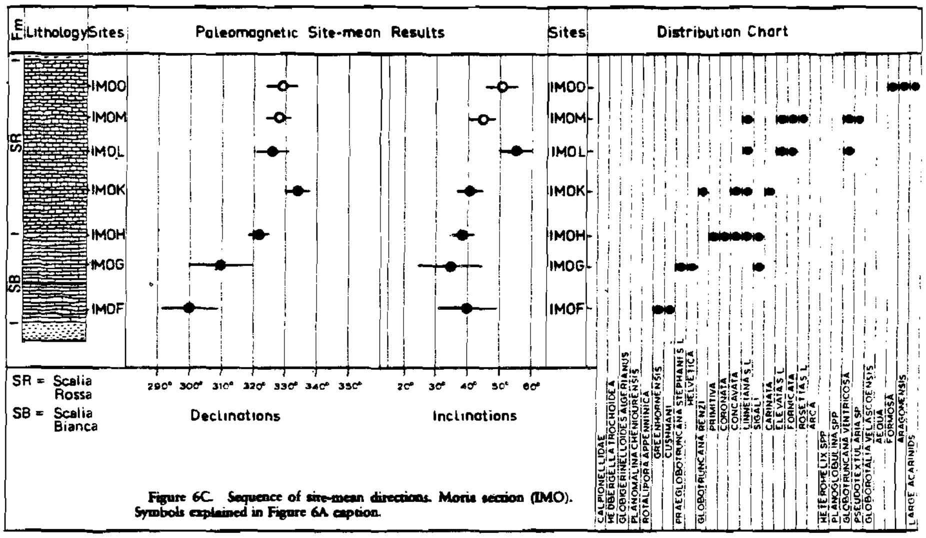


Figure 6C. Sequence of site-mean directions. Moria section (IMO). Symbols explained in Figure 6A caption.

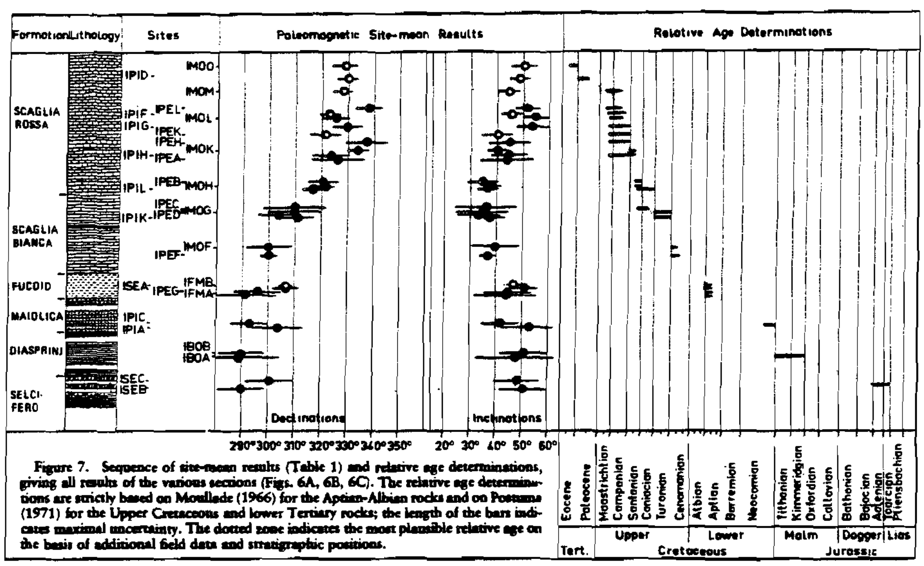


Figure 7. Sequence of site-mean results (Table 1) and relative age determinations, giving all results of the various sections (Figs. 6A, 6B, 6C). The relative age determinations are strictly based on Moullade (1966) for the Aptian-Albian rocks and on Postuma (1971) for the Upper Cretaceous and lower Tertiary rocks; the length of the bars indicates maximal uncertainty. The dotted zone indicates the most plausible relative age on the basis of additional field data and stratigraphic positions.

our paleomagnetic record, though the inclination values of individual sites are slightly more dispersed than recorded in the lower part of the sections.
The declination curve, which shows a nearly constant mean value of 300° up to the Turonian level, reveals a gradual increase to 330° in the Turonian, Coniacian, and Santonian rocks. This 330° declination value remains characteristic up to at least the lower Eocene level. It must be noted that our youngest (early Eocene) paleomagnetic data from the Umbrian sequence ($D=330^{\circ}$, $I=+49.5^{\circ}$, Table I) are still appreciably different from the present-day magnetic field direction in Umbria ($D=359^{\circ}$, $I=+59^{\circ}$).

REVERSAL STRATIGRAPHY

As is also indicated in Figure 7, normal polarity directions prevail throughout the sequence. The few reversed polarities found are of particular interest. The late Aptian reversed direction in the basal Fucoid Marls might be related to the Hissar reversed event as given by McElhinny and Burek (1971) or even to the updated Akoh interval (92 to 104 m.y. B.P., as given by Keating and others, 1975a). Alternatively, this reversed direction might represent the last reversed event before the middle to Late Cretaceous normal polarity interval (McElhinny and Burek, 1971; Irving and Couillard, 1973). This interpretation implies a late Aptian age for the top of the M-sequence of magnetic anomalies, that is, the Keathley-Hawaiian lineations. Such an age is in good agreement with the magnetic anomaly time scale as proposed by Larson and Pitman (1972, 1975) and that of Larson and Hilde (1975). It is hoped that a planned study of the underlying Maiolica beds will clarify these questions about the Cretaceous time scales as pointed out by Baldwin and others (1974).
Other reversed polarity directions were found in sites of Campanian and younger age (Fig. 7). This is in good agreement with the reversed events found by Lowrie and Alvarez (1975) in the Bottaccione gorge section, which were dated by them as late Campanian and late Maastrichtian. The reversal time scale of Premoli Silva and others (1974), based on preliminary data, shows mixed polarities in rocks from the Bottaccione section of Maastrichtian and Paleocene age, but unfortunately gives no clear information on Campanian rocks. The agreement of our Campanian and younger reversed events with Larson and Pitman's (1972, 1975) marine magnetic anomaly time scale as well as with Watkins's (1975) correlation between stratigraphic zones and magnetic polarities is remarkable. For these

reasons, and according to our present data, we favor the view that the Cretaceous normal polarity interval began in late Aptian time and ended in Campanian time. This working hypothesis is in conflict with the suggestion of Keating and others (1975a), backed by Sclater and Fischer (1974), that the Cretaceous quiet interval did not end before the beginning of Maastrichtian time. Consequently, they (Keating and others) preferred to interpret their recent findings of reversed polarity directions of Campanian and Aptian age in some Deep Sea Drilling Project cores (Keating and others, 1975b), as particular reversed events within the Late Cretaceous normal polarity interval. Anomalies 33 and 34 of Santonian and possibly Coniacian age, according to Larson and Pitman (1972, 1975), were not detected in the present study, nor were they detected by Lowrie and Alvarez (1975) in the Bottaccione gorge.

COMPARISON WITH RELATED STUDIES IN UMBRIA

Several groups are at present actively involved in research on the Scaglia Formation of the Umbrian sequence, and a number of studies have already been published (Premoli Silva and others, 1974; Lowrie and Alvarez, 1974, 1975; Channell and Tarling, 1975; Klootwijk and VandenBerg, 1975; VandenBerg and others, 1975). Sampling of geographically distributed sites as done by Channell and Tarling (1975) and Lowrie and Alvarez (1975) suffered from the drawback that relative ages were not obtained, since paleontologic data were either not or not rigorously applied. Only the well-known Scaglia section in the Bottaccione gorge near Gubbio was sampled in more detail by Premoli Silva and others (1974) and by Lowrie and Alvarez (1975). The paleomagnetic results of Premoli Silva and others (1974), although well dated, are widely dispersed and admittedly of questionable reliability (as stated by Alvarez and Lowrie, 1975, p. 1587). On the other hand, Lowrie and Alvarez' (1975) data seem much more refined, but as they noticed, the ages assigned to the successive sampling sites might be less accurate. These ages are based on simple linear interpolation through the various biostratigraphic zones distinguished by Renz (1936), and again as they noted, Renz had not been able to separate the three crucial stages Turonian, Coniacian, and Santonian.

In contrast, our sampling was confined to the northernmost outcrop of the Umbrian sequence. Three fresh and well-correlated sections were sampled in detail from road cuts, and the age of each site was established by planktonic foraminiferal analysis as described above.

The magnetization was known to be of a complex nature (Klootwijk and VandenBerg, 1975). Therefore, we separated and interpreted the various magnetic components by means of elaborate progressive AF and thermal demagnetization techniques. The orthogonal projection technique was used; this enabled us to distinguish different components of the natural remanent magnetization in complex multicomponent cases (Zijderveld, 1967, 1975) instead of the less-preferable optimum dispersion method, which was used by Premoli Silva and others (1974), Channell and Tarling (1975), and Lowrie and Alvarez (1974, 1975).

From the clearly visible pattern of gradual changes in declination and inclination (Figs. 7, 8), it is evident that an overall grouping of the Scaglia Rossa data leads to a loss of information despite claims to the contrary (Premoli Silva and others, 1974; Channell and Tarling, 1975). A stratigraphic differentiation of paleomagnetic results was made only for the Bottaccione gorge section (Lowrie and Alvarez, 1975). In contrast to the rather complex pattern that we observed in the data from our Scaglia sections, Lowrie and Alvarez (1975) discerned in their Bottaccione gorge section a gradual change to higher declination values only. This change was estimated by them to be of Campanian-Maastrichtian age in contrast to our present Turonian-Santonian dating that was obtained through micropaleontologic study. Close inspection of the site-mean results of Lowrie and Alvarez (1975) and Channell and Tarling (1975) reveals that the pattern of successive movements as found in our data seems to be present in their original data as well.

INTERPRETATION

Mean directions (Table 1, Fig. 8) were computed for the successive intervals that are characterized, as described before, by rather stable mean declination and (or) inclination values. Using the geocentric coaxial dipole formula, successive positions of the sampling area were computed from these data with absolute longitudinal positions, of course, remaining undeterminable; movements that are entirely longitudinal, as documented by Pitman and Talwani (1972), for example, cannot be deduced from the present data.

After extrapolating our Umbrian paleomagnetic data to the whole Italian Peninsula successive positions as shown in Figure 9 could be computed. Figures 8 and 9 reveal the following sequence of rotational and latitudinal movements.

From at least Toarcian-Aalenian to late Aptian time, the Umbrian depositional

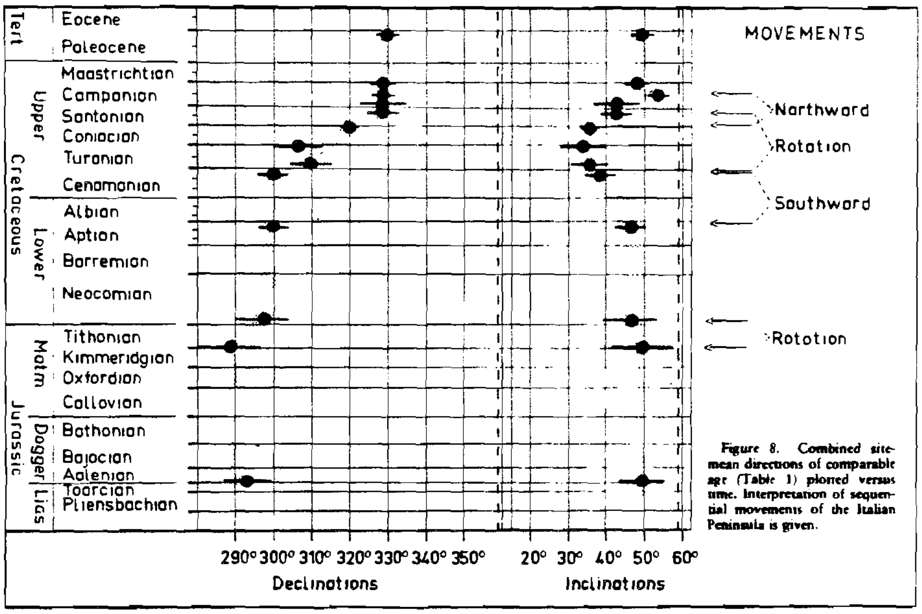


Figure 8. Combined site-mean directions of comparable age (Table 1) plotted versus time. Interpretation of sequential movements of the Italian Peninsula is given.

TABLE 1. NATURAL REMANENT MAGNETIZATION

Site	No. of samples	Initial intensity (× 10^{-6} gauss)	Site-mean direction* (°)	(°)	α_{95} (°)	Age	Mean direction* (°)	(°)	α_{95} (°)	Pole position lat (°N)	long (°W)	δp (°)	δm (°)
IMOO	5	27–113	149.2	−50.8	5.1	Late Paleocene to late Eocene	150.1	−49.7	3.0	63.0	96.0	2.7	4.0
IPID	11	15–159	150.5	−49.2	4.1								
IMOM	6	218–378	148.8	−44.9	3.8	Late Campanian to early Maastrichtian	329.7	+48.2	3.7	61.9	98.9	2.8	4.2
IPEL	5	387–996	338.5	+52.8	5.5								
IPIF	5	27–51	143.2	−46.9	4.6								
IMOL	5	119–196	326.2	+55.1	5.1	Early to late Campanian	328.1	+54.7	3.6	64.2	85.2	5.5	5.1
IPIG	5	141–701	330.1	+54.3	6.7								
IPEK	5	813–1,836	141.1	−40.6	6.7	Early Campanian	328.8	+43.3	6.1	58.7	102.9	4.7	7.6
IPEH	5	82–160	337.2	+45.3	8.8								
IMOK	6	113–153	334.8	+40.5	3.9	Late Santonian	328.5	+43.3	4.2	58.4	102.7	3.2	5.3
IPEA	6	86–142	326.5	+44.1	11.1								
IPIH	6	52–145	323.8	+44.6	7.5								
IPEB	6	57–112	321.3	+35.3	6.5	Late Coniacian to early Santonian	320.3	+36.6	2.7	49.7	99.5	1.8	3.1
IMOH	5	30–211	322.2	+38.1	3.6								
IPIL	6	78–156	317.7	+36.7	4.8								
IPEC	4	96–180	310.9	+36.1	12.5	Coniacian	307.1	+34.4	6.1	39.5	89.1	4.1	7.0
IPED	5	77–120	304.2	+32.9	8.0								
IMOG	5	165–2,829	310.8	+35.4	10.9	Early Turonian	310.9	+36.9	5.4	43.3	90.6	3.7	6.3
IPIK	5	188–1,484	311.0	+38.4	6.5								
IPEF	5	547–21,471	300.7	+37.4	3.3	Late Cenomanian	300.5	+39.2	4.3	36.9	80.9	3.1	5.2
IMOF	5	361–2,044	300.4	+40.9	9.5								
IFMA	5	410–3,880	291.7	+44.1	12.2	Late Aptian	300.2	+47.0	4.4	40.3	74.5	3.7	5.7
ISEA	6	102–112	127.8	−47.6	4.7								
IFMB	6	410–3,880	307.2	+51.6	5.8								
IPEG	10	104–259	296.3	+44.8	9.9								
IPIA	5	184–557	304.7	+53.1	10.7	Early Neocomian	298.6	+47.6	7.0	39.4	72.9	5.9	9.1
IPIC	5	241–279	293.7	+41.9	7.7								
IBOA	6	167–358	289.3	+48.4	16.2	Kimmeridgian to Tithonian	289.9	+50.0	8.0	34.4	65.4	7.1	10.7
IBOB	7	66–595	290.4	+51.3	9.6								
IBOC	4	123–325	109.6	−41.9	29.1								
ISEB	8	65–2,032	290.2	+51.2	9.3	Toarcian to Aalenian	294.7	+50.6	6.4	38.0	67.7	5.8	8.6
ISEC	5	43–53	301.4	+49.2	9.5								
IROC	6	65–131	321.4	+34.4	8.5								
IROD	5	76–132	289.3	+30.1	9.8								

Note: α_{95} = radius of the circle of confidence on the 95% level.
(δp, δm) = the oval of confidence on the 95% level about the pole position (δp = error in paleolatitude; δm = error in paleolongitude).
* First column is azimuth; second column is inclination. Positive inclinations represent downward-pointing directions.

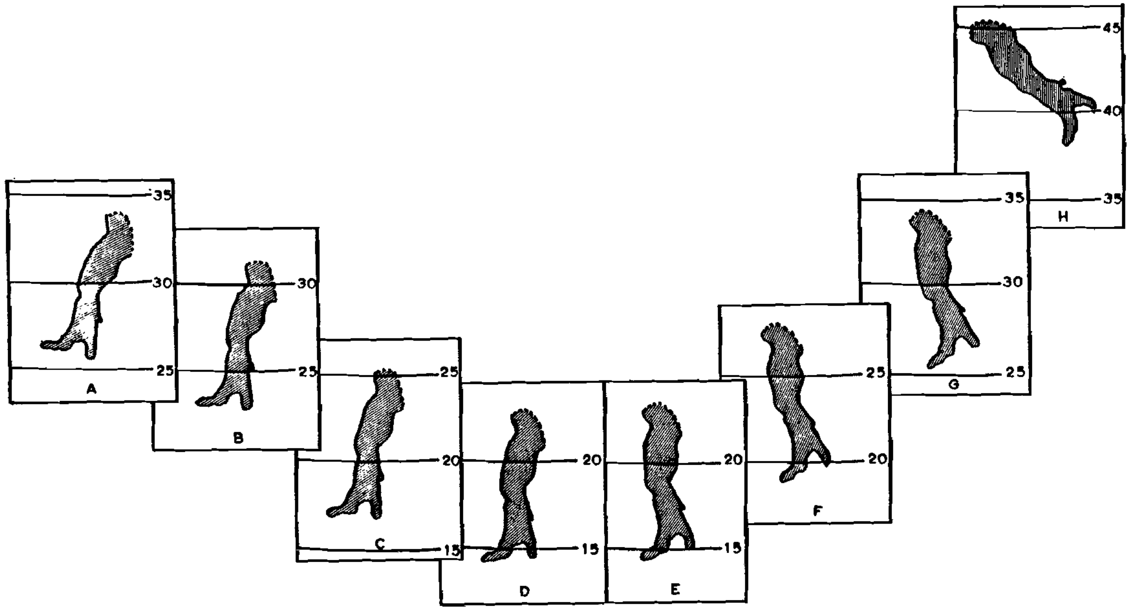


Figure 9 - Successive positions of the Italian Peninsula during late Mesozoic and early Tertiary time according to the combined site-mean data given in Table 1. The relative longitudinal positions of the diagrams are arbitrary. (A) Middle to Late Jurassic, (B) early Neocomian to late Aptian, (C) late Cenomanian, (D) early Turonian to Coniacian, (E) late Coniacian to early Santonian, (F) late Santonian to early Campanian, and (G) Campanian to early Tertiary time. (H) Present position given for comparison.

basin remained at about lat 30°N, and was rotated about 60° in dextral sense compared with its present orientation (Fig. 9A). A slight movement phase in about Tithonian time seems reflected in an increase in declination of about 10°. This paleomagnetically deduced phase is in accord with geologic knowledge, since Sander (1970, p. 110) noted diastrophic events in the Mediterranean realm at the beginning and at the end of Tithonian time (Figs. 9A, 9B). Moreover, Pitman and Talwani (1972) indicated a distinct change in the movement pattern of the Atlantic bordering continents by that time. Between late Aptian and late Cenomanian time southward movement of about 10° occurred (Fig. 9C), followed by a 30° counterclockwise rotation that took place during Turonian, Coniacian, and Santonian time (Figs. 9D through F). Beginning in the later stage of this rotation and lasting until a somewhat later date (that is, during Santonian and Campanian time), a 10° northward movement took place (Figs. 9F-9G). From Maastrichtian to at least late early Eocene time, no marked rotational or meridional movements occurred. Thus, the ultimate northward movement of more than 10° and counterclockwise rotation of about 25° toward the present position (Fig. 9H) are post-early Eocene.

These indications for large-scale tectonic events lead to the interesting question, To what extent is the present paleomagnetic pattern from the Umbrian sequence reflected in the paleomagnetic data from the African and European plates? Unfortunately, a direct comparison of results is hampered by a notable scarcity of Jurassic and Cretaceous data from Europe and Africa. We have tried to overcome this drawback by relying on indirectly determined paleomagnetic poles for the African and European plates. These simulated poles were computed by Van der Voo and French (1974), based on selected paleomagnetic data from the continents bordering the Atlantic, combined with reconstructions of successive stages in the opening of the Atlantic as deduced from sea-floor spreading data by Pitman and Talwani (1972).

The Early Jurassic to early Tertiary succession of paleomagnetic directions from the Umbrian sequence as actually found by us is shown in Figure 10A as a polar equal-area projection of the mean data compiled in Figure 8 and Table 1. For further elucidation, we have represented (Fig. 11) this trend in the form of a series of density distributions of sample directions. In Figures 10A and 10B we depicted the succession of paleomagnetic directions that are to be expected in the Northern Apennines in their present position according to Van der Voo and French's (1974) simulated poles, as extrapolated from Africa and Europe, respectively. The observed Umbrian patterns (Figs. 10C, 11) and the simulated

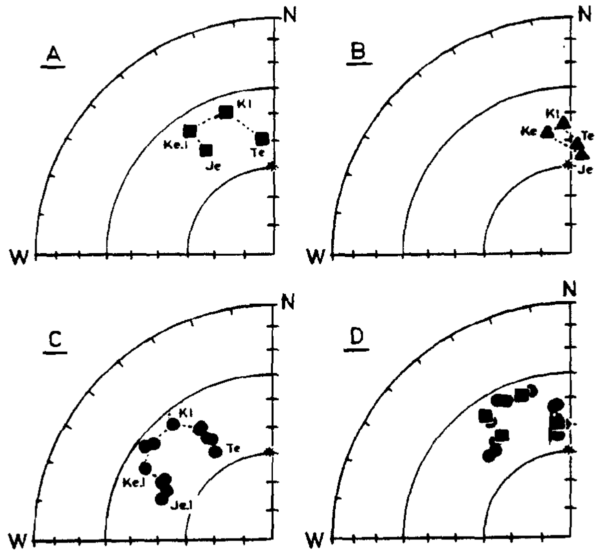


Figure 10 - In projection A the northern Apennines are considered as fixed to the African plate. The directions to be expected were computed from the poles for Africa of Van der Voo and French (1974). In projection B the Northern Apennines are considered as fixed to the European plate and the directions to be expected were computed from the poles for Europe of Van der Voo and French (1974). In projection C the present mean directions from the Umbrian sequence are shown (Table 1). Projection D shows the loop formed by the mean directions of the Umbrian sequence (dots) compared with the "African" pattern (squares) after accounting

"African" pattern (Fig. 10A) show distinct loops that are of comparable shape and of the same age as well; these patterns contrast with the simulated "European" pattern (Fig. 10B). Despite the remarkable overall conformity between the Umbrian and the "African" pattern, it appears that the actual positions of the loops fit well only after accounting for a further counterclockwise rotation of about 25^{o} of the Umbrian pattern relative to the "African" pattern as shown in Figure 10D. The youngest Umbrian data represented in this loop are of early Eocene age. Evidently, therefore, the further rotation of about 25^{o} of the Northern Apennines and presumably a larger part of the Italian Peninsula - as will be discussed - is of later, that is post-early Eocene, age.

DISCUSSION

It has been shown that Umbria was coupled with the African plate from at least

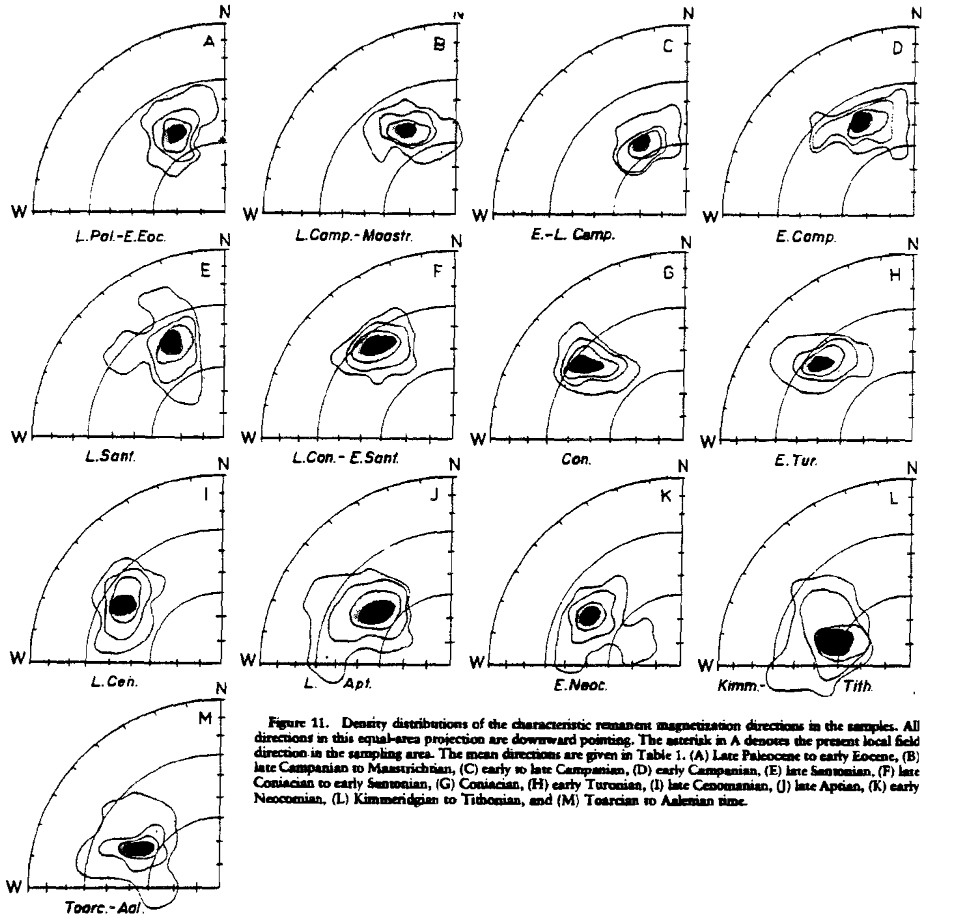


Figure 11. Density distributions of the characteristic remanent magnetization directions in the samples. All directions in this equal-area projection are downward pointing. The asterisk in A denotes the present local field direction in the sampling area. The mean directions are given in Table 1. (A) Late Paleocene to early Eocene, (B) late Campanian to Maastrichtian, (C) early to late Campanian, (D) early Campanian, (E) late Santonian, (F) late Coniacian to early Santonian, (G) Coniacian, (H) early Turonian, (I) late Cenomanian, (J) late Aptian, (K) early Neocomian, (L) Kimmeridgian to Tithonian, and (M) Toarcian to Aalenian time.

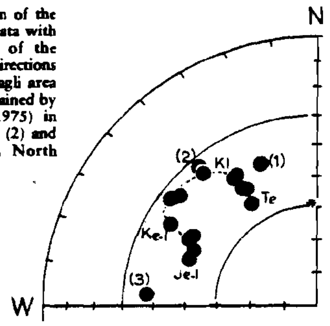
late Early Jurassic until early Eocene time, but that a post-early Eocene 25° counterclockwise rotation of this part of Italy occurred relative to the African plate.

A possible explanation for this separate movement in terms of a supracrustal rotation of the Umbrian sequence, with Triassic evaportie horizons acting as a major décollement surface, does not seem warranted by geologic data. As noted by Lowrie and Alvarez (1975), such a hypothesis would imply improbable horizontal movements in the more southern area of the Umbrian realm. Therefore, basement-inclusive movement is apparently the preferable interpretation, especially because paleomagnetic data from basement rocks in Tuscany support this (Vanden Berg and Wonders, 1976). If the different magnitudes of rotations documented for graphically distinct areas (Soffel, 1972, 1975a; Channell and Tarling, 1975; vandenBerg and Wonders, 1976) are considered, it is most interesting to trace the extension of the (micro-) plates that underwent a Tertiary counterclockwise rotation relative to Africa.

Concerning the Italian data, clear distinction has to be made between the paleomagnetic data from the Southern Alps and those from areas to the south of the Po plain. This is considered as support for Mueller and Talwani's (1971) suggestion that a profound discontinuity extending to the base of the crust exists between the Apennines and the Southern Alps in the Po plain. Such a zone is also shown by Ritsema (1969).

Delineation of the southern limit of the Italian tectonic unit(s) that rotated during Tertiary time is hampered by lack of data. Late Cretaceous paleomagnetic results from the Capo Passero basalts in southeast Sicily (Schult, 1973; Barberi and others, 1974), convincingly show that no significant post-Cretaceous movements occurred between southeast Sicily and Africa. The only other paleomagnetic

Figure 12. Comparison of the Umbrian paleomagnetic data with data from areas south of the Anzio-Ancona line. The directions were computed for the Cagli area from the virtual poles obtained by Channell and Tarling (1975) in Apulia (1) and Campania (2) and by Manzoni (1975) in North Calabria (3).



data from central and southern Italy are some results from bauxites on the Apulian and Campanian platform (Channell and Tarling, 1975) (see Fig. 12). These data, however, suffer from the drawback common to bauxite deposits that their age is only known within wide limits. The presence of a reversed polarity in the data of Campania and the appreciably younger dating of the bauxites in Campania-Lucania (Grandjacquet, 1963, p. 188-189) point to a Satonian-Campanian age, rather than to the suspected early Late Cretaceous age. The controversial ages give rise to some ambiguity. The paleomagnetic data for the bauxites, if they are of early Late Cretaceous age, are inconclusive as to whether a Tertiary rotation for this part of Italy may be expected. The most probable Late Cretaceous age, on the other hand, indoubtedly indicates the paleomagnetic data of the bauxites to accord with the Umbrian pattern, in which case, a Tertiary counterclockwise rotation for this area as well can be concluded. Manzoni (1975) reported paleomagnetic data (Fig. 12) from Northern Calabria that indicate such a rotation, but these data are not conclusive either, since they were taken from rocks in a nappe structure. If this ambiguity is considered, we cannot exclude the possibility that the Anzio-Ancona line acted as the southern limit of the rotated unit. Nardi's (1971) interpretation of this line as a major thrust fault, however, seems a more likely explanation on the grounds of the present data. In the absence of more limiting paleomagnetic data, we suggest that the southern boundary of the rotated unit has to be searched for farther south, most probably in the South Calabrian arc where the regional geology points to a transverse tectonic zone (Alvarez and others, 1974). Alternatively, it may be still slightly farther south on Sicily's northern margin (Barberi and others, 1974).

As to the western extension of the Italian plate, it can be noted that all Sardinian data fit well on the apparent polar wander path for the Italian Peninsula, whereas the Corsican data do not. This opens the interesting perspective that the late Oligocene-early Miocene or even earlier rotation of Sardinia (DeJong and others, 1973; Coulon and others, 1974) is related to the post-early Eocene rotation of the Italian Peninsula (VandenBerg and Wonders, 1976).

To the east, the Dinarides, Hellenides, and Central European and Balkan Alpine orogenic belts constitute a complex pattern of possible plate boundaries. Since very few, if any paleomagnetic data from these areas are available, the question about the eastern boundary of the Italian Peninsula microplate is open to further research.

On the basis of paleomagnetic data available at present, it can tentatively be concluded that during late Mesozoic times. the Italian Peninsula rotated and moved together with and as part of the African plate. Although the movements in the various parts of the Italian border zone of the African plate were mutually coherent, in detail, a certain individuality in movements seems apparent. Another subject of further research, therefore, is to what extent this absence of rigidity warrants the distinction and delineation of separate microplates.

MEDITERRANEAN AND ATLANTIC RELATIONSHIPS

The good agreement of the conspicuous loops of the simulated "African" paleomagnetic pattern for Umbria and the actually observed Umbrian pattern clearly indicates a direct relationship between the spreading history of the North Atlantic (Le Pichon and Fox, 1971; Smith, 1971; Phillips and Forsyth, 1972; Pitman and Talwani, 1972; Larson and Pitman, 1972, 1975; Dewey and others, 1973) and the proposed sequence of movements of the Italian Peninsula (Figs. 10A, 10C and 10D). Pitman and Talwani (1972) and Dewey and others (1973) recognized three main phases of movement between Europe and Africa : (1) (180 to 80 m.y. B.P.) Since the Early Jurassic beginning of the opening of the North Atlantic, Africa underwent a southeastward-directed divergent movement relative to Europe. A counterclockwise rotation of Africa started in the second half of this stage. (2) (80 to 53 m.y. B.P.) The relative movement changed with Africa moving westward relative to Europe. Until about 63 m.y. B.P. there was continuing counterclockwise rotation of Africa and compression between Europe and Africa. (3) (53 m.y. B.P. to the present) The movement essentially resulted in compression. The pattern of sequential movements of the Italian Peninsula as established from our Umbrian paleomagnetic data accords rather well with this scheme, and corresponding movements can be deduced for the Southern Alps (VandenBerg and Wonders, 1976). As far as the present Umbrian paleomagnetic data are concerned, the southeastward movement of Africa (1, above) seems reflected in the minor movement phase in about Tithonian time and in the late Aptian to late Cenomanian component of southward movement of the Italian Peninsula. The first rotation of our two-phase rotational hypothesis, that is, the Turonian to Santonian 30^{o} counterclockwise rotation, is contemporaneous with the rotational movement of the African plate as mentioned above (1 and 2), which supports our conclusion that Italy was part of the African plate during that time. Therefore, we disagree with Lowrie and Alvarez (1974) and do not think that this earlier rotation resulted from microplate adjustment to the predominantly compressive Late Cretaceous-Tertiary motion between Africa and Europe.

Rotation of Italy according to the ball-bearing concept as originally suggested by Van der Voo and Zijverveld (1969), elaborated by Smith (1971), and later on somewhat retracted (Zijderveld and Van der Voo, 1973; Lowrie and Alvarez, 1975) can be ruled out indeed. The movement of Africa relative to Europe was essentially dextral during the Turonian to Santonian rotation of the Italian Peninsula. According to the ball-bearing concept, however, one would expect a rotation in the opposite sense.

The paleomagnetically determined Santonian-Campanian northward movement of the Italian Peninsula, followed later on by a post-early Eocene phase of renewed northward movement agrees with the compressive phases mentioned above (2 and 3). In contrast to the first rotational movement phase of Italy as a coherent part of the African plate, the post-early Eocene rotation of Italy was presumably caused by microplate adjustment to compressive movement between the northward-moving African plate.

The extensive development of graben systems was described by Le Pichon and others (1971) in Sardinia, along the Mediterranean coast of France, and in more internal European regions as well. According to these authors, such graben formation postdated a paroxysmal phase in the Alpine orogenesis. It is probable, however, that the grabens are in fact related to the second rotation phase of Italy.

Mainly in the eastern Mediterranean, but in the western Mediterranean as well, Argyriadis (1974) could easily discern, in addition to the Tertiary paroxysmal Alpine phase, earlier tectonic phases of middle and Late Cretaceous age. Also Caby (1975) discerned two main phases of tectonic activity from analysis of patterns of transverse and longitudinal folds in the Western Alps. This polyphase model is also recongizable in the metamorphic events of the Alps (Jäger, 1973; Hawkesworth and others, 1974), the Apennines (Dal Piaz, 1974) and even in the Betic Cordilleras (Egeler, 1975).

It would be of interest to test whether other parts of the Mediterranean show an analogous two-phase development. For Spain, for instance, it is well known that available paleomagnetic data are seemingly in agreement with the African apparent polar wander path, but it cannot be established from these data whether Spain rotated as part of the African plate as documented here for peninsular Italy. More convincing in this respect is the recent interpretation of the opening of the Bay of Biscay by Williams (1975). This opening was dated between Barremian and Maastrichtian time, whereas according to Wilson (1975), most of the movement occurred between Aptian and Cenomanian time.

CONCLUSIONS

The dated paleomagnetic record of the Umbrian sequence details polyphase rotational movements of peninsular Italy during late Mesozoic and Cenozoic time. From Toarcian-Aalenian to late Aptian time, the paleomagnetic data do not indicate major rotational and latitudinal movements except for a minor Tithonian counterclockwise rotation of about 10°. During late Aptian to late Cenomanian time, a further southward movement over about 10° of latitude took place. A major phase of counterclockwise rotation over about 30° occurred during Turonian, Coniacian, and Satonian time, followed by a Santonian-Campanian northward movement over about 10° of latitude. From Maastrichtian to at least early Eocene time, no significant rotational and latitudinal movements occurred. The ultimate 10° northward and additional 25° counterclockwise rotation cannot be dated more closely than post-early Eocene.

The conspicuous loops of the actual Umbrian paleomagnetic pattern agree well with a simulated paleomagnetic pattern for Umbria that is based on the spreading history of the North Atlantic and on paleomagnetic data from the Atlantic-bordering continents. This indicates that peninsular Italy moved as part of the African plate during at least late Mesozoic time. The later post-early Eocene rotation of peninsular Italy occurred separately from movement of the African plate and was caused presumably by microplate adjustment to compression between Europe and the northward-moving African plate.

Much more study is needed to delineate the complex pattern of microplate movements in the Alpine-Mediterranean realm. The present data reveal the utility of paleomagnetic studies of dated carbonate sequences for detailing the tectonic history of the Mediterranean area.

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PALEOMAGNETIC EVIDENCE OF LARGE FAULT DISPLACEMENT AROUND THE PO-BASIN

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ABSTRACT

New paleomagnetic data are presented from Tuscany and the Southern Alps (Italy). A paleomagnetic study of the autochthonous Verrucano near Siena revealed two characteristic paleomagnetic directions, one of the Ladinian to Carnian Verrucano ($D=301.1^{\circ}$, $I=+60.2^{\circ}$, $\alpha_{95}=6.0^{\circ}$) and the other of the Late Carboniferous to Early Permian Farma formation ($D=318.8^{\circ}$, $I=+20.8^{\circ}$, $\alpha_{95}=12.8^{\circ}$). A paleomagnetic study on a limestone sequence in the Vicentinian Alps revealed characteristic directions for Late Jurassic ($D=328.5^{\circ}$, $I=+45.3^{\circ}$, $\alpha_{95}=3.0^{\circ}$), for Turonian-Coniacian ($D=345.5^{\circ}$, $I=+38.2^{\circ}$, $\alpha_{95}=3.3^{\circ}$), for Early Santonian ($D=344.2^{\circ}$, $I=+43.3^{\circ}$, $\alpha_{95}=5.3^{\circ}$) and for Late Santonian to Early Campanian rocks ($D=342.7^{\circ}$, $I=+50.9^{\circ}$, $\alpha_{95}=5.3^{\circ}$). Comparison of these new data with published data of Permian and younger age from the Southern Alps and from Umbria respectively, leads to conclusions about movements of crustal blocks North and South of the Po-basin. Further comparison of the data from the Northern Apennines with published Sardinian data seems to support that Sardinia belonged to the central Italian Peninsula until present times. It is argued that the Northern Apennines and the Vicentinian Alps belonged to the African plate and that their movements were defined by the opening history of the Atlantic. It was found, however, that during Late Cretaceous and again in Early Tertiary the two Italian crustal blocks must have been uncoupled to some degree. This supports the hypothesis of a major fault zone in the area of the Po-basin, which is now buried under a thick Late Tertiary to Quaternary sedimentary cover.

INTRODUCTION

The Po-basin, as it appears today, is an elongated plain between two entirely different fold belts of Alpine origin : the Alps in the North and the Apennines in the South. It is drained by the river Po and its tributaries, and the abundant water supply from the Alps and the Apennines causes rapid accumulation of terrigenous material in the plain. In the Northwest, the Po-basin is bordered by the most internal massif of the Alps and in the Northeast by the calcareous Bergamask and Vicentinian Alps. The latter can be considered as the western continuation of the Dinarides mountain chain in Yugoslavia. They essentially con-

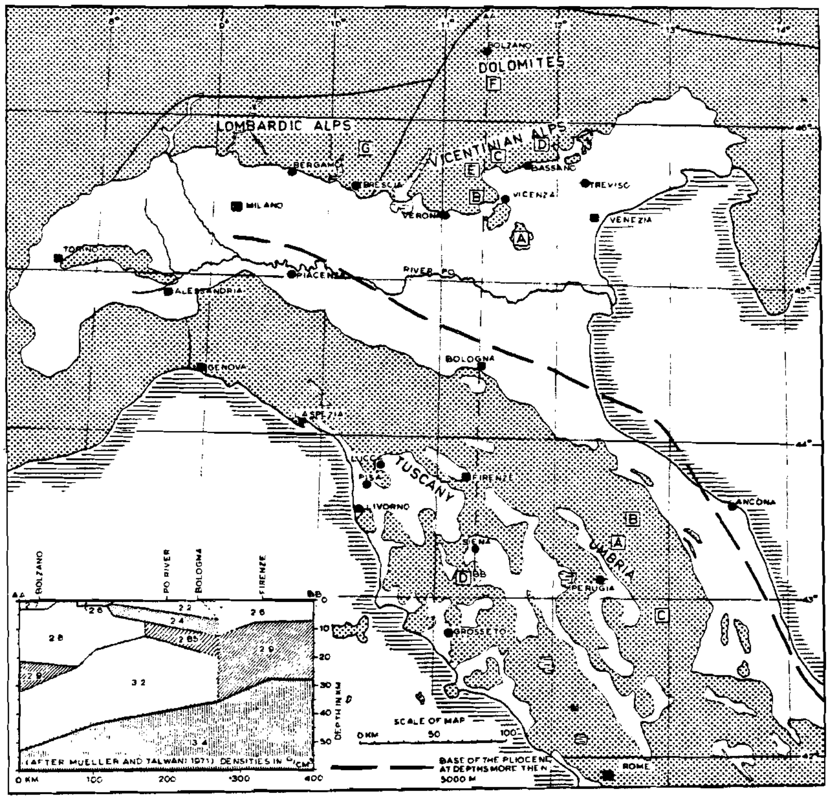


Figure 1 - Map of Northern Italy. Blank areas represent post-Middle Miocene deposits in the Tuscan-Umbrian area, and post-Upper Miocene sediments in the Po plain. The North-South profile is based on gravity and seismic refraction data according to Mueller and Talwani (1971). Dashed line gives location of the Pliocene through axis. The letters are referred to in Lists 1 and 2.

sist of Mesozoic and Early Tertiary rocks, forming a steep mountain belt, which emerges rather suddenly from the flat basin. The southern margin of the Po-basin is characterized by a low mountain belt containing N-NE dipping Tertiary deposits, which have been invaded, as late as Pliocene times, by olistoliths and olistostromes containing Mesozoic elements (Lucchetti et al., 1962). Subsurface investigations in the Po-basin revealed these allochthonous elements to be present some tens of kilometers North of the present basin margin (Agip Mineraria, 1959). In the North, on the contrary, an enormously thick, undisturbed series of clastics, ranging from Oligocene to Recent times, border the Alps. The Mesozoic and Early Tertiary sediments of the Alps dip steeply southward at this basin margin, suggesting normal faulting towards the South continuing until rather recent times.

The thickness of the authochthonous basin fill is enormous, as is shown by the asymmetric axis in Fig. 1, below which the base of the Pliocene reaches depths of more than 5000 meters (Ogniben, 1973). The considerable thickness of the Tertiary deposits in the Northern Apennines suggests a total thickness of Cenozoic sediments in the basin of some tens of kilometres. It is not surprising that little is known about the Mesozoic sediments which are supposed to be present at still greater depths. On the other hand, seismic studies indicate a normal crustal thickness of 30-35 km (Caloi, 1958; Giese and Morelli, 1973).

The gravity pattern and seismic refraction data indicate a major E-W striking fault zone, which is buried now underneath the thick sedimentary cover (Fig. 1; Mueller and Talwani, 1971). Our study supports the evidence for this fault zone and the relevant paleomagnetic data form the subject of this paper.

Evidence for large-scale crustal movements was previously found in the results from several paleomagnetic studies. The paleomagnetic directions of Permo-Triassic and Eocene rocks from the Southern Alps deviate systematically from the European directions for the same periods. Even North of the Insubric line, which is generally considered to be the fundamental boundary between the Southern Alps and the Central Alps, such deviating directions were found (Förster et al., 1975). On the other hand the paleomagnetic poles from the Southern Alps are very close to the African paleomagnetic poles (Zijderveld and Van der Voo, 1973). These authors concluded that the Southern Alps could have belonged to the African plate during their post-Hercynian evolution. However, this hypothesis must be refined, since it was found that the Northern Apennines also did belong to the African plate, but only until the Early Tertiary; afterwards an independent rotation occurred relative to the African plate (VandenBerg et al., 1976).

LIST 1

Paleomagnetic studies carried out in the Northern Apennines

Localities	Age covered by the samples	References
A	Late Camp. to Early Eoc.	Premoli Silva et al., 1974
A	Cenomanian to Eocene	Lowrie and Alvarez, 1974,1975
A	Cenomanian to Eocene	Channell and Tarling, 1975
B	L. Jurassic to Eocene	Klootwijk and VandenBerg, 1975
B	M/L. Jurassic to Eocene	VandenBerg et al., 1976
C	Cenomanian to Eocene	Lowrie and Alvarez, 1974, 1975
C	Cenomanian to Eocene	Channell and Tarling, 1975
D	L. Carboniferous to E. Permian and M/L. Triassic	Present paper

Letters refer to Fig. 1, South of the Po-basin.

Direct comparison of the scanty available data from the Southern Alps and from the Northern Apennines is difficult. The data from the Southern Alps are all from Permo-Triassic and Early Tertiary rocks, apart from some recently added Cretaceous data of the Vicentinian Alps (see List 2). On the other hand no comparable data have been obtained so far from the Permo-Triassic of the Apennines. We therefore decided to study paleomagnetically the Jurassic-Cretaceous limestone sequence of the Vicentinian Alps and the Verrucano of Tuscany in the Northern Apennines.

In this paper the first results of this attempt are presented and a tentative interpretation is given.

PREVIOUS STUDIES, GEOLOGY AND SAMPLING LOCALITIES

South of the Po-basin

Paleomagnetic data from areas South of the Po plain are available only from the Umbrian sequence and cover the Early/Middle Jurassic to Eocene timespan (see List 1). For a discussion of the results we refer to an other paper (VandenBerg et al., 1976).

In Fig. 2, the outcrops of the autochthonous basement in the Northern Apennines are indicated. An important problem in finding appropriate sampling localities is the metamorphism that has affected large parts of the Tuscan autochthon. This low-grade metamorphism was dated 11-14 m.y. B.P. (Giglia and Radicati, 1970). Sites must be found where the primary paleomagnetic directions have not been eliminated by remagnetization.

The non-metamorphic rocks of Late Triassic to Tertiary age of Central Tuscany, farther to the East, are supposed to be in allochthonous positions. Therefore they are not especially suitable for paleomagnetic research either.

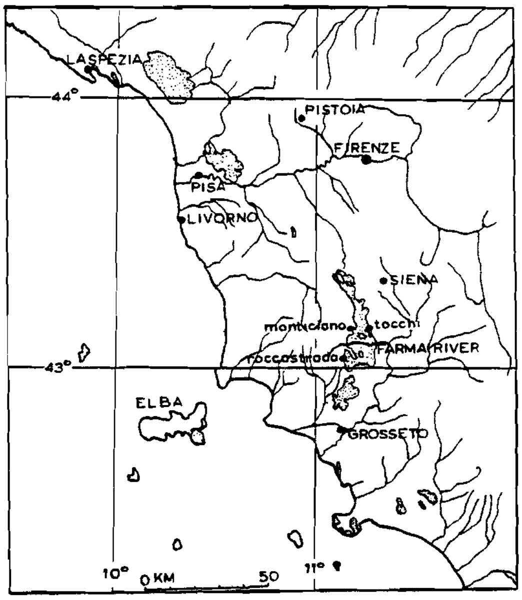


Figure 2 - Outcrops of the autochthonous basement (dotted: Verrucano) in Tuscany, after Dallan Nardi and Nardi (1972).

The grade of metamorphism of the autochthonous basement, however, varies from one place to another. Field study of the outcrops showed that the area between Grosseto and Siena was least affected. Another positive point in favour of this area is its simple tectonic structure, compared with other parts. The basement in the area near Roccastrada (Fig. 2) was only involved in minor folding and Pliocene normal faulting (Signorini, 1966).

The geological setting of the section is as follows : Folded dark-grey sandstones and dark shales of the Hercynian cycle (Farma Formation), containing Middle Carboniferous to Early Permian floras and faunas, and correlable with the Buti phyllites and quartzites 275 m.y. old (Bortolotti et al., 1970; Borsi et al., 1966), are unconformably overlain by Verrucano rocks. No direct age determinations of this Verrucano are known. A minimum age limit is given by the overlying Noric to Rhaetic Grezzoni and Calcare Cavernoso Formations (Bortolotti et al., 1970; Dallan Nardi and Nardi, 1972).

Several authors have pointed to the striking resemblance in facies and stratigraphic position between this "Siena" Verrucano and the Verrucano of the Alpi Apuane, which was dated as Ladinian to Carnian (Rau and Tongiorgi, 1968; Gelmini, 1969; Gianni et al., 1972; Gasperi and Gelmini, 1973). Provisionally, we assume this age for the "Siena" Verrucano.

Along the road from Monticiano to Tocchi (Fig. 2), the "Siena" Verrucano is exposed in its typical facies, containing polygenic conglomerates, quartzitic layers, grey and violet-red sandstones, grey siltstones and green phyllitic shales with sandstone and quartzite intercalations.
We restricted the sampling (8 sites) to fine-grained, grey and violet-red sandstones without visible crossbedding. Samples at one additional site were collected from rocks fitting this description for the Farma Formation (Bortolotti et al., 1970).

North of the Po-basin

In List 2 the previous work is compiled, and we refer to Zijderveld and Van der Voo (1973) for extensive discussion of the Permo-Triassic data.
Encouraged by the good paleomagnetic results we have obtained from red pelagic limestones, we searched for such deposits in the Southern Alps. For several reasons the Late Mesozoic to Eocene limestone sequence of the Vicentinian Alps was regarded to be the preferable target. This sequence has a stratigraphy nearly identical to that of the Umbrian sequence in the Northern Apennines, of which it seems to be the continuation (Aubouin, 1965). Tectonic disturbance is confined to normal faulting and folding along the Northern margin of the Po-basin related to its foundering. North of this margin, the sediments are in subhorizontal

LIST 2
Paleomagnetic studies carried out in the Southern Alps

Localities	Age covered by the samples	References
A	Eocene/Oligocene	Soffel, 1972, 1974
B	Eocene/Oligocene	Soffel, 1975a, 1975b
B	Eocene and Oligocene	De Boer, 1963, 1965
C	Upper Cretaceous	Channell and Tarling, 1975
D	Jurassic and Upper Cretaceous	Present paper
E	M/L. Permian and E/M. Triassic	De Boer, 1963, 1965
F	M/L. Triassic	Manzoni, 1970
F	M/L. Permian	Manzoni, 1970; Guicherit, 1964
F	E. Permian	Zijderveld et al., 1970; Van Hilten, 1960, 1962
G	M. Triassic and E. Permian	Zijderveld and De Jong, 1969

Letters refer to Fig. 1, North of the Po-basin.

position, overlying the thick Triassic dolomites, which, in turn, have an undisturbed stratigraphic contact with underlying older rocks.
Since previous Late Mesozoic data were confined to the Upper Cretaceous, and were not accurately dated , we directed our research to the Jurassic and Upper

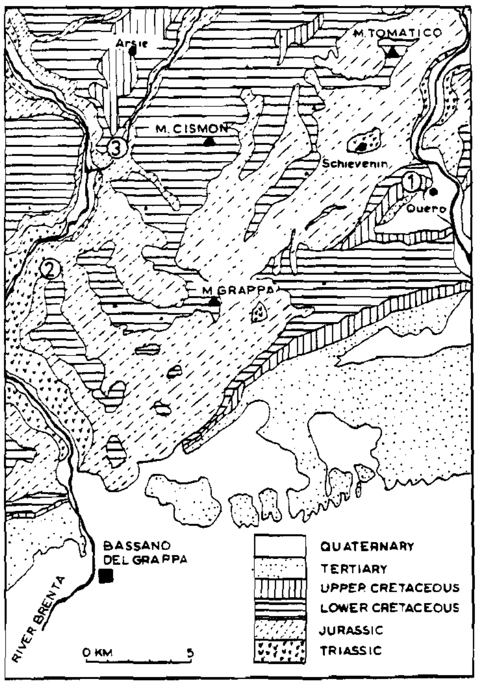


Figure 3 - Sketchmap of the outcropping rocks North of Bassano del Grappa (Fig. 1) with the sampling localities referred to in the text.

Cretaceous limestones. Several suitable levels in this sequence were found. At two different levels the limestones are developed in the "Ammonitico Rosso" facies, one of Kimmeridgian, the other of Tithonian age. Both were sampled (localities 2 and 3 in Fig. 3). The Lower Cretaceous rocks consist of white and green, well stratified limestones with shaly intercalations, which are sometimes dark and bituminous. The Upper Cretaceous is exposed as white (Cenomanian) and pink to red (Turonian to Maastrichtian), well stratified, pelagic limestones, containing abundant planktonic foraminiferal faunas. The latter were sampled in a continuous section along the road from Quero to Schievenin (locality 1 in Fig. 3). All samples could be dated accurately by studying the planktonic foraminifera in thin sections. The relative ages of the faunas were established by application of Postuma's zonation (1971).

Although the number of sites is still limited and further research is needed (the study is being continued), a record of dated paleomagnetic directions is now achieved and comparison with data from more southern areas is possible.

DEMAGNETIZATION DATA

In the paleomagnetic laboratory of the State University of Utrecht core specimens (2.2 cm height, 2.5 cm diameter) were drilled from the handsamples. The measurements were carried out on the very sensitive Czechoslovakian JR-3 spinner. The specimens were subjected to standard alternating fields for separation of the various magnetization components. No thermal cleaning was applied since these standard AF demagnetizations turned out to be most useful and adequate. Pilot specimens (at least one of each site) were progressively demagnetized in 10-15 steps up to the maximum obtainable peak value of 3100 Oe. According to the experiences with these pilot demagnetizations all specimens were partially demagnetized in 8-10 steps in the appropriate AF range. The characteristic and secondary magnetization components could be separated and their directions determined with the useful help of orthogonal projection figures (Zijderveld, 1967, 1975), which show sequential changes of the magnetization vector upon demagnetization.

The Mesozoic limestone sequence of the Vicentinian Alps

Fifty samples were collected from ten sites in this sequence. The initial intensities of remanent magnetization appeared to be low : 10^{-5}-10^{-6}Gauss, which is normal for pelagic limestones. The initial sample directions were distributed over the lower hemisphere (Fig. 4 A) in the northwestern quadrant only. Three components were discerned during demagnetization. The first remanent magnetization component was mostly removed from 0 to 200 Oe peak value, clearly related to the present local field (359^{o}, +62^{o}) and therefore of secondary origin. The

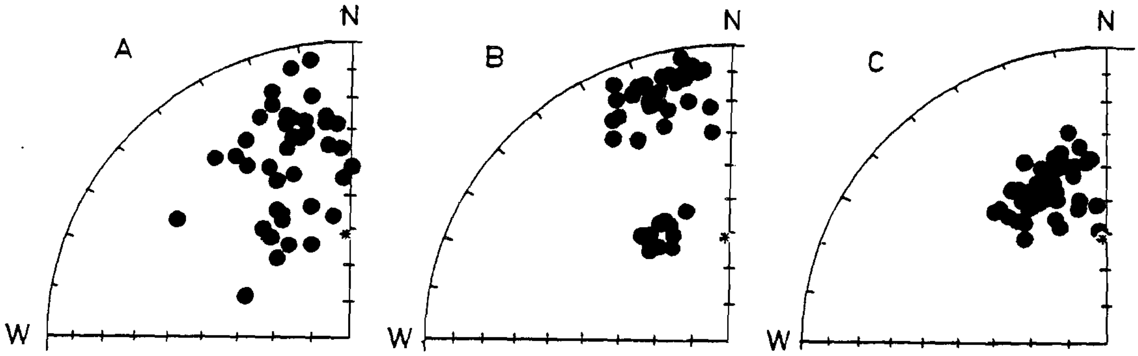
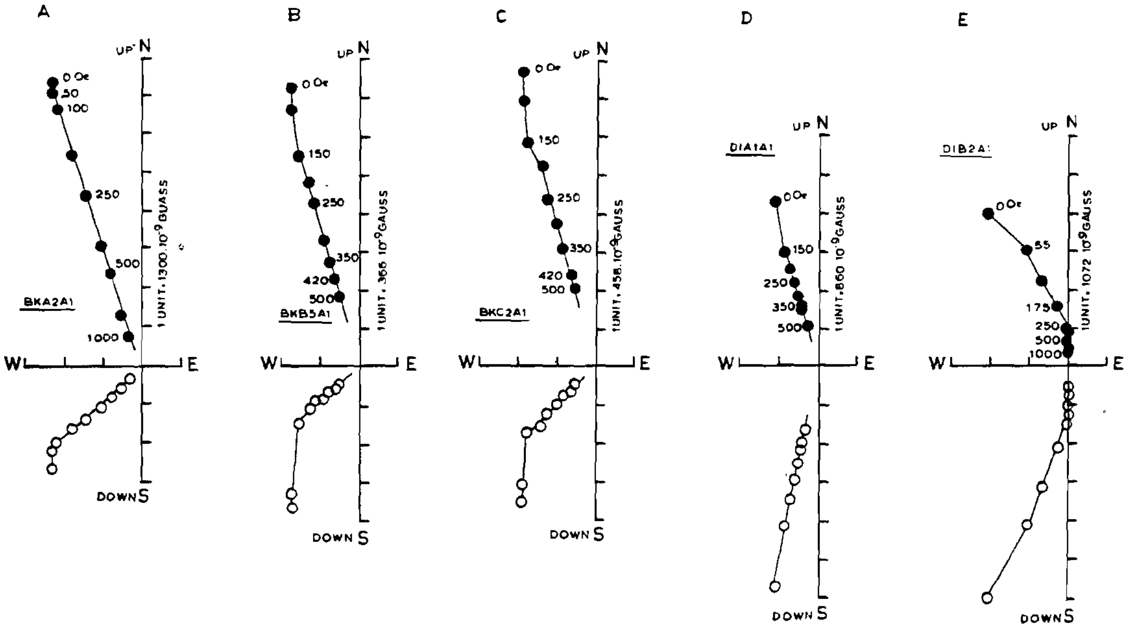


Figure 4 - Remanent magnetization directions in equal-area projection (of samples from the Vicentinian Alps), pointing downward in lower hemisphere projection. Asterisk denotes present local field direction. A. Initial N.R.M. sample directions. B. Characteristic sample directions, after demagnetization and before dip correction. C. Same, after dip correction.

supposedly characteristic component could be removed from 150 to 500 Oe peak value. A third very hard magnetization component was sometimes observed and could be removed from 500 to 3000 Oe peak value; being related to the present local field it too is therefore assumed to be of secondary origin.
The samples of two sites (BKG and TIA) contained only unstable remanence and revealed directions scattered over the lower hemisphere. Both sites were omitted from further considerations.



<u>Figure 5</u> _ Orthogonal projection figures of the vector path of the total remanent magnetization vector during AF cleaning of samples from the Vicentinian Alps. Circles are projections on the vertical East-West plane, dots are projections on the horizontal plane. Numbers denote Oersted peak values of the applied alternating fields.

Five orthogonal projection figures are shown in FIg. 5, which show the characteristics of demagnetization. Figs. 5 A, B and C show the removal of a secondary component in the so-called "Scaglia" (Turonian to Maastrichtian) samples from 0 to 150 Oe peak value. The characteristic magnetization component, having 60–80 % of the initial intensity, is removed upon further demagnetization, with the magnetization vector path going through the origin. The removal of the magnetization components in Fig. 5 D is similar; this specimen came from a Rosso

Ammonitico sample. In Fig. 5 E a secondary component is removed from 0 to 55 Oe peak value, and the characteristic component is removed in the 55-300 Oe peak value range. From 300 to 1000 Oe peak value a third secondary component is removed, having a direction close to the present field. Other specimens from the same site (DIB) had demagnetization curves similar to that shown in Fig. 5 D. The same phenomenon was observed in some samples of the Umbrian sequence (Van denBerg et al., 1976).

In Fig. 4 B the characteristic sample directions are plotted. The directions are clearly concentrated in two distinct groups, which is due to a different bedding tilt of the samples concerned. The unfolding is seen to be clearly positive in Fig. 4 C, where all characteristic sample directions are plotted having been corrected for the bedding tilts. For computation of the mean directions (Table I) Fisherian statistics were used. The overall mean direction of the Cretaceous samples is in good agreement with Channell and Tarling's (1975) result (List 2).

TABLE I

Remanent magnetization parameters, measured in samples from the Vicentinian Alps

Sites	Samples	Initial intens. (10^{-8} Gauss)	Mean direction *	α_{95} (deg.)	Age	Mean direction ** (deg.)	α_{95} (deg.)	Pole position (deg.)	*dp* (deg.)	*dm* (deg.)
BKG	5	52—104	unstable	—	Maastrichtian	—	—	—	—	
BKF	5	86—140	339.5 + 49.8	6.8	Late Santonian /Early Camp.	342.7 + 50.9	5.3	70.4 N 119.1 W	4.8	7.1
BKE	5	68—105	346.1 + 51.9	9.9						
BKD	5	142—768	337.6 + 44.8	8.6	Early Santonian	344.2 + 43.3	5.3	65.7 N 131.3 W	4.1	6.6
BKC	5	287—734	350.4 + 41.5	5.5						
BKB	5	275—740	343.7 + 39.4	3.8	Late Turonian /Coniacian	345.5 + 38.2	3.3	62.7 N 137.5 W	2.3	3.9
BKA	5	837—1265	347.3 + 36.8	6.3						
TIA	5	59—171	unstable	—	Tithonian	—	—	—	—	
DIA	5	475—950	328.3 + 44.0	5.5	Kimmeridgian	328.5 + 45.3	3.0	58.5 N 104.7 W	2.4	3.8
DIB	5	135—805	328.8 + 46.5	4.2						

* After cleaning and dip correction. ** N = 10.

The Tuscan Verrucano

46 samples were collected at nine sites throughout the "Siena" Verrucano. The initial intensities ranged from 3.10^{-5} to 1.10^{-6} Gauss, which is rather low.

In Fig. 6A the initial sample directions are plotted in an equal-area projection. Only normal polarities were observed. The directions show a reasonable scatter with a preference for the northwestern quadrant.

During AF demagnetization of most specimens a present-day local field direction (359°, +59°) appeared to be present, but in the samples of sites VUE, VUF, VUG and VUK this component was of minor importance. In the case of sites VUC, VUH and

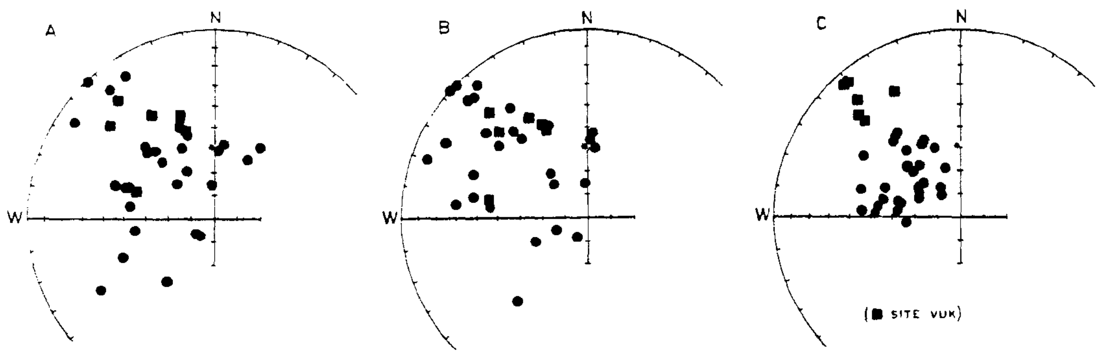


Figure 6 - Directions of remanent magnetization in equal-area projection (of samples from the Apennines), all directions pointing downward in lower hemisphere projection. A. Initial N.R.M. sample directions. B. Characteristic sample directions after demagnetization and before dip correction. C. Idem, after dip correction. Squares represent sample directions of Site VUK.

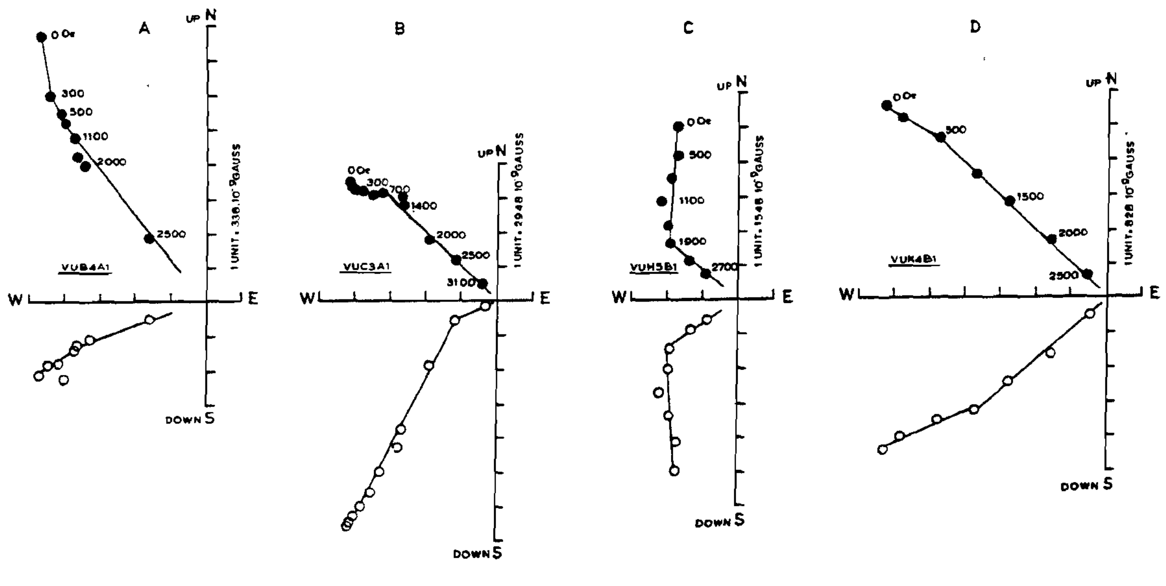


Figure 7 - Orthogonal projection figures of the vector path of the total remanent magnetization vector during AF cleaning, for samples from the Apennines.

VUB a rather rigorous cleaning was necessary to determine the characteristic magnetization components. Some examples of demagnetizations are given in Fig. 7. In Fig. 7A it is shown that a present local field component is removed from 0 to 500 Oe peak value and afterwards the harder (characteristic) second component is broken down in higher fields.

In Fig. 7D it is apparent that AF demagnetization results only in a minor change in direction of the magnetization component. In the case of Fig. 7B it is clear that, although the declination varies very little from 0 to 2500 Oe peak value demagnetization, the inclination reaches its characteristic value only in AF fields above 2500 Oe. Site VUC (Fig. 7B) was taken from a violet-red sandstone, as was site VUH (Fig. 7C). In Fig. 7C it is clear that the specimen from this site (VUH) has a notable present local field component, which is removed from 0 to 2000 Oe peak value.

Site VUA turned out to be too weak to reveal reliable components of magnetization during AF cleaning, and was therefore omitted. Site VUD appeared to be unstable during demagnetization. Two samples of site VUC could not be demagnetized properly in alternating fields up to the maximum obtainable peak value of 3100 Oe.

In Fig. 6B the sample directions are plotted which are assumed to be characteristic since removal of present field components was adequate, and these directions exhibit a positive fold test.

In Fig. 6C these characteristic sample directions are plotted corrected for dip. The scatter is clearly diminished. The results from site VUK (Table II) differ notably from the other results. The samples of site VUK were taken from an anticlinally folded sandstone bed and all had different dips; the fold test is definitely positive. The lower inclination may well be due to the fact that VUK was taken from Late Carboniferous to Early Permian r :ks of the Farma formation, while the other sites have an appreciably younger age (Ladinian to Carnian). In Table II the results are given with application of Fisherian statistics.

TABLE II

Remanent magnetization parameters, measured in samples from the Apennines

Sites	Samples	Initial intens. (10^{-8} Gauss)	Mean direction *	α_{95} (deg.)	
VUA	5	6—12	too weak	—	
VUB	5	118—337	327.2 + 55.7	11.6	
VUC	3	1808—2086	314.1 + 53.1	26.3	
VUD	5	1642—1875	unstable	—	Mean direction for sites VUB,C,D,E,F,G,H:
VUE	5	310—459	295.7 + 63.8	12.1	301.1 + 60.2, α_{95} = 6.0, N = 33
VUF	5	211—319	283.9 + 47.5	14.5	Pole position : 47.1 N 59.6 W (dp = 6.9°, dm = 9.1°)
VUG	5	124—212	288.1 + 68.0	20.5	
VUH	5	655—1126	300.1 + 64.8	10.6	
VUK	6	524—786	318.8 + 20.8	12.8	Pole position : 41.9 N 107.7 W (dp = 7.1°, dm = 13.5°)

* After cleaning and dip correction.

INTERPRETATION

North of the Po-basin

All data from the Vicentinian Alps (List 2 and Table I) are given in equal-area projection in Fig. 8A. The data from the other areas in the Southern Alps have not been plotted to avoid overcrowding. Zijderveld and Van der Voo (1973) showed that these do not differ significantly from each other. Figure 8A can be considered as representative for the Vicentinian Alps. In the following the paleomagnetic directions are interpreted as movements with respect to the pole.

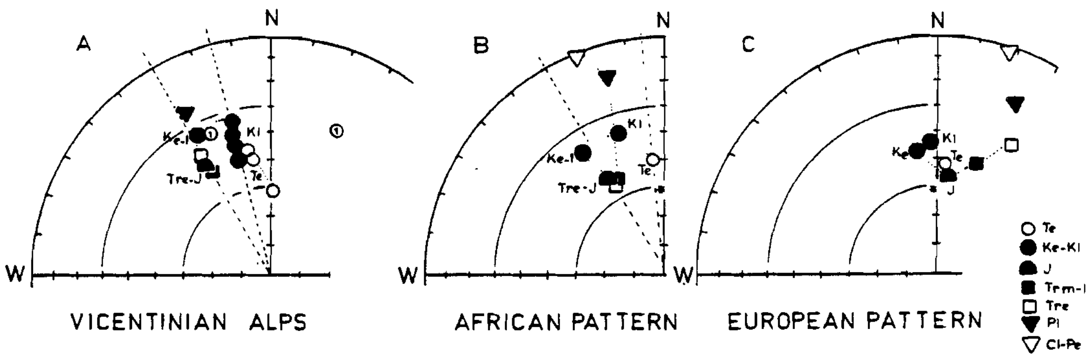


Figure 8 - Comparison of the mean directions from the Vicentinian Alps with African and European data; equal-area lower hemisphere projection. Asterisk denotes the present-day local field direction. All directions are pointing downward.
A. The actually measured directions from the Vicentinian Alps (List 2). Data from the Monte Lessini Volcanics (Soffel, 1975): (1)
B. In this projection the Vicentinian Alps are considered as fixed to the African plate. The directions to be expected were computed from the poles for Africa of Van der Voo and French (1974) for Paleozoic and Jurassic to Early Tertiary, and from the Triassic poles of McElhinny and Brock (1975).
C. The Vicentinian Alps are considered in this projection as fixed to the European plate and the directions to be expected were computed from the poles of Van der Voo and French (1974).

The Early to Middle Triassic directions do not differ from the Jurassic (Kimmeridgian) result (Fig. 8A), which means that no paleomagnetically detectable movements took place in the corresponding time span. A southward movement of about 10° of latitude is concluded from a correspondingly lower inclination value in the Cenomanian (Channell and Tarling, 1975). This movement may be correlated with the Late Aptian to Early Cenomanian southward movement phase in the Northern Apennines (VandenBerg et al., 1975, 1976). A 15° counterclockwise rotation of Late Cenomanian to Early Turonian age, followed by a northward movement of about 10^{o} of latitude in Santonian to Early Campanian times, is deduced from the change of paleomagnetic directions in this time interval. A further post-Cretaceous counterclockwise rotation (15^{o}) and an additional northward movement is suggested, since Late Cretaceous as well as Eocene data are still different from the present local field direction (see Fig. 8A). The paleomagnetic directions in Oligocene rocks (De Boer, 1963, 1965) are very close to the present local field direction, indicating that these ultimate latitudinal and rotational movements are of Late Eocene to Oligocene age. The results of Soffel (1975a, 1975b) from the Monte Berici and Lessini (see Fig. 8A) are interpreted as showing this final Late Eocene to Oligocene rotation. These data have comparatively aberrant low inclination values, which may be due to unidentified tectonic complications and/or to errors in the dip corrections. The mean result from the Eocene-Oligocene Colli Euganei (Soffel, 1972) is in good agreement with De Boer's findings (1963, 1965).

In Figs. 8 B and C those paleomagnetic directions are plotted, which would be expected in the Southern Alps, fixed with respect to either the African plate (Fig. 8B) or the European plate (Fig. 8C). In Fig. 8B these directions were computed from the paleomagnetic poles proposed for Africa by Van der Voo and French (1974) for the Paleozoic, Jurassic, Cretaceous and Early Tertiary. In Fig. 8C their paleomagnetic European poles were used for Paleozoic, Mesozoic and Early Tertiary times. These African and European paleomagnetic poles were deduced from the actually measured paleomagnetic poles of the Atlantic-bordering continents, and from the reconstruction of the sea-floor spreading history of the Atlantic (Pitman and Talwani, 1972). In Fig. 8B we used the Triassic African paleomagnetic poles published by McElhinny and Brock (1975), since these seem to have superseded Van der Voo and French's poles (1974) for this period.

It can be seen at a glance, that the Vicentinian (Southern) Alps belonged to the African plate rather than to the European plate. However, two important discrepancies can be observed. The African plate rotated during the entire Late Cretaceous about 30^{o}, while the Vicentinian Alps rotated only 15^{o}. The Early Tertiary rotation of the Vicentinian Alps was independent of and relative to the African plate. The Late Cretaceous (about 15^{o}) and the Early Tertiary (about 15^{o}) rotations bring the total rotation amount for the Vicentinian Alps up to about 30^{o}, relative to the pole. This explains the similarity of the Late Paleozoic data from the Southern Alps and Africa (Zijderveld and Van der Voo, 1973). Timing and amounts of the south- and northward movements of the Vicentinian Alps and Africa is nevertheless the same (within the accuracy of this study).

South of the Po-basin

In Fig. 9A the Northern Apennines pattern is plotted. For computation of the paleomagnetic directions, the data from Umbria of VandenBerg et al. (1976) were used, since these are carefully dated by a study of the planktonic foraminifera and cover the longest timespan (List 1). For comparison the Sardinian data (compiled by Manzoni, 1974) were averaged for the Permian, Tertiary and Quaternary, and plotted in Fig. 9A as well. In Fig. 9B the actually measured African directions for the Siena area in its present position are plotted, computed from the paleomagnetic poles compiled by McElhinny and Brock (1975). Comparison with Fig. 8B shows clearly the overall identity with this African pattern and that according to the simulated paleomagnetic poles of Van der Voo and French (1974). This firmly supports their basic assumption that the movements of the African plate were controlled by the opening history of the Atlantic (according to Pitman and Talwani, 1972). The following history of move-

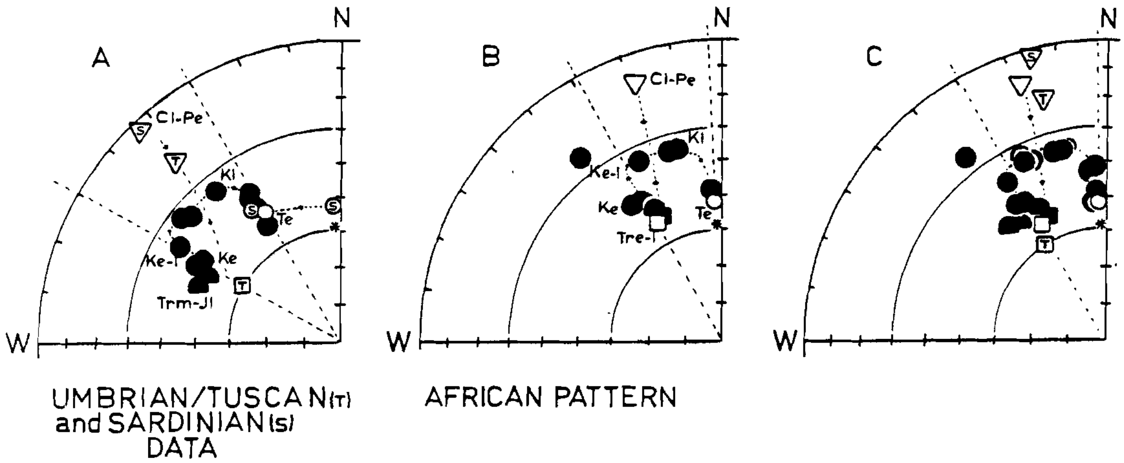


Figure 9 - Comparison of the mean directions from the Northern Apennines with the African data. Equal-area lower hemisphere projection. Asterisk denotes local field direction in the Siena area.

A. The actually measured directions from the Northern Apennines (VandenBerg et al., 1976) with the Tuscan (T) and the Sardinian data (S) added (Manzoni, 1974; present paper).

B. In this projection the Northern Apennines are considered as a part of the African plate and the directions to be expected were computed from the actually measured African poles (McElhinny and Brock, 1975). See Fig. 8B for comparison.

C. In this projection the Northern Apennines'pattern has been accounted for a 25-30^{o} rotation relative to Africa. The Sardinian data are rotated over the same amount for comparison.

ments with respect to the pole is deduced for the Northern Apennines : A southward movement took place in Albian to Early Cenomanian times, followed by a counterclockwise rotation of 30° during Turonian to Late Santonian/Early Campanian. Meanwhile a northward movement occurred in Santonian to Campanian. Campanian to Early Eocene data show no changes and still differ about 30° from the present local field direction. This indicates that a post-Early Eocene rotation must have taken place. Since the deduced movement pattern of the Northern Apennines and the African movement pattern (Figs. 9A and B) show a close identity, apart from the post-Early Eocene rotation, it is concluded that the Northern Apennines were part of the African plate until the Early Tertiary, when an independent counterclockwise rotation started relative to the African plate. After accounting for this rotation (25-30°) both patterns cover each other completely, as shown in Fig. 9C (VandenBerg et al., 1975, 1976).
In Fig. 9C it is shown that the newly obtained data from Tuscany are in very good agreement with the comparable African data. This rules out the possibility that the Tertiary rotation, shown for the Umbrian sequence, was caused by a dêcollement (Lowrie and Alvarez, 1975) of this sequence only.
The Sardinian data are in excellent agreement with the Northern Apennines' pattern (Fig. 9A) and with the African pattern (Fig. 9C) after accounting for a 25-30° rotation. This suggests that Sardinia belonged all the time to the Italian Peninsula. This raises interesting consequences for our understanding of the origin of the Tyrrhenian Sea.

The fault zone underneath the Po-basin

Comparison of paleomagnetic data from crustal blocks North (Fig. 8A) and South (Fig. 9A) of the Po-basin, covering a long timespan, is now possible. It has been shown that both blocks belonged to the African plate and that their movements were mostly defined by the opening history of the Atlantic (Fig. 8 A and B, Fig. 9 A and B). Differences between both movement patterns must have resulted in a fault zone in the area of the Po-basin, as argued below.
The first paleomagnetically observed difference in movements occurred in the Late Cretaceous. Both crustal blocks together with Africa started the Late Cretaceous rotation in the Turonian/Cenomanian, but the Vicentinian Alps did not continue through 30°, as the Northern Apennines and Africa did, but stopped after 15°. The Northern Apennines continued to rotate 15° during the Coniacian

to the Late Santonian/Early Campanian, while the Vicentinian Alps stopped the rotation in the Late Turonian. Nevertheless, both crustal blocks moved Northward with the African plate during the Santonian to Campanian. The reason why the northernmost extension of the African plate did not rotate another 15^{o} can possibly be sought in a Late Cretaceous collision with parts of the European plate.

The second observed difference occurred in the Early Tertiary (Late Eocene to Oligocene). The Northern Apennines and the Vicentinian Alps were subjected to an independent counterclockwise rotation relative to Africa of about 25^{o} for the first and about 15^{o} for the latter. The volcanic activity in the Southernmost Alps is probably related to the relative movements involved.

The precise nature of the relative movements can only be surmised since the rotation-poles are not known. No significant difference in inclinations is observed, but North-South movements of less than 400 km fall within the accuracy of our paleomagnetic data and are therefore not detectable.

CONCLUSIONS

(1) The Vincentinian Alps (possibly all of the Southern Alps) belonged to the African plate until the Late Turonian. Afterwards the "Vicentinian crustal block" was partially uncoupled from the African plate as well as from the Italian Peninsula.

(2) The Northern Apennines (possibly the whole Italian peninsula + Sardinia) were part of the African plate until the Early Tertiary when the "Northern Apennines crustal block" was partly uncoupled from the African plate by a counterclockwise rotational movement.

(3) During the Late Cretaceous (Coniacian to Late Santonian/Early Campanian) and again in Early Tertiary (Late Eocene to Oligocene) a fault zone must have been active in the area of the Po-basin. This supports Mueller and Talwani's hypothesis (1971). Thus the Po-basin can be seen as a fault zone, buried under a thick Late Tertiary to Quaternary cover.

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PALEOMAGNETIC EVIDENCE OF LARGE FAULT DISPLACEMENT AROUND THE PO BASIN - REPLY

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The supposed Tuscan Autochthon (i.e. the Monticiano area) was chosen for paleomagnetic research in order to establish, whether the detailed movement patterns deduced from paleomagnetic data of NW Umbria was representative for the entire Northwestern Apennines. As it could not be exluded that the offset to the west of the Umbrian paleomagnetic data relatively to the African and Southern Alpine data was the result of a rotational décollement to its basement of the whole Umbrian sequence (VandenBerg et al., 1978); VandenBerg and Wonders, 1976).
In their comment, Kligfield and Channell question the autochthony of Tuscany, i.e. the Monticiano area, and therefore question our conclusion that the offset of the Umbrian pattern is representative for the entire Northwestern Apennines indeed.
We have proposed a two phase differential movement for the Northwestern Apennines and the Southern Alpine block, Kligfield and Channell raise doubt about the second (Tertiary) phase only, stating that the Monticiano area probably is not autochthonous and therefore a rotational décollement remains to the possibilities.
The Monticiano area (about 200 km^2 large) is part of an important horst system and bounded on all sides by normal faults (Giannini and Lazzarotto, 1975). The amount of vertical uplift of this area relative to the western and eastern sru-roundings is about 2500 meters. It comprises Hercynian folded sediments, of Middle to Late Carboniferous age, covered discordantly by subhorizontal continental clastic sediments of Permian to Late Triassic age, 700 m total thickness (Cocozza et al., 1975; Cocozza et al., 1974a; Cocozza et al., 1974b). The Middle/Late Triassic clastic sediment is concordantly overlain by Miocene sediments. In other areas in western Tuscany, the thickness of the Triassic clastics varies rapidly and in several outcrops the Paleozoic rocks are found directly overlain by Latest Triassic to early Jurassic anhydritic layers of the Mesozoic Tuscan sequence (Azzaro et al., 1976). This Mesozoic sequence forms essentially the Tuscan nappe.

REMARKS ON THE INTERPRETATION OF THE GEOLOGICAL SETTING

Kligfield and Channell assume that the slaty cleavage S1 is the result of a large recumbent fold with a flat lying axial plane, this is not supported by field observations, since no overturned strata nor the hinge of such a structure was mapped by Giannini and Lazzarotto (1975). Recumbent folds in the Tuscan nappe can be found in the "Montagnola Senese", north of the Monticiano area, and possibly in the southern and western parts of Tuscany, but there they are always related to the presence of anhydrite below the Tuscan nappe. These structures are developed in

the most superficial tectonic compartment of the Tuscan nappe and cannot be extrapolated to the presently underlying compartment.
Taken into account the considerable uplift and rapid decrease to the West of the Permo-Triassic continental sediments (Azzaro et al., 1976), the presence of par--autochthonous slabs at the base of drillings in more western, and therefore more internal, areas of Tuscany shows merely that directly below the Tuscan nappe a superficial tectonic compartment was reached belonging to the autochthon. That compartment, in which "rabotage" (abrading) is a common feature, was never present or has been removed together with the Mesozoic Tuscan sequence in a pre-Miocene phase from the Monticiano area.
The mineral associations related to the low grade metamorphism of the Alpi Apuane and the Monticiano area are quite different. The typical minerals for the Alpi Apuane and Monti Pisani are : quartz, albite, white-K-mica, epidote and rare biotite. This association is diagnostic for the chlorite-biotite zone of the greenschist facies (Hyndman, 1972). As for the Monticiano area the typical mineral association is : muscovite and phengite in the Hercynian folded rocks, indicating subchlorite zone, however sericite/phengite, kaolinite and possibly montmorillonite are present in the Permo-Triassic rocks, indicating for the later the zeolite facies (Hyndman, 1972; Azzaro et al., 1976). For the Alpi Apuane and Monti Pisani only compressive phases and a high geothermal gradient can account for these conditions (Carmignani et al., 1978), in contrast for the Monticiano area the very low metamorphic conditions point to a burial metamorphism with a low geothermal gradient. It is more likely that during the burial of the Monticiano section the slaty cleavage was formed, parallel to the bedding of the Permo-Triassic sediments, as a reaction to the sedimentary pile (Tuscan sequence?) and not necessarily during a deformation phase. The presence of a crenulation cleavage was only observed in the Paleozoic sediments (Azzaro et al., 1976; personal observation) and was assumed to be related to the tight Hercynian folding, axial planar to the isoclinal folds. The later metamorphism (zeolite facies) was not able to reopen the previous Hercynian system, because the temperature was too low (Azzaro et al., 1976).

REMARKS ON OUR PALEOMAGNETIC STUDY

During our first visit to the area (VandenBerg and Wonders, 1976) we collected handsamples throughout the Monticiano area from six localities all with different bedding tilts and widely dispersed. During a second party in October 1977, we cored 60 samples with an electric drill in a 100 meter section only. Kligfield and Channell refer abusively in their comment to this particular locality, since drillholes were the only traces they found. The results of this 100 meter section (VandenBerg, in prep.) support our previous findings in more than one way. The characteristic paleomagnetic directions, after thermal cleaning, are in excellent agreement with the earlier result. Besides in this section two levels were found that have complete opposite directions, proving the existence of at least two reversals in the section. The presence of reversals is a common feature in Middle-Triassic times (McElhinny and Burek, 1971), the period in which this sediment was formed (Cocozza et al., 1975). The paleomagnetic directions of the geographically distributed sites showed a positive fold test (VandenBerg and Wonders, 1976) and the presence of reversals within the section practically excludes the possibility of remagnetization during the very low grade metamorphism (Pullaiah et al., 1975; Dunlop and Buchan, 1977).

PALEOMAGNETIC DATA FROM SOUTHEAST ITALY

Paleomagnetic data are available for comparison not only from the Northwestern Apennines and outside the Southern Alps, but also from the autochthonous platform in Southeast Italy : Campania and Gargano/Apulia (Channell and Tarling, 1975; Channell, 1977). The platform sediments belong to the stable Adriatic block and form the backbone of the Adriatic plate (Channell and Horvath, 1976). The Umbrian sequence is the lateral equivalent of these autochthonous platform sediments, and a transitional facies can be observed. Comparison of paleomagnetic data from Umbria with those from the platform sequences is possible, providing the quality (accuracy) is corresponding. Such a condition is common use in statistics. Channell (1977) was very generous to his new data from Gargano/Apulia and used all site mean results with an α_{95} smaller or equal 33^o (sic) to compute a mean value. One should realize that we are dealing with rotations of 15^o-30^o at maximum. The values of α_{95} for the site mean results from the Umbrian and Southern Alpine paleomagnetic data practically never exceeded the 16^o (VandenBerg and Wonders, 1976; VandenBerg et al., 1978; Lowrie and Alvarez, 1974; Channell and Tarling, 1975).
In Fig. 1 we have plotted the site mean results from Campania and Gargano (Channell and Tarling, 1975) as well as the newly available data from the platform carbonates in Gargano/Apulia (Channell, 1977) as full squares, using only

those data which had an α_{95} that did not exceed 15°. These directions and the mean value for the platforms (Dec. 327.1°, Inc. +37.5°. α_{95}=5.9°) were computed for the site of Cagli (43°33' 12°41') in Umbria. These paleomagnetic data cover the timespan Turonian to Maastrichtian, and can directly be compared with the Umbrian data in Fig. 1. The mean value for this timespan from our data (VandenBerg et al., 1978) (Dec.322°, Inc. +42°, α_{95}=6°) was not plotted to avoid overcrowding.

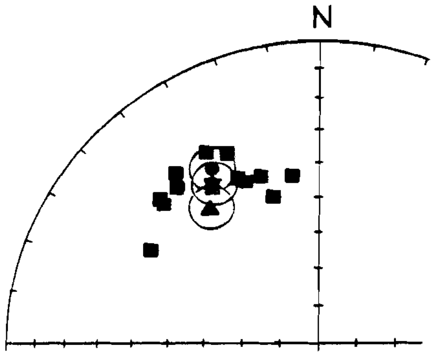

Figure 1 - Comparison of Turonian to Maastrichtian paleomagnetic data from Northwest Umbria and Southeast Italy. Full squares indicate site mean directions from Campania and Gargano/Apulia (Channell and Tarling, 1975; Channell, 1977). The full star is the mean value for these areas. Full dot indicates the mean value of the Northwestern Umbrian data according to Channell and Tarling (1975). Full triangle indicates the mean value of the Northwest Umbrian data according to Lowrie and Alvarez (1974). Circles indicate the cones of confidence on the probability level of 95% for the mean values. All directions downward pointing in lower hemisphere projection.

The elongated site mean distribution (squares) is in good accordance with the Umbrian pattern for this interval (VandenBerg and Wonders, 1976), and the overall mean values show no significant statistical difference, as can easily be seen in Fig. 1.

CONCLUSIONS

Kligfield and Channell's simple extrapolation of the tectonic development of the Alpi Apuane and Monti Pisani to the Monticiano area seems highly speculative.

There is no reason to assume that the paleomagnetic directions from the Monticiano area are not the result of primary magnetizations.
If at all the Umbrian sequence was detached from its basement during a dĕcollement, than that movement was not rotational relatively to the Monticiano area nor to the Southeast Italian platform, since paleomagnetic data with an acceptable accuracy from those areas do not differ and are in excellent agreement to each other. Since especially the Southeast Italian platform (Gargano/Apulia) is considered to represent the backbone of autochthonous Italy, the conclusion seems justified that the detailed movement pattern deduced from paleomagnetic studies in NW Apennines are representative not only for the Northwestern Apennines (VandenBerg et al., 1978), but for all peninsular Italy.

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A DUTCH CONTRIBUTION TO THE PALEOMAGNETIC RESEARCH IN ITALY

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RIASSUNTO

Vengono riassunti in questo lavoro i risultati di più campagne di studi paleomagnetici condotti su terreni mesozoici e terziari di varie zone dell'Italia. I dati di declinazione e inclinazione indicano per l'Umbria due rotazioni antiorarie di 30° dal Turoniano al Santoniano e di 25° dal Maastrichtiano all' Eocene inferiore. Contemporaneamente si ha un movimento verso Sud di 10° di latitudine dall'Aptiano alto al Cenomaniano ed uno pure di 10° di latitudine verso Nord dal Santoniano al Campaniano. Ancora uno spostamento verso Nord si è avuto dopo l'Eocene inferiore. Tali movimenti almeno dal Giurassico inferiore al Cretaceo inferiore, concordano con quelli della placca africana mentre la rotazione di 25° posteriore all'Eocene inferiore è del tutto indipendente. I dati della Toscana (Verrucano dell'area di Siena)concordano sia con quelli giurassici dell'Umbria che con quelli della Sardegna, suggerendo così che quest' ultima era solidale con l'area appenninica durante la sua storia post-ercinica. I dati paleomagnetici relativi alle Alpi meridionali (zona di Vicenza) differiscono da quelli dell'Umbria per l'entità delle rotazioni antiorarie pre e post-Maastrichtiano e per la coincidenza con gli attuali valori dei dati Oligomiocenici. Tale differenza di comportamento fra Alpi Meridionali e Umbria e Toscana porta necessariamente a presupporre l'esistenza di una faglia trascorrente sinistra probabilmente localizzata nella pianura padana. Correlando alle fasi dell'orogenesi alpina i dati paleomagnetici peninsulari si può riferire il movimento verso Sud dell'Albiano-Cenomaniano alla fase distensiva delle Alpi Centrali (Pennidi) mentre la rotazione del Cretaceo superiore coincide con la fase Pre-Gosau. I movimenti verso N della fine del Cretaceo e le rotazioni terziarie corrispondono alla fase alpina s.s.

INTRODUCTION

Paleomagnetic research was directed to the Mesozoic sediments of the Central Apennines (Umbria and Tuscany) and the Southern Alps, in order to obtain a detailed record of changes in declination and inclination of their characteristic magnetization. In the summer of 1973, Dr. C.T. Klootwijk sampled the Mesozoic sequence in the Cagli area (Umbria) for a preliminary collection. The results were encouraging (Klootwijk and VandenBerg, 1975) and in the summer of 1974 the investigation was rigorously extended. Three Late Cretaceous sections and additional sites in Early Cretaceous and Jurassic rocks were sampled. The result of one section was published as a progress report (VandenBerg, Klootwijk and Wonders, 1975), while the results of the complete study are still in press (VandenBerg, Klootwijk and Wonders, 1976). In order to check to what areal extent the Umbrian data were applicable, a Mesozoic sequence in the Southern Alps (Bassano del Grappa) and Early Mesozoic rocks in Tuscany (Siena) were sampled for paleomagnetic research too. Comparison of the obtained results from various localities was then possible (VandenBerg and Wonders, 1976). In this contribution the results of these paleomagnetic studies will be summarized, whereas for the details about the laboratory treatment of the samples the reader is referred to the before mentioned publications. Changes in declination are interpreted as rotations with respect to the pole and changes in inclination as latitudinal movements (i.e. N/S movements) with respect to the pole. One should be aware that E-W movements are not detectable by paleomagnetic studies. All samples were carefully dated by Dr. A.A.H. Wonders by studying the planktonic foraminifera content in thin sections. In the case of the Tuscan-Verrucano we rely upon the work of the Geological Department of the Siena University (Cocozza, Lazzarotto and Pasini, 1975).

INTERPRETATION OF THE RESULTS

South of the Po-basin

1) Umbria

Paleomagnetic directions of Toarcian-Aalenian to Late Aptian sites group fairly well, implying absence of major rotational and latitudinal movements of the sampling area during that interval. Late Aptian to Campanian directions indicate: a southward movement over 10° of latitude during Late Aptian to Late Cenomanian times, a 30° counterclockwise rotation during Turonian, Coniacian and Santonian, and in addition a northward movement over 10° of latitude during Santonian and Campanian. Reasonably well grouping Maastrichtian to Early Eocene data, which also deviate from the present local field direction, indicate a further 25° counterclockwise rotation and an additional northward movement over more than 10° in post-Early Eocene times. These paleomagnetically deduced movements for Umbria conform during at least Late Early Jurassic to Early Tertiary times with the movements of the African plate as established from seafloor spreading (Pitman and Talwani, 1972) and the paleomagnetic data (VanderVoo and French, 1974). Moreover the paleomagnetic data indicate that this coupled motion of the Italian peninsula and the African continent did not persist until present times : a post-Early Eocene 25° counterclockwise rotation of the Italian peninsula must have occurred with respect to Africa.

2) Tuscany

Paleomagnetic directions obtained from the autochthonous Verrucano s.s. (Middle-Late Triassic) in the Siena area group reasonably well, and are in good agreement with the Jurassic data from Umbria. This rules out the possibility that the Tertiary rotation shown for the Umbrian sequence in the Cagli area was caused by a décollement only. It is conspicuous that also the Sardinian data agree with the Central Apennines'data, suggesting that Sardinia was attached to the Central Apennines'plate during its post-Hercynian history.

North of the Po-basin

Vicentinian Alps

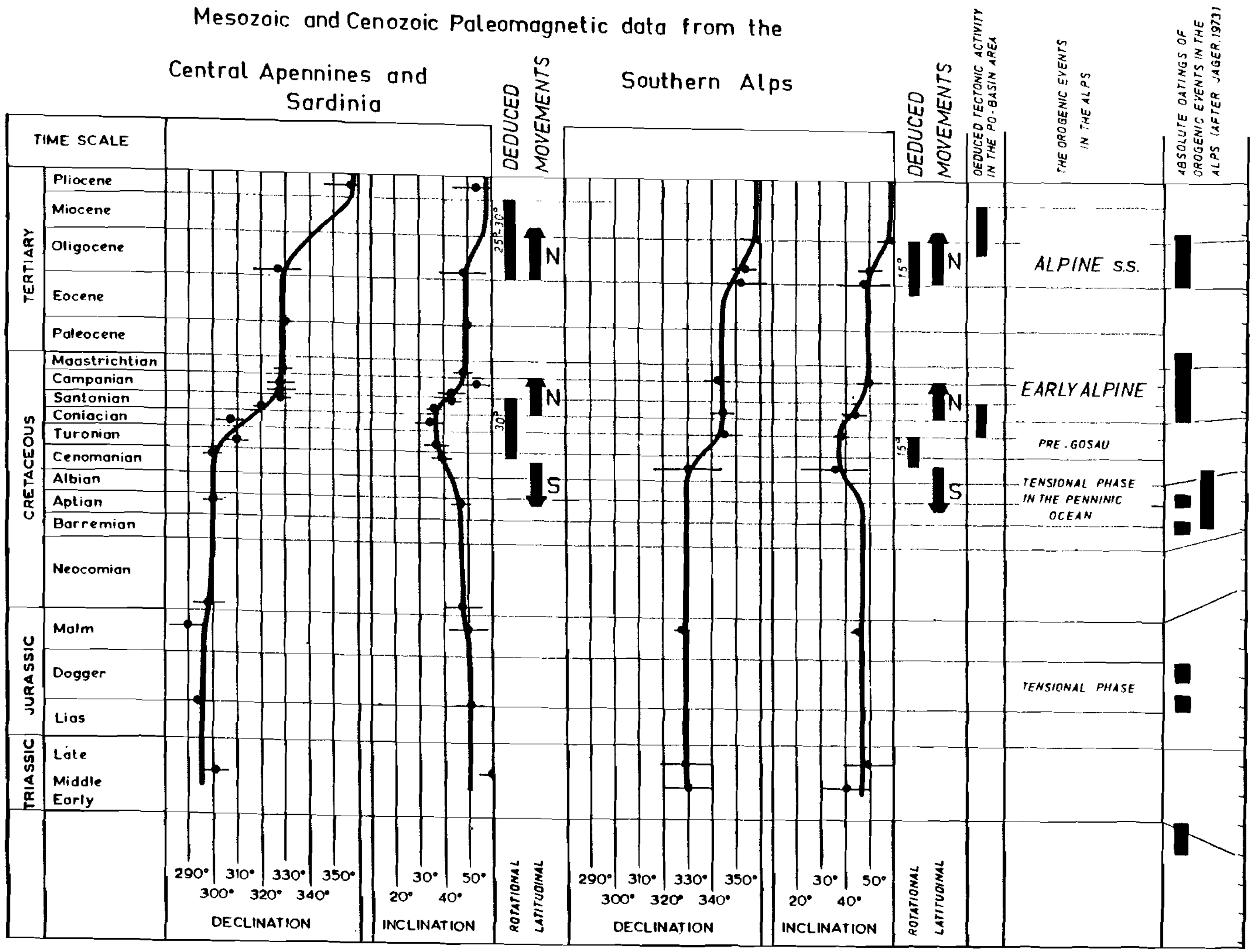
The Early to Middle Triassic directions do not differ from the Jurassic (Kimmeridgian) result, which means that no paleomagnetically detectable movements took place in the corresponding timespan. A southward movement of about 10° of latitude is concluded from a correspondingly lower inclination value in the Cenomanian. This movement may be correlated with the Late Aptian to Early Cenomanian southward movement phase in the Northern Apennines. A 15° counterclockwise rotation of Late Cenomanian to Early Turonian age, followed by a northward movement of about 10° of latitude in Santonian to Early Campanian times, is deduced from the change of paleomagnetic directions in this time interval. A further post-Cretaceous counterclockwise rotation (15°) and an additional northward movement is suggested, since Late Cretaceous data are still differing from the present local field direction. The paleomagnetic directions in Oligocene/Miocene rocks are very close to the present local field direction, indicating that these ultimate latitudinal and rotational movements occurred in the Early Tertiary. The movement pattern of the Southern Alps shows more identity to the African pattern than to the European movement pattern, therefore one has to assume that the Southern Alps belonged to the African plate.

A FAULTZONE UNDERNEATH THE PO-BASIN

Differences in movement patterns between the crustal blocks north and south of the Po-basin must have resulted in a fault-zone in the area of the Po-basin. The first paleomagnetically observed difference in movements occurred in the Late Cretaceous. Both crustal blocks together with Africa started the Late Cretaceous rotation in the Turonian/Cenomanian, but the Vicentinian Alps did not continue through 30^{o}, as the Northern Apennines and Africa did, but stopped after 15^{o}. The Northern Apennines continued to rotate 15^{o} during the Coniacian to the Late Santonian/Early Campanian, while the Vicentinian Alps stopped in the Late Turonian. Nevertheless, both crustal blocks moved northward with the African plate during Santonian to Campanian. The reason why the northernmost extension of the African plate did not rotate another 15^{o} can possibly be sought in a Late Cretaceous collision with parts of the European plate.
The second observed difference occurred in the Tertiary. The Northern Apennines and the Vicentinian Alps were subjected to an independent counterclockwise rotation relative to Africa of about 25^{o} for the first and about 15^{o} for the latter.

POSSIBLE CORRELATION WITH ALPINE OROGENESIS

Changes in declination and inclination were interpreted as movements with respect to the pole. One expects these movements to coincide with events in the history of Alpine orogenesis. However, absence of a paleomagnetically detectable movement does not necessarily mean absence of an (important) event, since E-W movements cannot be detected paleomagnetically.
It seems very likely that the Italian peninsula was involved in a West-East movement during the Jurassic, when in the Alpine realm basic and ultrabasic rocks were created (Jäger, 1973), the future basement of the Eugeosynclinal se-



Mesozoic and Cenozoic Paleomagnetic data from the Central Apennines and Sardinia / Southern Alps

diments in the Apennines and the Western Alps.
The bulk of an important southward movement took place during Albian and Early Cenomanian times according to our data. This movement can be correlated with an important tensional phase in the Central Alps (i.e. in the Penninicum), causing once again the emplacement and creation of basic and ultrabasic rocks in the Penninic ocean, datings range from 120 to 100 m.y. (Jäger, 1973).
The onset of the Late Cretaceous rotation seems to coincide with the Pre-Gosau phase, dated as Late Turonian. The deduced northward movement during Santonian and Campanian times coincides with the Early Alpine phase, when crustal shortening reached a climax in the Central Alps.
The Tertiary rotational and northward movement coincides with the Alpine phase sensu stricto.
In a page filling figure all the information that was poured out over the reader is arranged in one scheme. The figure itself needs only a short explanation: in the declination/inclination columns averaged site mean results are given with the radius of the top angle of the cone of confidence on the 95% level, indicated by the length of the bars.
For a justification of the data is referred to our papers.

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DISCUSSION

C. W. Alvarez - Let me start by complimenting this really first class example of a tectonic and paleomagnetic study. I would also like to point out a discrepancy between one aspect of your results and our results, not to quarrel, but just to point out that this discrepancy is not yet accounted for. One of the striking feature of your results from Umbria is the decrease in inclination at the bottom of the Upper Cretaceous in the Cenomanian. Our work which will be presented by W. Lowrie also covers the time when we should see this inclination change. But in the Bottaccione section, which we covered with samples that are spaced about one meter apart, the inclinations are absolutely constant. I think we should all be aware of this discrepancy and attempt to resolve it.

C. J. Channell - As with the data of Lowrie & Alvarez, my data from geographically distributed Umbrian sites show no apparent change in inclination throughout the Late Cretaceous. The African polar wander path for the Mesozoic of Van der Voo & French is based on the Atlantic magnetic anomaly data and on available paleomagnetic data. Due to the paucity of African and European Mesozoic paleomagnetic data, the Mesozoic paleomagnetic data used by Van der Voo & French comes almost entirely from North America. How much interpretation can be based on this inferred African polar wander path ?

C. J. VanderBerg - I can give you the African pattern which is not completely in agreement with their data.

C. J. Channell - African Mesozoic paleomagnetic data are themselves too scarce to give a meaningful polar wander curve. I agree that the Van der Voo & French data are , at present, the only means of comparing the Italian paleomagnetic data with Africa. I would like to know what happens to the "African pattern" of directional changes when the circles of confidence are superimposed.

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PALEOMAGNETISM OF LATE MESOZOIC PELAGIC LIMESTONES FROM THE SOUTHERN ALPS

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ABSTRACT

Paleomagnetic data are presented from the Southern Alps (Belluno-Bassano del Grappa). These paleomagnetic data specify the megatectonic movements of the Southern Alps for the Late Mesozoic. The detailed paleomagnetic data of the upper Albian, Cenomanian, and Turonian show the presence of upper Albian reversals and a period of substantial instability of the geomagnetic field, with occurrence of reversals in the Cenomanian.

INTRODUCTION

Channell and Tarling (1975) started the research in the Southern Alps on pelagic sediments and they first recognized differences between paleomagnetic data from the Southern Alps and from the Central Apennines. Further paleomagnetic research (VandenBerg and Wonders, 1976) was carried out and showed that the movement pattern of the Southern Alps was closely related to the movements of Africa and of Peninsular Italy. Discrepancies in amounts of rotation between the Southern Alps and the Central Apennines were explained by differential movements of both crustal blocks in the Late Cretaceous and Tertiary. Although these paleomagnetic data were rather convincing we felt that they had to be backed up by still more intensive studies.

The aim of the present study was to specify in detail possible the changes in declination and inclination of paleomagnetic directions in continuous sections of Cretaceous pelagic carbonate rocks. Therefore we choose for a very close sampling of restricted intervals. Since our earlier work had shown that megatectonic movements were to be expected in the Mid-Cretaceous, we mainly directed our attention to the Late Albian, Cenomanian, and Turonian limestones. In this way it became also possible to obtain information about polarity changes and to compare them to the results from the Gubbio section (Lowrie and Alvarez, 1977; Alvarez et al., 1977).

SAMPLING LOCALITIES

Two sections were studied. One is located close to Bassano del Grappa and is referred to as the "Quero-Schievenin" section (See Fig. 1). The other section is not far from Belluno and is called the "Valle del Mis" section (See Fig. 1).

1 Quero-Schievenin section :

This section ranges from Triassic to Maastrichtian and is composed of gently folded rocks, while at some places normal faults are present. Only the Upper Cretaceous part was studied. The Cenomanian is exposed as white well stratified pelagic limestones with black chert lenses intercalated. The Turonian to Maastrichtian contains pink to red pelagic limestones with rare chert. The whole section contains rich planktonic foraminiferal faunas. The studied interval (Cenomanian to Early Campanian) is some 100 meters thick, which means that the sedimentation rate is 5 m/my. No hiatus seems to be present.

The globotruncanoides and cushmani zones of the Cenomanian were sampled in 36 levels, several cores per level. The position of the levels was entirely de-

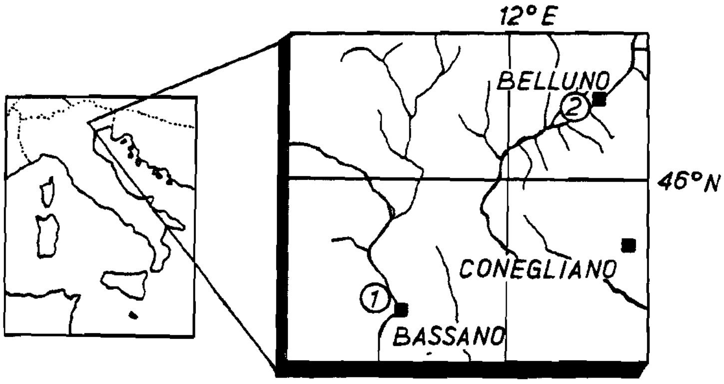


Figure 1
Map showing the geographic position of the "Quero-Schievenin" section (1) and the "Valle del Mis" section (2) in Northern Italy (Southern Alps).

fined by the absence of chert intercalations. The upper part (Turonian to Early Campanian) was sampled with a larger spacing : one site about every 5 meters (14 sites and 82 samples). This part of the section was studied before (Vanden Berg and Wonders, 1976).

2 Valle del Mis section :

Upper Triassic to Maastrichtian rocks are exposed in subvertical position in the valley of the river Mis. Only the upper part of this section was sampled. The Albian is developed as a sequence of siliceous thin bedded limestones with nodules, lenses and beds of chert. The limestones are fossiliferous micrites and biomicrites, with a sedimentation rate of about 7 m/my. The sedimentation rate drops abruptly towards the end of the Albian. The Cenomanian is represented by about 50 centimeters of pink marly limestone. The Turonian (± 10 m thick) consists of pink to red marly limestones with occasionally siliceous beds. Higher stratigraphic units are badly exposed, with exception of the Maastrichtian, which is composed of very marly limestones. From the Cenomanian to the Maastrichtian this section is very reduced compared with other sections (Casati and Tomai, 1969).

The upper Albian (about 19 m thick) was sampled at 55 levels. The reduced Turonian sequence was sampled at 100 levels. The whole sequence contains rich planktonic foraminiferal faunas, and could be dated appropriately.

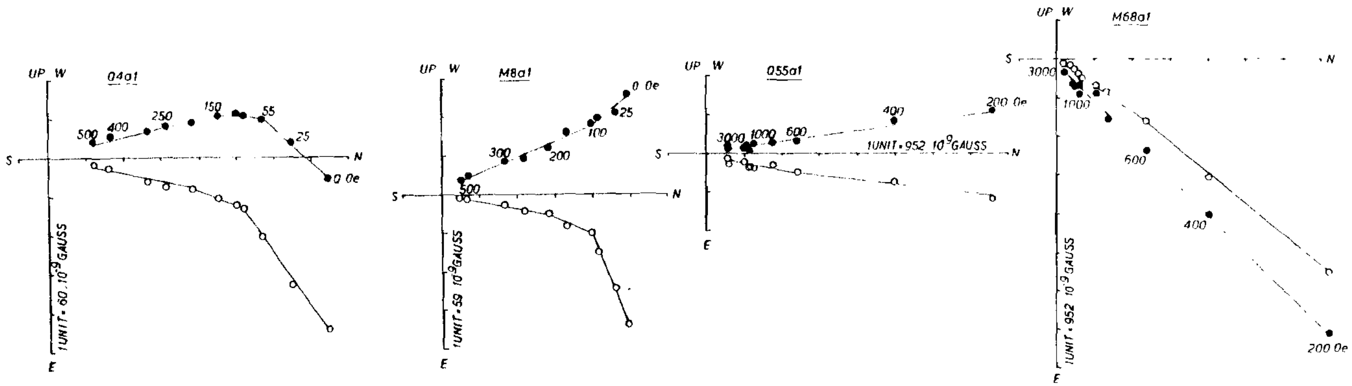


Figure 2

Orthogonal projection figures of the vector path of the total N.R.M. vector during A.F. demagnetization. Circles denote projections on the vertical N-S plane; dots are projections on the horizontal plane. Numbers represent values of the applied Alternating Fields in Oersteds.

TABLE I

Planktonic Foraminiferal Zone	Mean direction (Deg.)(1)		a_{95} (Deg.)	N	n
elevata	347.6	+50.0	-	2	11
carinata	346.7	+49.4	8.3	3	17
concavata	343.4	+45.7	8.4	3	16
sigali	345.1	+42.9	7.4	8	50
helvetica	343.8	+39.5	5.5	11	66
aprica	340.4	+37.7	9.5	8	50
globotruncanoides	336.4	+36.2	4.6	8	44
breggiensis	325.8	+38.2	5.4	8	48

(N= number of "sites"; n= number of samples)

(1) Giving unit weight to each site. Data from Cushmani zone omitted.

TABLE II

Age	Pole Position Plat.	Plong.	dp	dm
			(Deg.)	
Early Camp.	72.0 N	228.7 E	-	-
Santonian	71.1 N	230.0 E	7.3	11.0
Late Coniacian	67.0 N	232.6 E	6.8	10.7
L. Tur./E. Con.	65.7 N	226.7 E	5.6	9.1
Turonian	62.9 N	226.6 E	3.9	6.5
Early Turonian	60.4 N	231.4 E	6.6	11.2
Early Cenomanian	57.6 N	236.7 E	3.1	5.3
Late Albian	52.9 N	252.3 E	3.7	6.3

MAGNETIC PROPERTIES AND LABORATORY TREATMENT

Every core was sliced into cylinders (2.2 x 2.5 cm) at Fort Hoofddijk Laboratory. All measurements were carried out on a two axis ScT Cryogenic magnetometer. The Initial Natural Remanent Magnetization intensities for the white limestone specimens from the Valle del Mis section ranged from 0.2 to 2.0 x 10^{-6}Gauss, while the white specimen from the Quero-Schievenin section revealed somewhat lower intensities : 0.02 to 1.0 x 10^{-6}Gauss.

The red to pink limestones appeared to have appreciably higher initial N.R.M. intensities : in the Valle del Mis section : 7.0 to 30.0 x 10^{-6}Gauss and in the Quero-Schievenin section : 1.0 to 20.0 x 10^{-6}Gauss.

From both sections about 20 pilot specimens were demagnetized progressively in alternating fields in about 10 steps, the white limestone specimens in the range from 0 Oe to 500 Oe and the reddish limestone specimens from 0 Oe to 3000 Oe alternating field peak values. The magnetic behaviour was studied by means of orthogonal projection figures of the vector path during demagnetization. Secondary magnetization components in the white limestone specimens were removed in alternating fields above 50 Oe already, and for the reddish specimens this value was about 200 Oe. This is in good accordance with the behaviour observed in pelagic carbonates from Umbria (VandenBerg et al., 1978). Therefore all white limestone specimens were demagnetized in 4 to 6 steps in alternating fields with peak values of 50 Oe to 250 Oe. The reddish specimens were treated in fields of 200 Oe to 800 Oe. In Fig. 2 representative examples are given of the magnetic behaviour of white and reddish limestone specimens during demagnetization.

RESULTS AND THEIR INTERPRETATION

In Fig. 3 A, B and Fig. 4 A, B the results on sample level are compiled. The declination and inclination of the characteristic primary components, after cleaning and after correction for the bedding tilts are plotted versus the stratigraphic position in these figures. On the lefthand side the planktonic foraminiferal zones are given,as they could be recognized in thin sections. Both sections gave for corresponding intervals paleomagnetic directions that were in agreement, despite the quite different bedding tilts for the sections, and therefore the results of both sections were combined on basis of the assigned ages. In Table I and II the mean results are given applying Fisherian statistics.

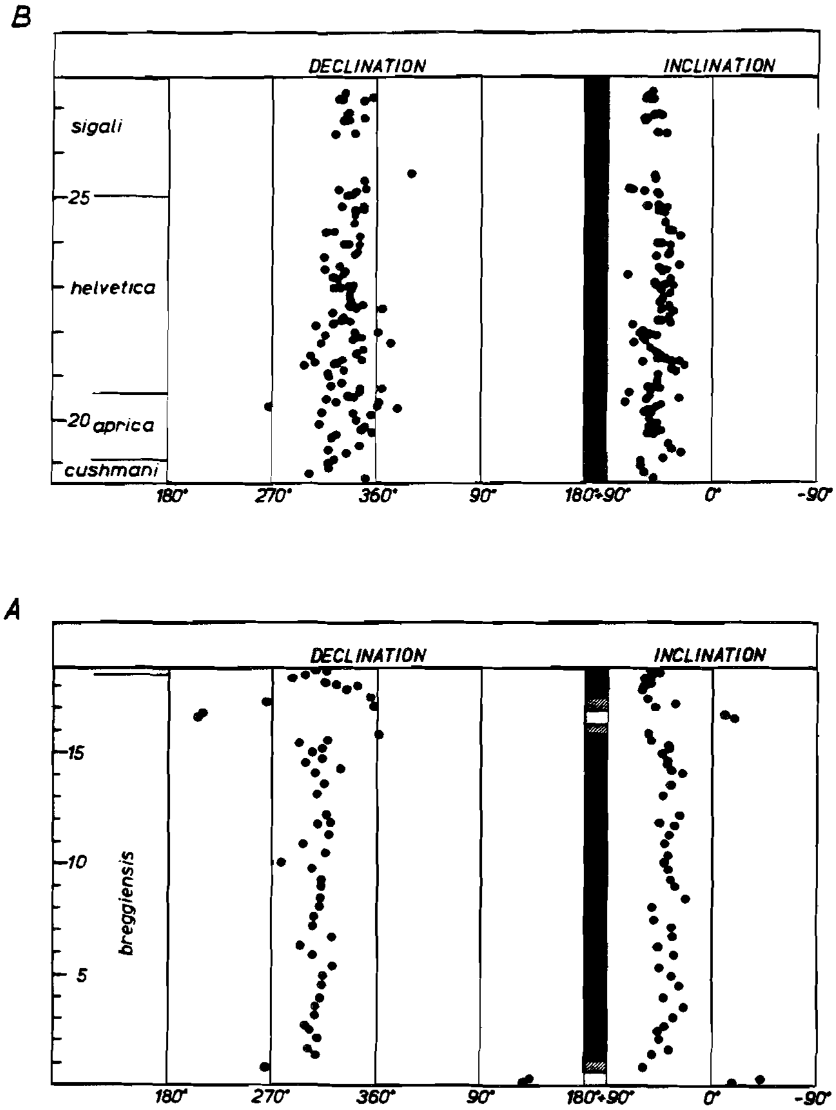


Figure 3 A, B

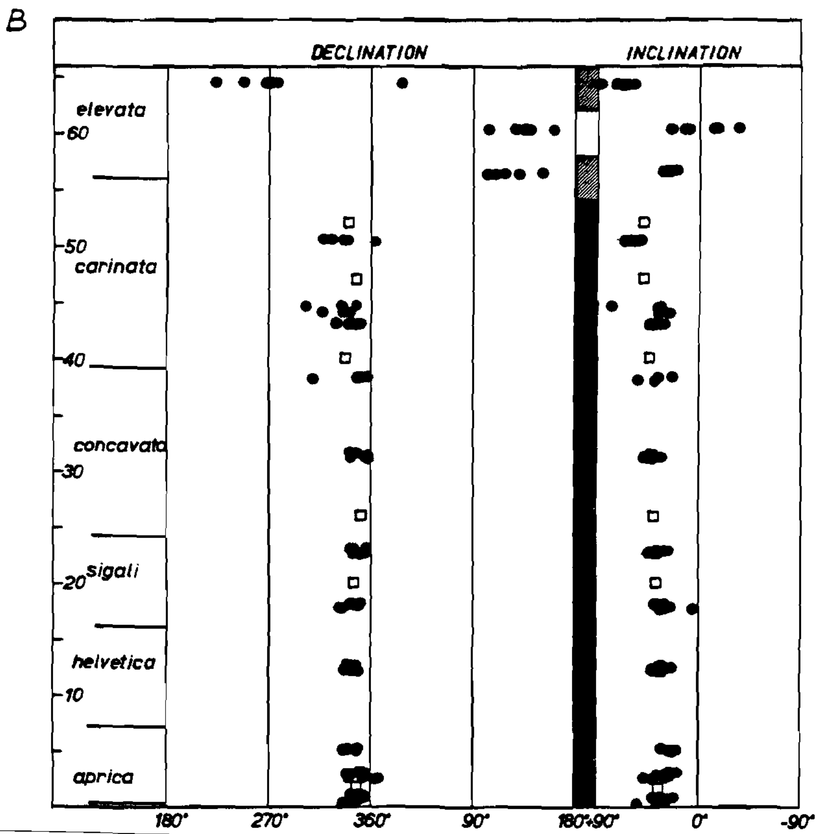
Sequence of sample directions plotted versus stratigraphic position for the lower part of the "Valle del Mis" section (A) and idem for the upper part (B). Planktonic foraminiferal zones are given in the left column.

Interpretation of the magneto-stratigraphy :

a) Valle del Mis section :

The lower part of this section of Late Albian age (Fig. 3 A) reveals very constant values of declination and inclination throughout the 19 m sequence. At the base and near the top reversed magnetic directions are present, indicating at least 2 reversals in the Upper Albian. Both reversals roughly have lasted about 150.000 years, a length of time that is comparable with the duration of Neogene reversals. In paleomagnetic studies on cores of DSDP site 263 (Green and Brecher, 1974; Jarrard, 1974) reversals in this very same interval have been reported, but could not be dated appropriately. Only 1 m above the upper reversal the declination reaches the value of the previous interval, showing a rather slow recovery of the geomagnetic field.

The upper part of the section, Late Cenomanian and Turonian in age, shows an appreciably larger scatter in declination and inclination (fig. 3 B). No reversed directions seem to be present.



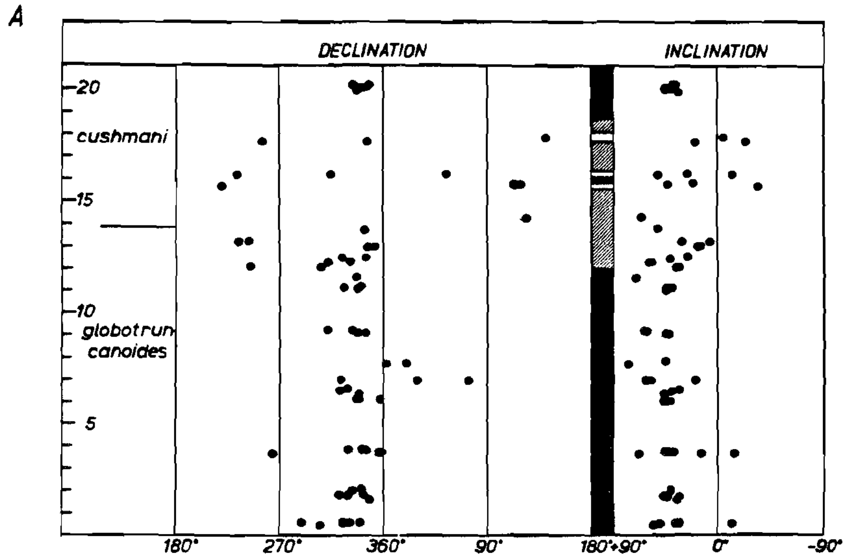


Figure 4 A, B

Sequence of sample directions plotted versus stratigraphic position for the lower part of the "Quero-Schievenin" section (A), and idem for the upper part (B). Planktonic foraminiferal zones are given in the left column of the figures. Open squares pertain to earlier results (VandenBerg and Wonders, 1976).

b) Quero-Schievenin section :

The lower part of this section (Fig. 4 A) represents biostratigraphically most of the Cenomanian and turned out to be of particular interest. The first 12 meters revealed rather constant declination and inclination values, but in the upper half directions change erratically. An interval of about 6.5 meters (estimated to represent $\pm$ 1.3 my) is characterized by intermediate directions. In this interval both reversed (at 3 levels) and normal magnetic directions are present. However, it is very probable that in this period of great instability of the geomagnetic field more reversals are to be expected. Only roughly an estimation about the duration of the reversals can be given : a timespan shorter than 100.000 years. Until present no reversals or a period of important instability of the Earth magnetic field have been reported for the Cenomanian (Lowrie and Alvarez, 1977; Channell et al., 1978).

The upper part of this section (Fig. 4B) covers a longer timespan : Turonian to Early Campanian. The results of our earlier study are incorporated in Fig. 4 B as open squares. The declination and inclination values are very constant up to the upper 3 sites. It can be observed that below and above the only site with reversely magnetized samples, intermediate paleomagnetic directions are present. The age assignment makes it very probable that these magnetic directions are related with the Gubbio "A" reversal (Lowrie and Alvarez, 1977; Alvarez et al., 1977). It is of particular importance to note that in pelagic limestones not only the periods of normal and reversed polarities can be traced but, apparently, also the transitional zones.

Interpretation of movements with respect to the pole :

When the directional variations of a paleomagnetically deduced record of a sequence are to be interpreted in terms of megatectonic movements with respect to the pole, all changes of the geomagnetic field itself have to be cancelled rigorously. Changes in the geomagnetic field due to secular variation are assumed to be of minor importance, because it is averaged out during the relative long time of acquisition of the N.R.M., related to the low sedimentation rate of pelagic carbonates. Therefore only long term variations of the paleomagnetic field (more than 10.000 years) can possibly be traced in these sediments. The duration of polarity transitional zones was apparently long enough to leave its marks in pelagic sediments with a sedimentation rate of more than or equal to 5 m/my.

In this particular study intermediate directions were omitted, and the mean values given in Table I and II were calculated from only those samples that were close to the overall mean value of the interval concerned. These results allow an interpretation about megatectonic movements of the Southern Alpine block and entirely support earlier conclusions (VandenBerg and Wonders, 1976).

In Fig. 4 B can be observed the slight change to higher inclination values, but this is more pronounced and substantiated in the mean results of Table I and II. Apparently the Southern Alpine crustal block remained at the same latitude during Late Albian to Turonian times and moved northward later in the Cretaceous. The inclination values of the Albian to Turonian data are lower than those of Late Triassic and Jurassic age (see Fig. 5), implying a southward movement during Early Cretaceous. These very same movements could be interpreted from the paleomagnetic data of Umbria (VandenBerg et al., 1978).

The declination values (about 330^{o}) of upper Paleozoic and Early Mesozoic rocks remain constant until Upper Albian. Data from Late Cretaceous rocks show an increase of about 15^{o}. The mean declination value of the Late Cretaceous and Early Tertiary rocks is about 345^{o} (Fig. 5). This implies an anticlockwise rotation of about 15^{o} during latest Albian and Cenomanian. A further 15^{o} anti-

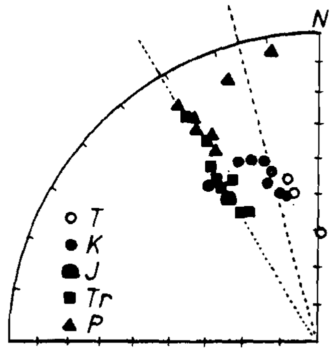


Figure 5

Mean paleomagnetic directions for the Southern Alps in equal area plot (lower hemisphere) of the presently available data. For Permo-Triassic and Tertiary is referred to Zijderveld and Van der Voo (1973); for Jurassic data to VandenBerg and Wonders (1976); for the Cretaceous data to present paper.

clockwise rotation of post-Early Tertiary age and an additional northward movement are necessary to reach the present declination and inclination value of the geomagnetic field.

The deduced two phase rotational movement scheme is in good accordance with that deduced for the Central Apennines (VandenBerg et al., 1978), as far as the timing of the movements is concerned. The rotation values, however, do differ appreciably as was noted before (VandenBerg and Wonders, 1976; Channell and Tarling, 1975). The conclusion that differential movements must have occured between the Southern Alpine block and the Central Apennine block during the Late Cretaceous and Tertiary is supported again by the present data.

CONCLUSIONS

The deviation towards the west of paleomagnetic directions from the Southern Alps were caused by two rotations of about 15° each, the first during the latest Albian and Cenomanian and the second during the Tertiary.

The assumption that in the Cretaceous quiet interval from the Late Aptian to the Early Campanian only normal polarity magnetic field has existed needs revision, at least for the Late Albian and the Cenomanian.

Intermediate magnetic directions apparently related to polarity transitional zones are recorded in pelagic carbonates and may lead to wrong conclusions about megatectonic movements with respect to the pole, if they are not excluded from the results.

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IMPLICATIONS OF NEW PALEOMAGNETIC DATA FROM THE VERRUCANO (TUSCANY, SIENA) FOR ITS AGE AND TECTONIC POSITION.

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ABSTRACT

Paleomagnetic results are presented from the lower lithostratigraphic unit of the Monte Quoio formation (Verrucano, Monticiano-Siena). The inclination value of the mean paleomagnetic result and the presence of magnetic field reversals point to an Early-Middle Triassic age.

INTRODUCTION

The supposed Tuscan Autochthon (viz. the Monticiano area) was subject of an earlier study in order to establish, whether the detailed movement pattern deduced from paleomagnetic data of N.W. Umbria was representative for the entire N.W. Apennines crustal block (VandenBerg and Wonders, 1976). It could not be excluded that the offset to the West of the Umbrian paleomagnetic data was the result of a rotational décollement over its basement of the whole Umbrian sequence (VandenBerg et al., 1978; Channell et al., 1978). As the paleomagnetic results from the Monticiano area are crucial for the interpretation of the paleomagnetic data from peninsular Italy the research was continued.

GEOLOGICAL SETTING OF THE MONTICIANO AREA

Traditionally the Monticiano area is supposed to be autochthonous, because of its stratigraphical position under the anhydritic layers (Latest Triassic), which mark the base of the Tuscan nappe. In its nucleus the oldest known sediments are exposed in a continuous (700 m) thick stratigraphic succession (Cocozza et al., 1975). The Monticiano area (about 200 km^2 large) is part of an important horst system and bounded on all sides by normal faults (Gianni and Lazzarotto, 1975). The amount of vertical uplift of this area relative to its western and eastern surroundings is about 2500 meters. It comprises Hercynian folded, middle to late Carboniferous sediments (Cocozza et al., 1974a), covered discordantly by subhorizontal continental clastic sediments of Permian to late Triassic age (Cocozza et al., 1975; Cocozza et al., 1974a; Cocozza et al., 1974b). The late Triassic sediments are concordantly overlain by Miocene sediments, indicating tectonic and/or erosional denudation in a pre-Miocene phase. Normal faults separate the Monticiano area in the North-East from the "Montagnola Senese" area, and in the South-West from the Monte Leoni area, where the Tuscan nappe is exposed, in association with the anhydritic layers. Tectonic deformation in those areas is quite distinct. In western Tuscany, the thickness of the Middle to Late Triassic clastic sediments varies rapidly and in several outcrops the Paleozoic rocks are found directly overlain by the anhydritic layers (Azzaro et al., 1976). In the Monticiano area a slaty cleavage is developed parallel to the bedding in the finer parts of the Permo-Triassic sediments. No flattening was observed in the conglomeratic levels of the Monticiano section. Comparable rock sequences are exposed in the Alpi Apuane and the Monti Pisani. However, the mineral associations related to the low grade metamorphism of the Alpi Apuane and the Monticiano area are quite different. The typical minerals for the Apuane Alps and the Monti Pisani are : Quartz, Albite, Chlorite, white K-mica, Epidote and rare Biotite. This association is diagnostic for the Chlorite/-Biotite zone of the Greenschist facies (Hyndman, 1972). This facies has P/T conditions of 400-500^{o} C and 2-7 kbars. For the Monticiano área the typical mineral association is : Muscovite and Phengite in the Paleozoic rocks, indicating subchlorite zone, and Sericite/Phengite, Kaolinite and possibly Montmorillonite in the Permo-Triassic rocks, indicating for the latter the Zeolite facies (Hyndman, 1972; Azzaro et al., 1976). The P/T conditions for the Zeolite facies are 250-350^{o}C and 2-5 kbars. For the Alpi Apuane and Monti Pisani only compressive phases and a high geothermal gradient can account for its present condition (Carmignani et al., in press), whereas for the Monticiano area the very low metamorphic conditions point to a burial metamorphism with a normal geothermal gradient. It is most likely that during the burial of the Monticiano section the slaty cleavage was formed, parallel to the bedding of the Permo-Triassic sediments, as a reaction to the sedimentary pile and not necessarily during a deformation phase. The presence of a crenulation cleavage was only observed in the Paleozoic sediments (Azzaro et al., 1976; personal observation) and is assumed to be related to the tight Hercynian folding, axial planar to the isoclinal folds. The later metamorphism (Zeolite facies) was not able to reopen the previous (Hercynian) system, because the temperature was too low (Azzaro et al., 1976).

SAMPLING AND MAGNETIC PROPERTIES

In contrast to the earlier study, when on different localities handsamples were collected (8 sites) in the present investigation our attention was directed to a short section (about 100 meters) along the road Monticiano-Tocchi. With an electric drill 62 cores were taken from 10 levels in this section. Mainly violet-red siltstones were sampled and some cores were drilled in the quartzite intercalations. In the laboratory Fort Hoofddijk these cores were sliced into cylinders (2.2 x 2.5 cm).

The initial Natural Remanent Magnetization (N.R.M.) intensities ranged from 2 to 10 x 10^{-6} Gauss. From each level several pilot specimens were demagnetized thermally in 11 steps from 100^{o} to 700^{o}C. All samples showed a rather uniform magnetic behaviour during thermal demagnetization. It was only between 600^{o} and 700^{o}C that the intensities of the N.R.M. decreased rapidly (see Fig. 1). Several

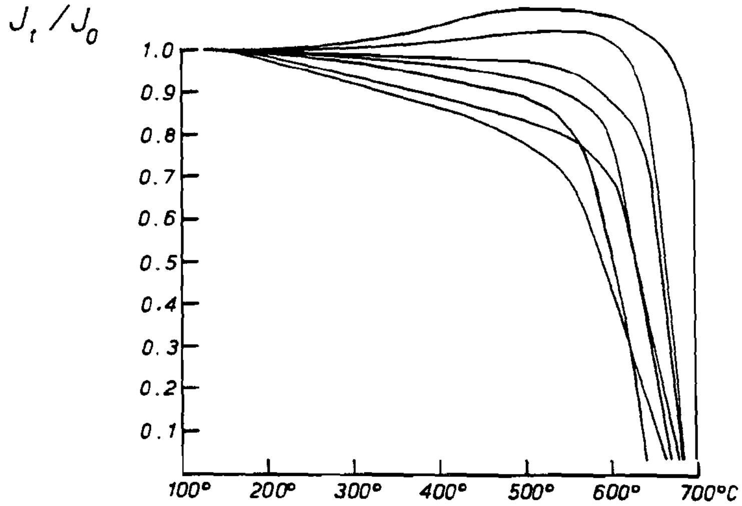

Figure 1
Some normalized curves, showing the decrease of total remanent magnetization during thermal cleaning; Jt/Jo is normalized intensity.

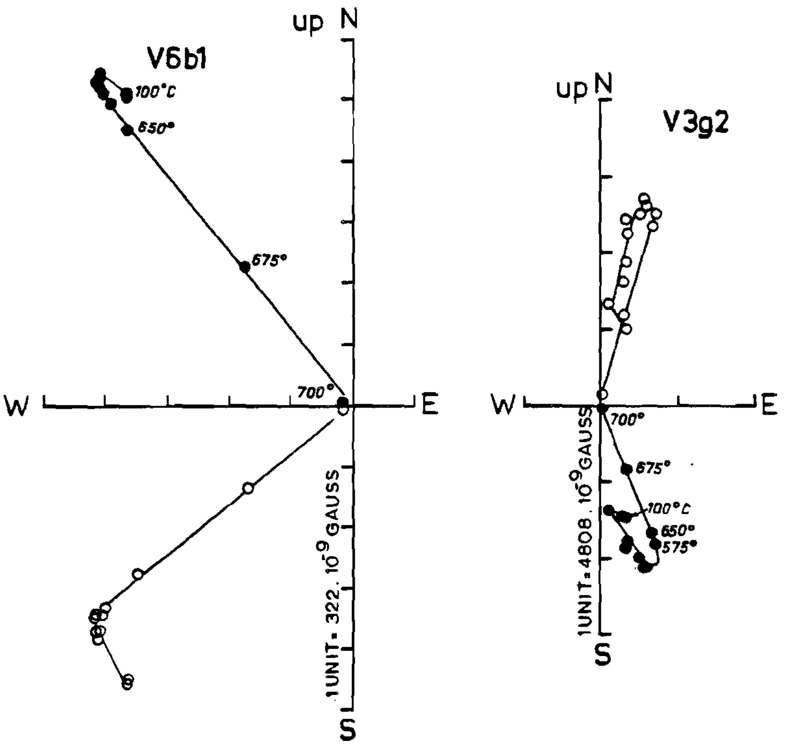

Figure 2
Orthogonal projection diagrams of the vector path of the total remanent magnetization vector during thermal cleaning. Circles are projections on the vertical east-west plane; dots are projections on the horizontal plane. Numbers denote values of applied temperatures in degrees Celsius.

specimen showed an increase in intensity of the N.R.M. before its removal. These particular specimens turned out to have reversed polarities. At 600°C at least 80% of the initial intensity survived and between 600° to 700°C a stable remanent magnetization component was removed (see Fig. 2). It is obvious that this stable remanent magnetization component with very high blocking temperatures resides in hematite grains and is characteristic for these siltstones. Therefore all specimens were demagnetized in 4 to 5 steps in that range.

From the original 62 cores 11 samples of mainly quartzites were rejected, because they revealed only viscous remanent magnetizations. In Fig. 3 stereographic projections show the distribution of the characteristic remanent magnetization components on sample level, before and after tectonic correction. In Table I the mean results are compiled with application of Fisherian statistics.

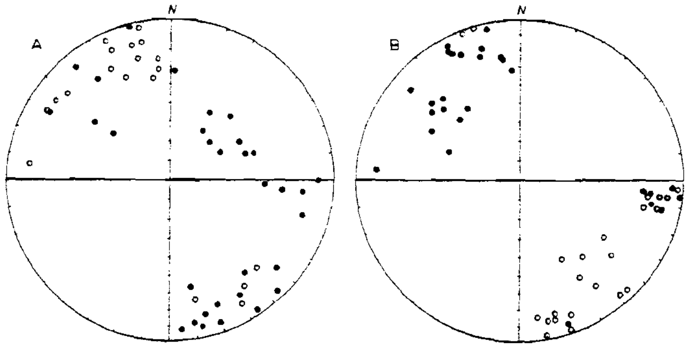

Figure 3

Equal area projection of characteristic remanent magnetization directions in the Monticiano redbed samples; A) after cleaning but before tectonic correction; B) after cleaning and after tectonic correction.

INTERPRETATION

The paleomagnetic directions obtained from Verrucano rocks are interpreted as primary N.R.M. directions, which reflect the direction of the geomagnetic field during time of deposition or slightly later. This conclusion is based on the following reasoning.

Theoretical and practical studies (Dunlop and Buchan, 1977; Pullaiah et al., 1975) have shown that primary N.R.M. residing in hematite grains can very well survive Zeolite and Pumpellyite facies conditions during millions of years and that laboratory cleaning techniques still are effective enough to separate se-

TABLE I

Remanent magnetization parameters.

Levels	Samples	Mean direction*	a_{95} (Deg.)	Mean direction for 9 levels, 51 samples :
V1	010	164.2 -15.9	12.7	312.0 +18.0, a_{95}=10.6
V2	002	321.9 +22.9	-	
V3	003	124.3 - 8.2	-	
V4	006	275.6 +30.5	19.5	Pole position :
V5	005	306.3 +32.5	14.2	
V6	006	336.6 +11.0	11.9	36.3 N 103.4 W (dp=5.3°,
V7	005	342.6 + 7.9	15.3	dm=10.4°)
V9	010	92.5 + 5.2	12.2	
V10	004	131.6 -31.1	22.3	

* After cleaning and dip correction.

condary and primary magnetization components. Taken into account also a positive fold test (VandenBerg and Wonders, 1976) and the presence of reversed and normal polarities in the same section, there can be little doubt about the primary nature of the N.R.M. directions.

The siltstones sampled for this study are described as the M. Quoio formation by Cocozza et al. (1975), who were able to attribute an age to this Formation : Scythian to Lower Anisian. During the Early and Middle Triassic timespan many polarity changes occurred (McElhinny and Burek, 1971). The presence of several reversed levels in the short section and the age assignment are therefore in agreement. For the earlier study only the violet and grey quartzite stratigraphic unit was sampled, which according to Azzaro et al. (1976) belongs to a higher stratigraphic unit directly below the Tocchi Formation (Carnian). The absence of reversed N.R.M. directions in those results (see Table I) is possibly related with the normal polarity interval in the Upper Triassic (McElhinny and Burek, 1971), while the higher inclinations also point to a younger (Late Triassic ?) age.

In Fig. 4 the paleomagnetic directions of the two Lithostratigraphic-units of the Monticiano Verrucano are compared with published results of comparable age from the Southern Alps and from Sardinia. The westward offset of the Verrucano paleomagnetic data relative to the Southern Alpine data is evident. The inclination value of the new result is comparable with the late Permian-early Triassic inclination values of the paleomagnetic data from the Southern Alps. The paleomagnetic result from Sardinia is of Permian age and shows a lower inclination, while the declination only slightly differs.

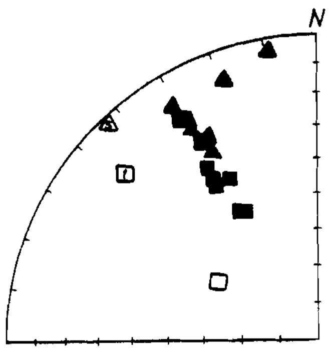

Figure 4

Comparison of paleomagnetic directions.

Southern Alps	: full squares and triangles represent Triassic and Permian data respectively (Zijderveld and VanderVoo, 1973).
Central Italy (Tuscany)	: open squares (present paper $\boxed{t}$; VandenBerg and Wonders (1976) : $\square$.
Sardinia	: open triangle (s) (combined result, Westphal et al., 1976; Zijderveld et al., 1970).

The difference in declination between the Tuscan Verrucano and the Southern Alpine data can be interpreted in terms of differential movement along a fault-zone in the area of the present Po-basin (VandenBerg and Wonders, 1976). The newly obtained data support this interpretation, while the proximity of the Sardinian result suggest no major movements between the Sardinian and Tuscan block since Hercynian times (VandenBerg and Wonders, 1976).

DISCUSSION

It was suggested (Kligfield and Channell, 1978) that the Monticiano Verrucano section is not autochtonous and that interpretations, as given by VandenBerg and Wonders (1976), are not valid. It was suggested as well that the westward offset of the Umbrian paleomagnetic data relative to the Southern Alpine and African results was caused by a rotational dêcollement of the whole sequence relative to its basement only (Channell et al., 1978). We oppose these suggestions with the following.

I) Early Jurassic paleomagnetic data from Umbria (Cagli) are in excellent agreement with the Middle to Late Triassic data from Tuscany as is to be expected from the African and European polar wander curves (VandenBerg and Wonders, 1976).

II) It was shown (VandenBerg and Wonders, 1978b) that Late Cretaceous paleomagnetic data from Umbria (Cagli/Gubbio) are not differing significantly from Late Cretaceous data of similar accuracy from Abruzze and Apulia (Southern Italy). If any rotational décollement occurred for the Umbrian sequence or for the Monticiano Verrucano then these movements were not rotational relative to each other or to the Abruzze and Apulian platforms. Since the latter is generally supposed to be autochthonous we conclude that paleomagnetic data do not indicate that the Monticiano Verrucano is not autochtonous.

CONCLUSIONS

I) Despite the very low grade metamorphism that affected the Monticiano Verrucano, the appropriate laboratory techniques turned out to be succesfull in determining primary Natural Remanent Magnetization directions.
II) The paleomagnetic results, i.e. the presence of reversals and the inclination values, are in good agreement with the age assignment (Scythian-Lower Anisian) for the Monte Quoio formation.

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PRELIMINARY RESULTS OF A PALEOMAGNETIC RESEARCH ON EOCENE TO MIOCENE ROCKS OF THE PIEMONTE BASIN (N.W. APENNINES, ITALY)

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ABSTRACT

Preliminary paleomagnetic data from Late Eocene to Early Oligocene rocks, belonging to the base of the Piemonte series, show a counterclockwise rotation of about 25^{o} with respect to the pole. Early Miocene paleomagnetic data suggest tentatively that this movement occurred during Late Oligocene to Early Miocene. The tentative Early Tertiary result is in excellent agreement with paleomagnetic data from other areas in Italy and Sardinia.

INTRODUCTION

The subject of this paper is a paleomagnetic investigation of Tertiary turbiditic sediments, which belong to the base of the Piemonte sequence. The particular area was chosen for its special stratigraphic (Labesse, 1966; Vervloet, 1966) and structural relationship (Görler and Ibbeken, 1963; Ten Haaf, 1975) with the Western Alps and Apennines as well. The belt of unconformable Piemonte sediments extends from the western border of the Voltri Massif (Western Alps) to the outermost North Western Apennines and is not dislocated by any of the important north-south faults, on the contrary the series truncates all north-south striking structures, exposed along the Ligurian coast. The continuous Oligocene sediments at the base of the Piemonte sequence overlay structural units in the West such as the "Schistes Lustrés" and metamorphic ophiolites of the Voltri Massif, which is cut off to the East by the Sestri-Voltaggio zone. This same series overlays the Sestri-Voltaggio zone and eastwards the Early Cretaceous "Argilloscisti" and the Late Cretaceous Helminthoid flysch, belonging to the Antola unit (Ten Haaf, 1975).

The aim of this investigation was to find out whether the post-Early Tertiary rotation that was deduced for the Northern Apennines (Umbria) (Lowrie and Alvarez, 1974; VandenBerg et al., 1978) and the Western and Southern Alps (Heller, 1973; Lanza, 1977) could be established as well for this particular area.

DESCRIPTION OF THE SAMPLING LOCALITY

The area in which rocks were sampled for this investigation is known as the syncline of San Sebastiano Curone-Varzi (see Fig. 1). A detailed stratigraphic study on the sediments of this syncline was published by Labesse (1966) and his age assignments for the different lithostratigraphic units are followed. The Tertiary series of the San Sebastiano Curone-Varzi syncline contains epicontinental clastic sediments, dominated by blue-grey marls. Lithostratigraphic differences mainly depend on the importance of sandstone and conglomeratic intercalations. The base of the sequence is Upper Eocene and in the centre of the syncline Lower Miocene sediments form the top. The Upper Eocene sediments discordantly cover the Cretaceous-Paleocene series, which belong to the Antola unit. In the Oligocene part of the section, the marl and sandstone sequence is substituted laterally towards the South by conglomerates, which can reach locally the impressive thickness of more than 2000 meters.

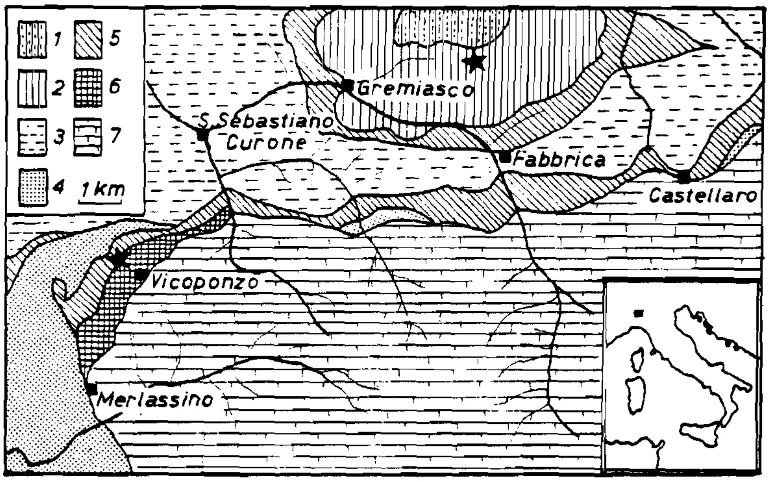

Figure 1
Schematic map of the San Sebastiano Curone region (North Western Apennines), after Labesse (1966). Legend: 1 and 2= Early Miocene; 3,4 and 5= Oligocene (3: marls with sandstone intercalations; 4: conglomerates; 5: marls dominating); 6= Late Eocene; 7= Late Cretaceous-Paleocene (Flysch à Helminthoid). Asterisks denote sampling localities.

Testsamples collected in 1974 had revealed that the sandy layers could be used in paleomagnetic research. And in 1976 59 handsamples were collected from the sequence of the San Sebastiano Curone-Varzi syncline, from the basal Eocene-Oligocene and Lower Miocene units (see Fig. 1). Since the sandstones are mostly turbiditic it seemed advisable to take only samples from the fine-grained top, and not more than 2 samples per sandy level.

LABORATORY TREATMENT AND MAGNETIC PROPERTIES

In the Paleomagnetic Laboratory cores were drilled from the collected handsamples and sliced into cylinders (2.2 x 2.5 cm). Measurements were carried out on a Jelinek JR3 spinner magnetometer. The initial Natural Remanent Magnetization intensities ranged from 400 to 3000 x 10^{-8} Gauss. Several specimens per locality were demagnetized in alternating fields up to 1500 Oe. These progressive demagnetizations revealed the presence of two magnetization components. One magnetization component was removed in alternating fields that did not exceed 150 Oe and this magnetization component was in most cases aligned along the present

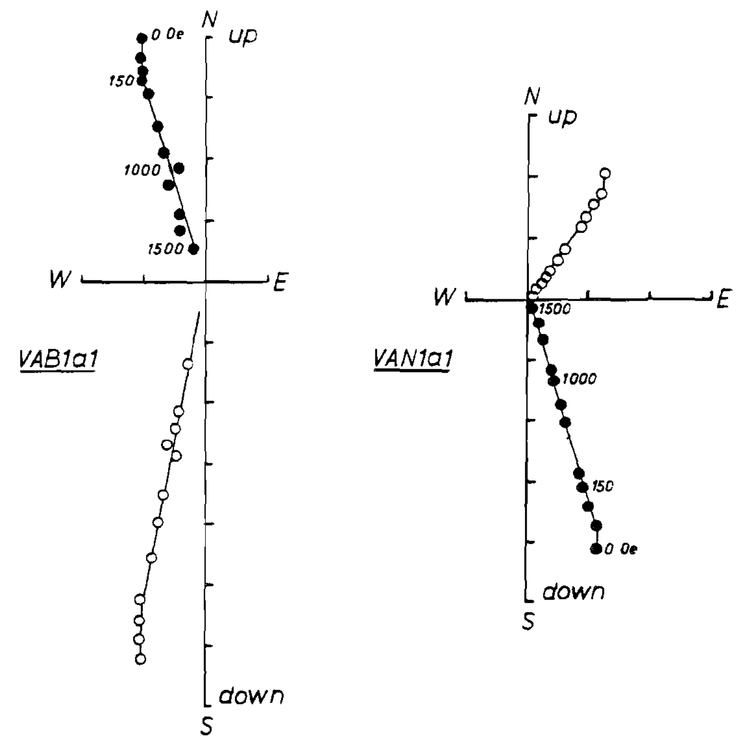

Figure 2
Orthogonal projection diagrams of the vector path of the total remanent magnetization vector during a.f. cleaning. Dots are projections on the horizontal plane and circles are projections on the vertical East-West plane. Numbers denote peak values of the applied alternating fields in oersteds. Specimen codes are underlined.

local magnetic field direction, while the second component was removed for the greater part in higher alternating fields up to 1500 Oe (see Fig. 2). This magnetization component appeared to have constant declination and inclination values in the range from 150 to 1500 Oe. The magnetic behaviour during demagnetization of the magnetic components was studied in orthogonal projection figures, and for this second component the vector path went straight to the origin (see Fig. 2). It was assumed to represent the characteristic magnetization component for these rocks. However, some specimens contained only the first magnetization component, and these were assumed to have acquired this magnetization only very recently, since it was aligned along the present local magnetic field direction. All remaining specimens were then partly demagnetized in alternating fields from 150 to 750 Oe in at least 5 steps. Fisherian statistics were applied and mean directions computed per lithostratigraphic unit, which are represented in Table I.

TABLE I

Remanent Magnetization parameters

AGE	N	Mean Direction Decl.	Incl.	a_{95}	Pole Position Plat.	Plong.	dp	dm
Early Miocene	21	12.9	+50.7	7.6	73.1 N	148.0 E	6.9	10.2
Late Eocene/ Early Oligocene	33	333.5	+50.6	5.8	65.3 N	254.6 E	5.2	7.8
id.	25	333.7	+53.1	8.3	(normal polarities)			
id.	8	159.0	-44.2	4.0	(reversed polarities)			

RESULTS AND INTERPRETATION

There are several reasons to assume that the characteristic magnetization component is also the primary magnetization component of the studied Tertiary rocks. First the presence of 25% reversely magnetized samples, which revealed directions opposite to the magnetic directions of the normally magnetized samples from the Late Eocene to Early Oligocene rocks (Table I). Secondly the different tectonic corrections that had to be applied for the different layers is improving the overall mean result appreciably. The a_{95} diminished after bedding tilt correction

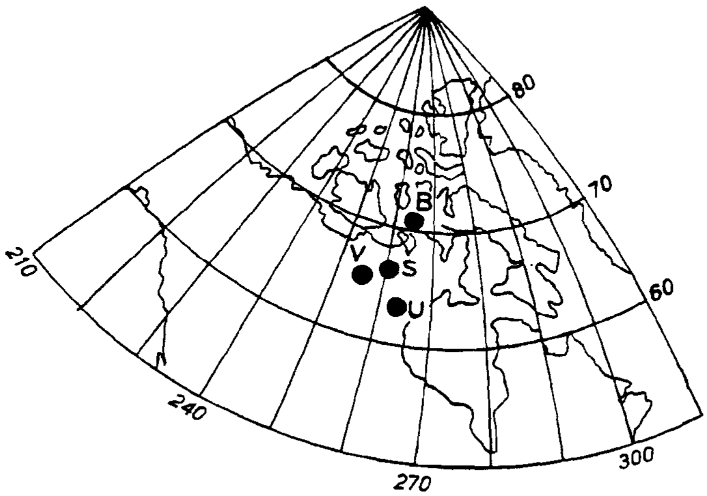

Figure 3

Equal area projection of the Early Tertiary paleomagnetic poles from Italy (V= present result; B= Bergell granite (Heller, 1973); U= Umbria (VandenBerg et al., 1978) and from Sardinia (S= Sardinia, Manzoni,1974).

from 7.7°to 5.6°, while the K factor increased from 7.4° to 15.0°for 54 samples. The folding that affected the sediments of the San Sebastiano Curone-Varzi syncline is of Late Miocene-Pliocene age. The fast sedimentation rate of turbiditic sandstones makes it very likely that secular variations and magnetic field variations during transitional zones are not averaged out in single sandstone beds, but despite the limited number of samples it is assumed to be averaged out in the mean result.

In Figure 3 the paleomagnetic pole,that was calculated from the mean result of the Early Tertiary rocks,is plotted. In addition other Early Tertiary paleomagnetic poles have been plotted for comparison. These paleomagnetic poles come from the Southern Alps (Bergell granite; Heller, 1973), from Sardinia (see review of Manzoni, 1974) and from Umbria (Northern Apennines; VandenBerg et al., 1978). Although it is fully realized that the present results are only tentative the proximity of all plotted Early Tertiary poles is very evident, and suggests that also this area rotated counterclockwise in a post-Early Tertiary phase over an angle of about 25° with respect to the pole. In addition the difference between the Eocene/Oligocene result and the Early Miocene result (see Table I) gives an indication for the timing of this movement, but further research will have to substantiate this.

CONCLUSION

The present paleomagnetic result of Late Eocene-Early Oligocene age supports the conclusion that a post Early Oligocene counterclockwise rotation over about 25° with respect to the pole is not a local phenomenon but is related to the movement of a vast continental block.

ACKNOWLEDGEMENT

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NEW PALEOMAGNETIC DATA FROM THE IBERIAN PENINSULA

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ABSTRACT

The results of a paleomagnetic investigation on Mesozoic sediments from the Betic Cordillera, the Iberic Chain and Cantabria in general confirm earlier conclusions about the rotation of the Iberian Peninsula. The start of the rotational movement could be specificated as have been occurred after Barremian-Aptian times. Paleomagnetic results from the Bilbao synclinorium show that the Iberia-Europe plate boundary is situated south of the synclinorium. Along the coast of Cantabria near Gijon paleomagnetic results of Mesozoic age have yielded European-like poles probably indicating a complicated fault system along which the rotational movement of the Iberian Peninsula was achieved. A model for the development of the Iberia-Europe plate boundary in its final stage is presented.

INTRODUCTION

The rotation of the Iberian Peninsula has become a well established and documented phenomenon by studies on the magnetic anomaly pattern in the Bay of Biscay (Matthews and Williams, 1968; Williams, 1975), on the paleomagnetism of Paleozoic, Mesozoic and Tertiary rocks (Zijderveld and Van der Voo, 1973) and by studies on the pattern of Hercynian trends in Spaín with respect to adjacent Europe (Cogné, 1971; Bard et al., 1971).
From published paleomagnetic data could be concluded that most of the rotation occurred between the Kimmeridgian and Maastrichtian (Stauffer and Tarling, 1971; Zijderveld and Van der Voo, 1973).
Studies on the magnetic anomaly pattern of the Bay of Biscay have contributed additional information, since anomalies 34-31 could be recognized. This implies that spreading was still active in Campanian and Maastrichtian times (Williams, 1975). The spreading ceased between anomaly 32 and 31 (Early Maastrichtian). If constant spreading is assumed the onset of the rotational opening of the Bay of Biscay can be extrapolated to Mid-Cretaceous. An accurate calibration of the Mesozoic and Tertiary reversal scale with the relative and absolute timescale was proposed by LaBrecque et al. (1977), and that changes slightly the timing of the various stages of opening as suggested by Williams (1975). Accordingly, from 130 My until 110 My the Bay of Biscay was the location of a sinistral strike-slip faultzone, with Iberia moving in southeasterly direction away from its "best fit" position against France and North America. After about 110 My the Mid-Atlantic ridge curved eastwards into the Bay of Biscay and the rotational opening of the Bay of Biscay took place. This movement ceased at about 68 My and the Iberian peninsula stayed attached to Europe.
The paroxysmal phase in Pyrenean orogeny was about 40 My ago, and therefore postdates the rotational opening of Biscay. Compressional phases of older age have not been reported, apart from the Hercynian orogeny; it was therefore argued that the rotation of the Iberian peninsula took place along an East-West striking faultzone in the Pyrenean region (LePichon et al., 1970, 1971; LePichon and Sibuet, 1971; Le Borgne et al., 1971; Choukroune et al., 1973). What is left of the North Pyrenean faultzone is generally considered as a remnant of that faultzone. The compressional Eocene Pyrenean orogeny and the associated extensive flysch deposits obliterated major parts of the fault zone and caused its present course. Paleomagnetic studies are very appropriate to delineate the plate boundary between stable Europe and the Iberian continent, and were succesfull in the Pyrenean region (see Fig. 1). Van der Voo and Boesenkool (1973) were able to show that the Permian of the Cinco-Vilas Massif

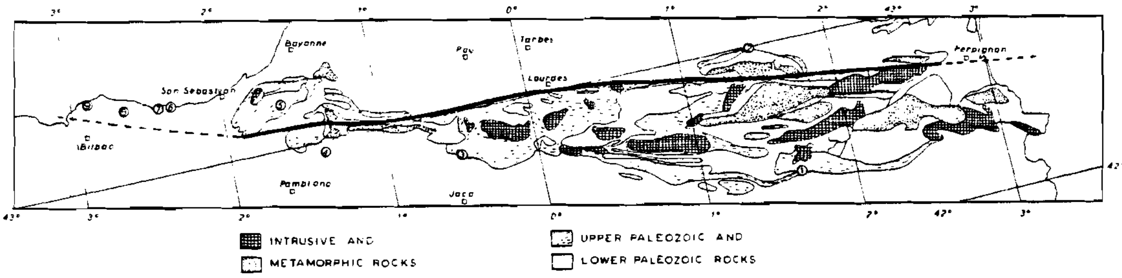


Figure 1. Rough delineation of the North Pyrenean fault zone. Numbers refer to paleomagnetic studies that have been carried out. 1) Van Dongen, 1967; 2) Girdler, 1968; 3) Van der Lingen, 1960; 4) Van der Voo, 1969; 5) Van der Voo and Boesenkool, 1973; 7-9) present study.

(Western Pyrenees) revealed European paleomagnetic directions and therefore most probably belonged to the European continent. Girdler (1968) showed this for the Satellite Massif in the North-East Pyrenees. Several studies on the southern side of the Pyrenees (Fig.1) showed counterclockwise rotated paleomagnetic directions, confirming that this part belonged to the rotated Iberian continent.

The timing of the rotation, however, is not as closely defined with paleomagnetic data as for Italy, and needs further specification.

GEOLOGICAL SETTING AND DESCRIPTION OF THE SAMPLING LOCALITIES

BETIC CORDILLERA

Two localities were visited in the Betic Cordillera to collect Late Cretaceous pelagic limestones, see Figure 2. The limestones belong to the Sub- and Prebetic zones (Miogeosynclinal) and are strongly folded and faulted.

1) El Burrueco (SEB)

This is a small village east of Cordoba (see Fig. 2). North-west of the village a continuous section of Late Santonian and Campanian limestones is exposed. The tectonic position of the rocks is allochtonous, on the N.W. flank of a diapiric structure. Sedimentologically, the El Burrueco upper Cretaceous is a good example of a hardly altered, friable pelagic foraminiferal nanno-ooze. The facies is comparable with that of the Scaglia Rossa formation in the Northern

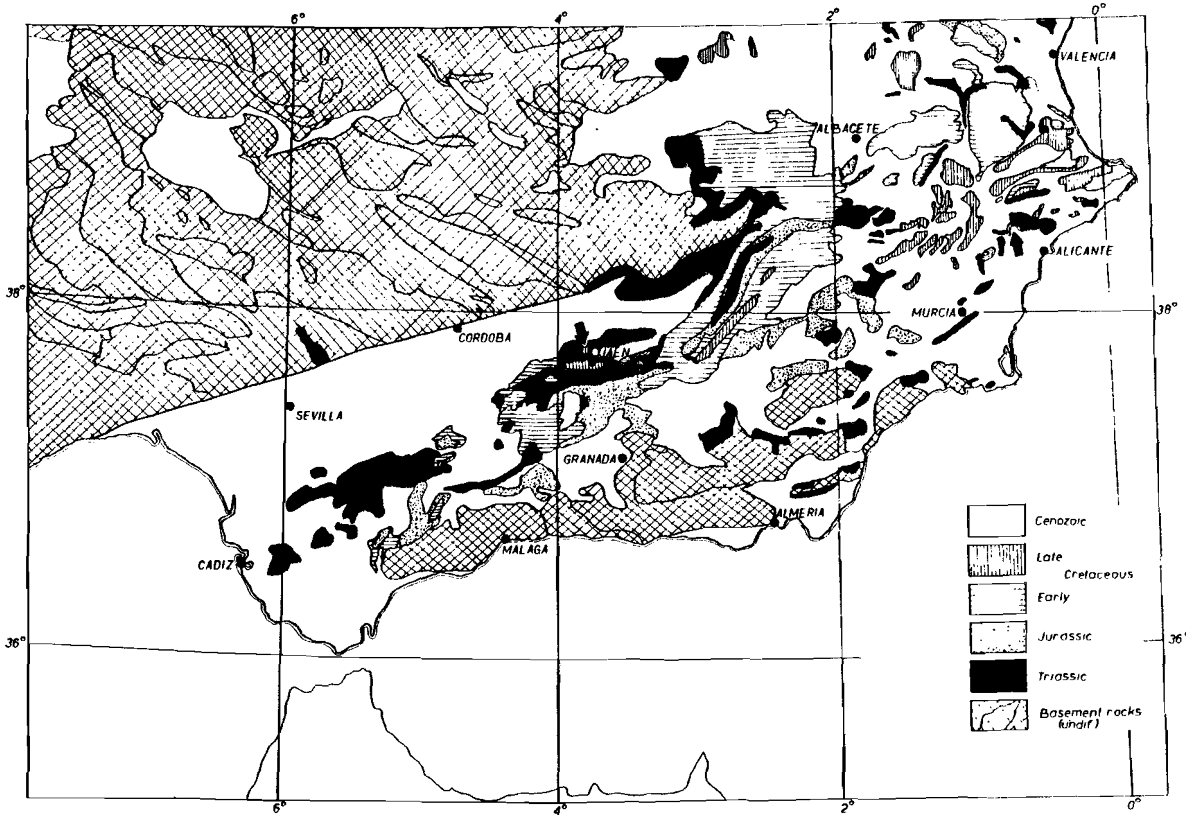


Figure 2. Geological map of the Betic Cordillera. Two arrows point to sampling localities, West of Alicante and East of Cordoba.

Apennines, but the rocks are hardly affected by diagenesis. Foraminifera and calcareous nannofossils can easily be isolated and are well preserved. The positions of the sampled levels depended entirely on the presence of relatively hard consolidated layers, absent in the upper part of the section.

2) Agost (SAG)

Agost (prov. Alicante) is situated in an area with Mesozoic and Tertiary rocks of the Prebetics, which form a coherent chain of N.W. vergent folds. The area was described in detail by Leclerc (1971). Sampling was restricted to the upper Cretaceous part of the series, the reddish Campanian limestones, developed in the reddish "couches rouges" facies comparable to that of El Burrueco. These are fine grained, possibly (haemi-) pelagic, and contain abundant planktonic foraminifera and Inoceramus fragments, other fossils are rare.

IBERIC CHAIN

1) Soria (SPI / STE)

This city is situated in the northwestern part of the NW-SE trending Iberian mountain chain, an intra-cratonic fold belt. A series of Mesozoic and Early Tertiary continental and shallow marine sediments is exposed there, unconformably overlying the Hercynian basement. We sampled the Late Cretaceous limestones in the southern flank of Picofrentes (close to Soria). This section was described in detail by Wiedmann (1975) and is well-known for its rich ammonite faunas.

The Upper Jurassic (Kimmeridgian) North of Soria was subject of an earlier paleomagnetic study by Stauffer and Tarling (1971). It consists of continental deposits, mainly conglomerates, sandstones and red siltstones. For the present study at 4 localities samples were taken from homogeneous siltstones, known as the Tera group.

BILBAO SYNCLINORIUM

In the Bilbao synclinorium (Fig. 3) mostly Cretaceous rocks are cropping out. Only at a few places around diapiric dome structures black Jurassic limestones are exposed, covered by massive sandstones and coarse grained conglomerates of the Early Cretaceous Wealden facies. The Barremian to Aptian contains black shales with rare sandstone intercalations. These shales are sometimes laterally substituted by reef limestones of Aptian age. In the Albian and Cenomanian tur-

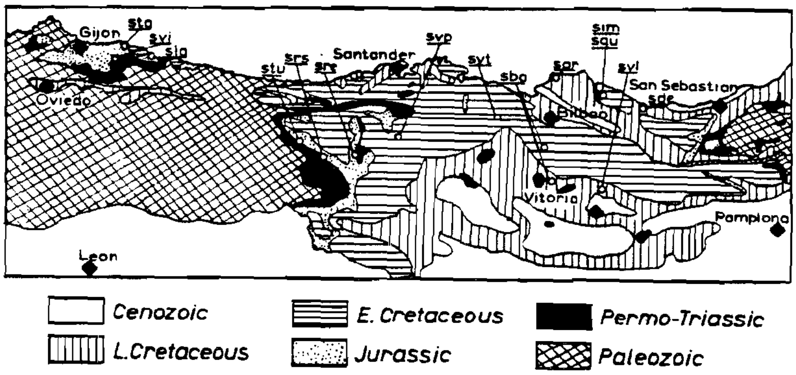


Figure 3. Geological map of Northern Spain (Cantabria). Sampling localities have been indicated.

biditic sandstones are intercalated in the still predominantly black shales. During the Late Cretaceous the turbiditic sandstones became dominating and the shales were substituted by grey marls. In the Middle Maastrichtian the turbiditic sandstones disappeared completely and a more open marine sedimentation occurred with pelagic carbonates and marls often red and pink coloured. The Late Paleocene and Early Tertiary contained once again an alternation of turbiditic sandstones and marls. Intercalated in the Late Cretaceous sediments at several places a succession of pillow lavas is exposed. Deformation of the Bilbao synclinorium becomes more intense towards the southwest, when tight folds with subvertical axial planar schistosity occur. This abruptly changes south of the line Bilbao-Pamplona, where the Mesozoic sediments crop out in a monoclinal sequence slightly dipping towards the southwest.

1) Deva (SDE)

At the coast from Deva to Zumaya a continuous section of Late Cretaceous to Early Tertiary sediments is exposed. These deposits belong to the Northern flank of the Bilbao synclinorium. This section was previously described by Herm (1965). Roggenthen (1976) sampled the top of the section in detail for a paleomagnetic study. We sampled the Late Albian flysch sequence in five levels at 10 m distance each. Sampling was restricted to the topmost layers of the turbiditic sandstones that have a red colour, when weathered.

2) Guernica (SQU / SIM)

Northeast of Guernica an Aptian reef limestone, intercalated in black shales with rare sandstones, is exposed. In a quarry the reef is mined and fresh outcrops are easily accessible. The reef limestone and the reef debris at the flank are red coloured. The bedding planes have a vertical position. The reef limestones were sampled.

Southwest of the quarry black fetide limestones and shales of Triassic/Jurassic age crop out in a 100 m section along the Ria de Mundaca. The section gently dips northwards. At several levels samples were taken from the limestones.

3) Arminza (SAR)

North of Bilbao along the coast Late Cretaceous and Tertiary sediments are exposed. A few intercalations of pillow lavas can be observed. It is a great pity that the sediments are heavily tectonized in general and have mostly vertical bedding tilts. Close to the village Arminza the Late Albian sediments in a distal flysch facies compose of dark grey marls with regular intercalations of thin turbiditic sandstones and here moderately dip northwards. The topmost layers of the turbiditic sandstones were sampled.

CANTABRIAN CORDILLERA

West and southwest of the Bilbao synclinorium (Fig. 3) the eastern part of the Cantabrian Cordillera is exposed, and this part consists mainly of Cretaceous sediments. South of the coast between Santander and Gijon the Paleozoic basement, forming the bulk of the Western Cantabrian Cordillera, raises high above sealevel in the "Picos de Europa". Only near the coast close to Gijon, Mesozoic rocks are exposed in the western part of the Cantabrian Cordillera. The Paleozoic basement is discordantly covered by Permian conglomerates and conglomeratic sandstones. These pass into finer grained clastics such as red-violet shales and siltstones of Permo-Triassic age. The Triassic is developed in its characteristic variegated evaporite facies, with on top the Carniolas formation. The Permo-Triassic reaches a thickness of $\pm$ 1500 meters. The Jurassic and Neocomian consist of a monotonous sequence of dark grey shales with limestone intercalations and has a thickness of about 600 m. The upper Early Cretaceous is developed in Wealden facies : an alternation of sandstones, conglomerates and red-violet siltstones, more than 1000 m thick. Black shales cover the Wealden and sometimes reef limestones are intercalated of Aptian age. In Albian times an alternation of black shales and sandstones developed, which passed into grey marls and pelagic limestones during the Late Cretaceous. The Upper Cretaceous has an enormous thickness of about 5000 m in the surroundings of Vitoria. The Tertiary contains continental clastics.

1) Villaviciosa (SVI)
The Permo-Triassic close to the village Villaviciosa along the road to Infiesto is nicely exposed. Here we sampled on several levels a section of about 50 m, containing red-violet siltstones and massive marls.

2) Lastres/Tazones (SLA / STA)
Along the coast near the villages Lastres and Tazones the Upper Jurassic is cropping out consisting of sandstones, shales and mudstones, which are mainly red coloured. At Lastres these are directly overlying Liassic marls and limestones. At both localities the strata dip moderately and were sampled in several levels.

3) Tudanca (STU)
Opposite this village a sequence is exposed that contains Permo-Triassic through Jurassic sediments and which moderately dips northward. At several localities Permo-Triassic red-violet siltstones were sampled, close to the base and higher in the section. Also the black Liassic limestones were sampled at 3 different localities.

4) Vega de pas (SVP)
Stratigraphically high in the subhorizontal Wealden facies red massive marls and sandstones were sampled in two levels. The age assigned to the upper part of the Wealden here, based on determination of Orbitulinas present in limestone intercalations at the top, is Barremian to Aptian.

5) Rio Saja / Reinosa (SRS / SRE)
At two other localities close to the city Reinosa the Permo-Triassic red violet marls and siltstones were sampled.

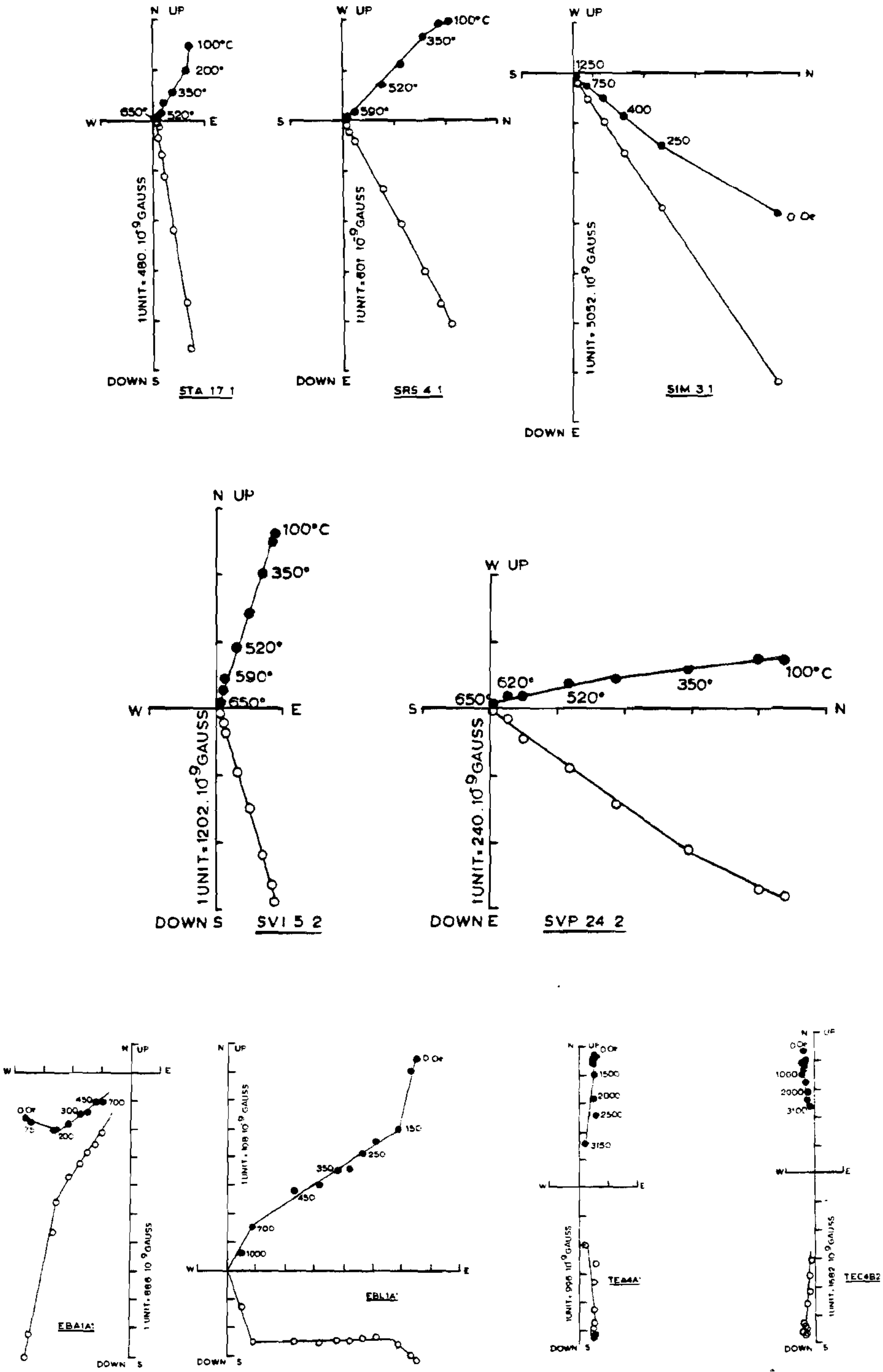
6) Villaverde de Trucios (SVT)
North of this village dark shales of Aptian age crop out in a subhorizontal position. Carbonatic intercalations were sampled.

7) Barambio (SBA)
West of the city Vitoria the river Barambio cuts through the Cretaceous sequence, and causes very nice exposures. Grey Turonian/Coniacian limestones were sampled at three localities with different bedding tilts. Also dark grey Albian sandstones were sampled in a north dipping section.

8) Villareal (SVL)
Along the road from Durango to Vitoria at several places the Cretaceous is exposed. Close to the village Villareal a sequence of grey marls and light grey limestones is exposed, which range from Albian to Coniacian age. This sequence was sampled at 4 localities.

MAGNETIC PROPERTIES AND LABORATORY TREATMENT

In the field samples were cored with an electric drill and the cores were sliced into cylinders (specimens) of 2.2 x 2.5 cm. at the Fort Hoofddijk Laboratory. All measurements were carried out with a spinner magnetometer (JR3) and/or with a ScT cryogenic magnetometer.
The initial Natural Remanent Magnetization (N.R.M.) intensities of such different rock types varied notably, as can be concluded from Table I. Almost all sampled rock types turned out to be measurable and only most white limestones from Picofrentes (Soria-SPI) had marginally intensities of the N.R.M.
Several pilot specimens per locality were progressively demagnetized in 10 to 15 steps in alternating fields up to the maximum obtainable value of 3000 Oe. From those localities, where red beds were sampled also several pilot specimens per locality were thermally demagnetized in 8 steps up to 700^{o}C.
The vector path of the total remanent magnetization was analysed in orthogonal projection diagrams for the treated specimens. All specimens from carbonatic rock types could be properly demagnetized in alternating fields, while for the red beds better results were obtained by thermal demagnetization. In Figure 4 characterstic examples of demagnetization curves are given for different rock types. All remaining specimens were demagnetized in at least 5 steps in that range where the characteristic magnetization component was removed.
Evaluation of some paleomagnetic results proved to be a difficult task. Because of the distributed nature (geographically as well as in age) of the sampling localities and rocks, common paleomagnetic reliability tests, as fold test, reversal test, etc., in most cases could not be applied. Some indication about the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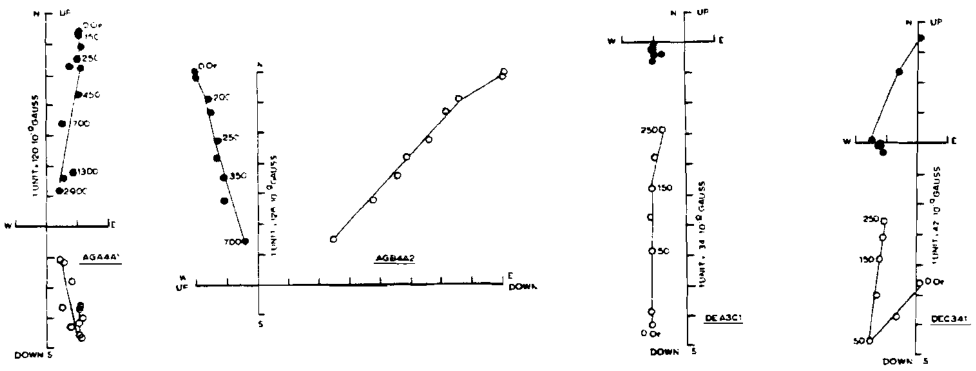


Figure 4. Orthogonal projection figures of the remanent magnetization vector path during demagnetization. Solid dots denote projections on the horizontal plane and open circles on the vertical E-W or N-S planes. Numbers are Oersted values of the applied field or values of the furnace temperature during thermal cleaning in Celsius. Specimen code is given underlined.

reliability of paleomagnetic results is given by the consideration that paleomagnetic directions close to the present geomagnetic field might be of recent origin.

The paleomagnetic results from this study have been divided into two groups. In Table IIa the site mean directions have been compiled, which are regarded as being paleomagnetic results that can be used for reconstruction purposes. The pole positions, corresponding to these paleomagnetic directions have been added. In Table IIb are given the paleomagnetic directions of questionable reliability or with uncertain reference. This Table IIb includes paleomagnetic directions, which either before or after bedding tilt correction are close to the present field direction; which give a negative fold test; and which come from a known allochtonous sequence in the Betic Cordillera. Since these results might become of interest in future research, the mean directions are given before and after bedding tilt correction. Pole positions, however, are suppressed in order to emphasize the uncertain character of most of these paleomagnetic directions.

INTERPRETATION OF THE RESULTS

BETIC CORDILLERA

Since the rocks sampled near El Burrueco (SEB) are situated in an allochtonous block (Wonders, in prep.) their paleomagnetic results can be used for magneto-

Table I

Locality	Initial N.R.M. x 10^{-6} Gauss	Rock Type
SEB	0.08- 33.0	pelagic limestone
SAG	0.3 - 2.4	pelagic limestone
SPI	0.05- 0.4	white limestone
STE	5.0 - 22.0	red siltstone
SDE	0.4 - 0.88	turbiditic sandstone
SQU	1.9 - 3.7	reef limestone
SIM	5.5 - 82.0	black limestone
SAR	0.04- 9.6	turbiditic sandstone
SVI	2.2 - 17.0	red siltstone
SLA	5.9 - 19.4	red mudstone
STA	1.3 - 11.3	red mudstone
STU-PT	4.7 - 13.9	red siltstone
STU-J	3.9 - 20.4	black limestone
SVP	4.5 - 38.4	red marl
SRS	1.6 - 9.6	red siltstone
SRE	5.0 - 16.3	red sandstone
SVT	2.5 - 6.9	black limestone
SBA	0.09- 3.7	black limestone and sandstone
SVL	2.4 - 7.5	grey limestone

Table IIa

Remanent magnetization parameters

Locality	N	n	Mean Direction		a_{95}	Pole position				dp	dm	AGE
SAG	7	40	330.3	+53.9	4.8	65.8	N	90.9	W	4.7	6.7	Campanian
STE	4	24	352.2	+44.9	3.6	70.4	N	156.3	W	4.4	7.3	Kimmeridgian 1)
SDE	5	27	359.6	+45.1	3.4	73.3	N	178.9	E	2.7	4.3	Late Albian
SIM	2	13	44.0	+18.0	1.6	38.7	N	115.6	E	0.9	1.6	Triassic-Juras. ?
SVI	5	28	13.0	+20.3	4.3	55.1	N	151.6	E	2.3	4.5	Permo-Triassic
STA	3	20	6.0	+62.5	2.9	85.6	N	78.4	E	3.5	4.5	Late Jurassic
STU-PT	5	30	333.3	+26.6	5.8	52.9	N	138.1	W	3.4	6.3	Permo-Triassic
SVP	7	45	349.4	+38.2	0.9	66.5	N	158.3	W	0.6	1.0	Barremian-Aptian
SRS	2	12	333.1	+32.2	9.5	55.7	N	134.3	W	9.6	16.	Permo-Triassic
SRE	1	8	327.0	+26.5	25.5	49.4	N	130.0	W	14.	27.	Permo-Triassic

Table IIb

Remanent magnetization parameters for not usable rock samples

Locality	N	n	Mean Direction Before tect.		a_{95}	Mean Direction After tect.		a_{95}	AGE
SEB	1	24	40.5	-03.2	13.5	12.4	+52.3	10.7	Sant. -Camp.
SPI	1	15	-	-	-	-	-	-	Late Cretaceous
SQU	1	10	272.0	+72.5	2.0	243.3	+06.4	2.0	Aptian
SAR	5	36	350.1	+26.0	9.4	345.1	+58.8	8.9	Albian
SLA	3	22	283.6	+69.2	3.2	332.2	+52.0	2.0	Late Jurassic
STU-J	7	38	345.1	+62.5	2.3	1.3	+43.7	1.7	Liassic
SVT	2	15	358.0	+61.7	4.0	347.0	+67.7	4.0	Aptian
SBA	6	36	354.4	+60.9	4.0	14.4	+49.9	3.7	Late Cretaceous
SVL	10	67	359.0	+47.0	2.8	321.0	+66.9	2.6	Late Cretaceous

N :Number of sites ;n :Number of samples; 1) Mean direction for present study; Pole position was calculated from present data combined with data from Stauffer and Tarling (1971),giving unit weight to each site .Mean directions in both parts were calculated only from cleaned samples.

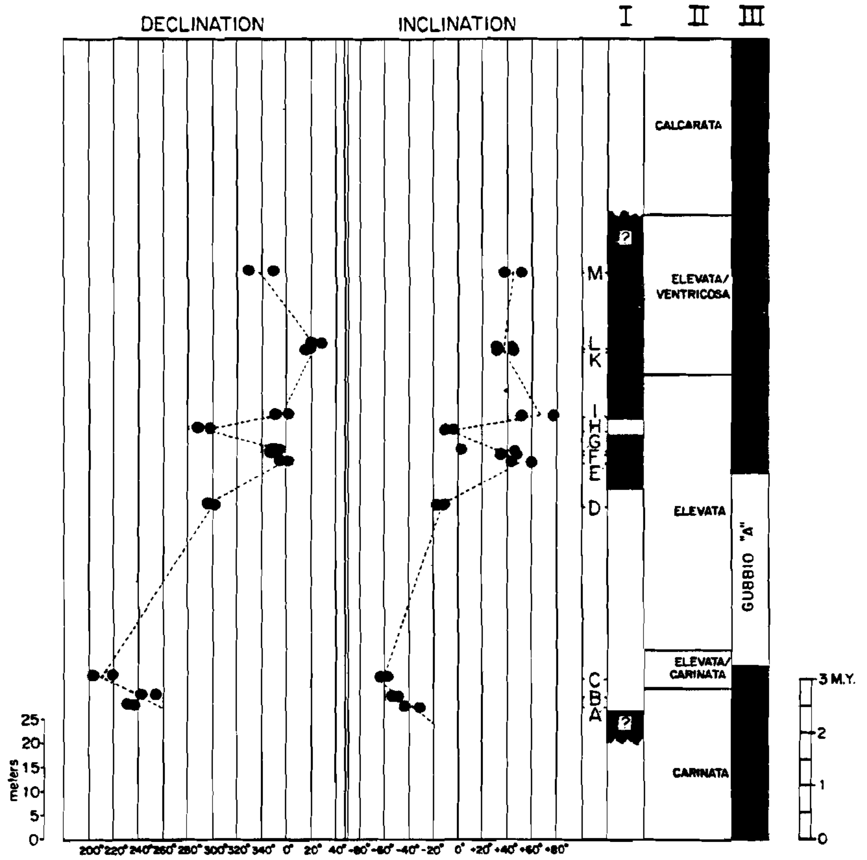


Figure 5. Paleomagnetic directions versus stratigraphic position of the El Burrueco section (Betic Cordillera). Sampled levels are indicated with letters. Column I gives interpretation of the paleomagnetic data. Column II gives planktonic foraminifera distribution through the section (Wonders, in prep.). Column III gives magnetostratigraphy from the Gubbio section (Alvarez et al., 1977). Shaded regions normal polarity and unshaded reversed polarity.

stratigraphy purposes only. In Figure 5 the declination and inclination of the primary magnetization components from the short El Burrueco section are plotted versus stratigraphic position. The study of the planktonic foraminifera of this section (Wonders, in prep.) as given in column II of Figure 5, enables direct comparison with the results from the Gubbio section (Lowrie and Alvarez, 1977; Premoli Silva, 1977) as represented by column III of Figure 5. Although there are no paleomagnetic data between level C and level D, simply due to absence of suitable sampling possibilities, the Gubbio "A" reversal can be recognized in

this El Burrueco section. A discrepancy exists on the timing of the lower polarity change. Premoli Silva (1977) places the concurrent range of Elevata and Carinata on the lower boundary of the Gubbio "A" reversed interval, while in the El Burrueco section this zone falls entirely within the lowermost part of the reversed interval. The discrepancy in timing is about 1 Million years. Whether a short event or just an excursion of the geomagnetic field is recorded in the normal interval above the Gubbio "A" reversal cannot be decided from the deviating result of level H.
The pelagic sediments sampled close to Agost have yielded only normal polarities and an excellent grouping of the primary magnetization components, see SAG in Table II. A very accurate age could be assigned on basis of planktonic foraminifera : Middle Campanian. The westerly deviating result from Agost (Prebeticum) is tentatively interpreted as a consequence of the allochtonous position of the Prebetics in this part of the Betic Cordillera.

IBERIC CHAIN

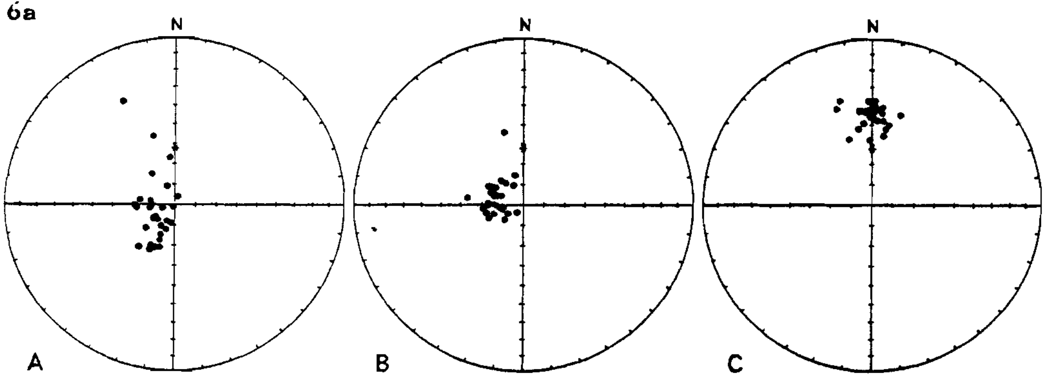
The Late Cretaceous samples (SPI) from the section close to Soria (Picofrentes) revealed besides very low intensities of the N.R.M. also very scattered directions. The secondary magnetizations could not be removed sufficiently, because of the low intensities.
The Kimmeridgian siltstones from the Tera group (STE in Table II) could be cleaned satisfactory and the minor tectonic corrections improved the result. The newly obtained result is in excellent agreement with the earlier results of Stauffer and Tarling (1971). Their conclusion that the Iberian Peninsula rotated after the Late Jurassic with respect to Europe is therefore justified, as can be ascertained from Figure 8.

BILBAO SYNCLINORIUM

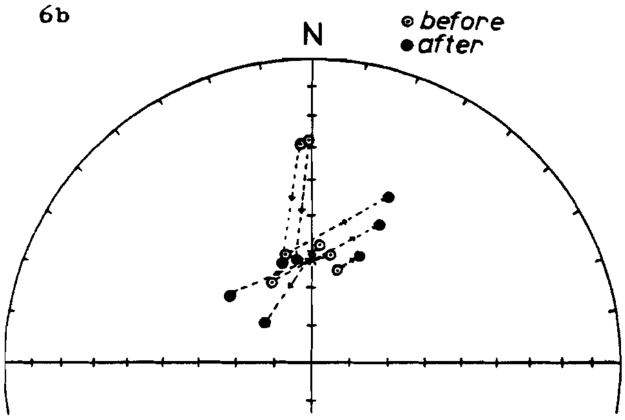
The northern flank of the Bilbao Synclinorium was sampled at 4 localities (see Fig. 3), but only the paleomagnetic results of 2 localities seem to be usable for reconstruction purposes. The directions which have been found in the reef limestones (SQU-Guernica) are very close to the present field before bedding correction and were therefore rejected. This was also the case with the majority of the magnetic directions from turbiditic sandstone samples, which were collected at Arminza (SAR).

The sandstone samples collected near Deva (SDE) have yielded good grouping magnetic directions (see Fig. 6a), which were distinctly far off the present field direction before and after bedding tilt correction. The mean result differs only slightly from the mean direction found by Roggenthen (1971) for the Paleocene limestones, that belong to the very same section. Both results have been plotted in Figure 7, and fall within the range of European poles.
The result from locality SIM (Guernica) can also be considered, since a.f. cleaning improved the grouping of the characteristic magnetic directions and because their mean direction was quite different from the present field direction even before the minor tilt correction. Unfortunately the age is uncertain (Carniolas

6a



6b



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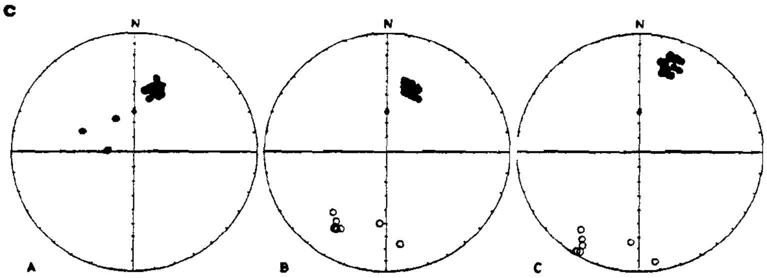

Figure 6. Stereographic projection figures (lower hemisphere) of paleomagnetic directions. Asteriks denotes the direction of the present local magnetic field. 6a) Paleomagnetic directions from samples collected near Deva (SDE), A) initial remanent magnetization directions, B) characteristic magnetization directions before tilt correction, C) idem after correction for the bedding tilt. 6b) distribution of characteristic sample directions of localities SVL and SBA, before (open circles) and after (full dots) tectonic correction, showing negative fold test. 6c) As 6a but now for samples from locality SVI; notice that normal as well as reversed polarity samples are found.

Formation) and cannot be established more precise than Late Triassic to Early Jurassic. The mean result is plotted in Figure 8 and its position is somewhat aside the Late Triassic European poles.
In fact the Permian pole from the Cinco-Vilas massif (Vander Voo and Boesenkool, 1971) is equally aside the European Permian poles, as can be seen in Figure 9.

The paleomagnetic directions from the Deva-Zumaya section show that the crustal block, which they belong to, did not rotate during the Albian-Paleocene timespan. The presently available paleomagnetic data from the Cinco-Vilas massif and from the northern flank of the Bilbao synclinorium seem to justify the conclusion that the major Iberia-Europe plate boundary is situated south of these areas.

CANTABRIAN CORDILLERA (EAST)

Unfortunately the paleomagnetic results from several localities had to be rejected. In the area around Vitoria grey limestones and sandstones of Cretaceous age (Albian-Coniacian) have been sampled (SVL and SBA). Although a very stable magnetization component was removed during a.f. cleaning, this characteristic magnetization is not of primary origin, since the mean directions

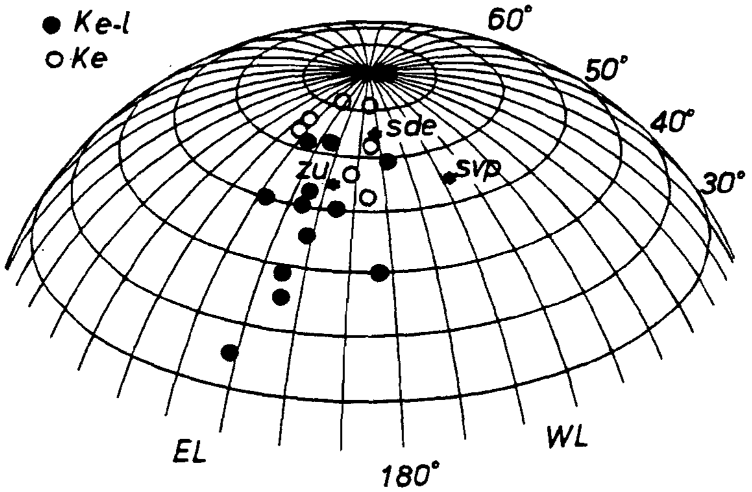

Figure 7. Distribution of Cretaceous Eurasian paleomagnetic poles in orthographic projection. Open circles denote Neocomian poles and full dots represent Barremian to Maastrichtian poles (Khramov, 1977). Results from Iberia indicated by full-stars. ZU = Zumaya (Paleocene), Roggenthen, 1976; SDE = Deva (Upper Albian), and SVP = Vega de Pas (Barremian-Aptian), all present paper.

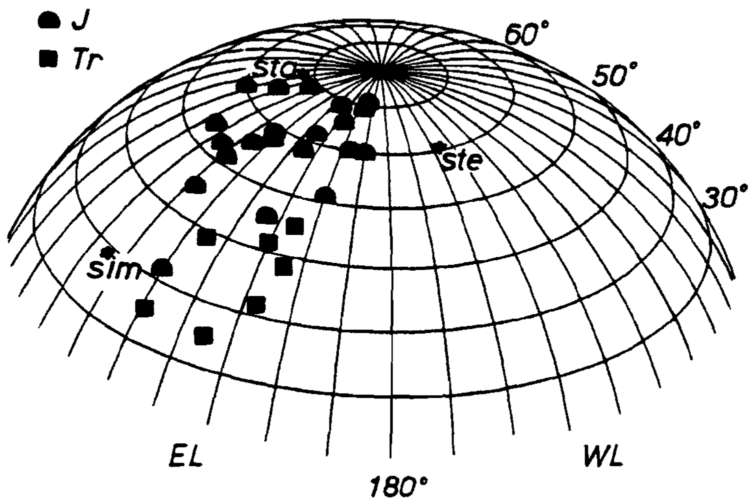

Figure 8. Distribution of Late Triassic and Jurassic Eurasian paleomagnetic poles in orthographic projection (Khramov, 1977). Half full dots represent Jurassic data, full squares Late Triassic data. Results of present study plotted as full stars. STA = Tazones (Upper Jurassic); STE = Tera group (Kimmeridgian); SIM = Guernica (Triassic-Jurassic ?).

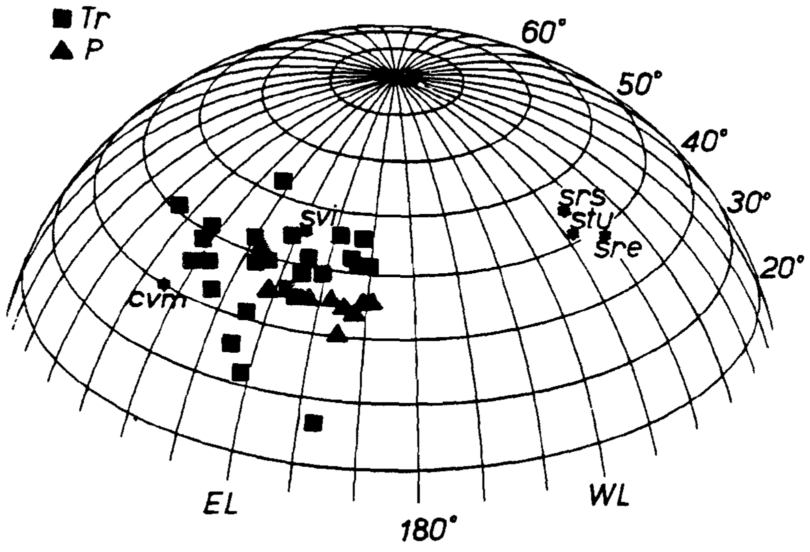

Figure 9. Distribution of Permo-Triassic Eurasian paleomagnetic poles in orthographic projection. Full squares represent Early Triassic data and full triangles Permian data (Khramov, 1977). Results from Iberia denoted by full stars, CVM = Cinco-Vilas Massif (Permian, Van der Voo and Boesenkool, 1973; SVI = Villaviciosa (Permo-Triassic); SRS = Rio Saja (Permo-Triassic); STU = Tudanca (Permo-Triassic); SRE = Reinosa (Permo-Triassic); All present study.

from all the different localities very clearly showed a negative fold test, see Figure 6b. The Aptian black limestones sampled near Villaverde de Trucios (SVT) revealed magnetization directions closely aligned according the present magnetic field, and this was also the case with the black limestone samples (Jurassic), which came from Tudanca (STU-J).

On the other hand the magnetic directions obtained from (Permo-) Triassic red siltstones (SRS/SRE/STU-PT) are very similar and revealed even a better grouping after dip corrections. Thermal cleaning showed the absence of important secondary magnetization components and the characteristic magnetization directions are different from the present geomagnetic direction, both "in situ" and with respect to the bedding. Since, moreover, the inclinations are typical for the Triassic paleomagnetic field, it is most likely that the characteristic remanences found are of primary origin.

The pole positions have been plotted in Figure 9 and it is very clear that these new paleomagnetic poles deviate appreciable from the European poles.

At Vega de Pas red marls and sandstones have been sampled (SVP), that are intercalated in the Wealden facies and could not be better dated as Barremian-Aptian. These samples have yielded a good paleomagnetic result. After thermal and a.f. cleaning the grouping of the characteristic magnetization directions was excellent and they are quite different from the present field direction before as well as after bedding tilt correction. It is likely that these characteristic magnetizations are of primary origin. The mean result is plotted in Figure 7 and it is clearly deviating from the Cretaceous poles of stable Europe. This Barremian-Aptian direction is only differing in inclination from the Kimmeridgian result STE, see Table II. This implies that no major rotations with respect to Europe have occurred yet in the Early Cretaceous. This new Barremian-Aptian paleomagnetic result probably just predates the anti-clockwise rotation of the Iberian Peninsula with respect to Europe.

CANTABRIAN CORDILLERA (NORTHWEST)

In the Western Cantabrian Cordillera Late Jurassic and Permo-Triassic rocks were sampled (SLA/STA/SVI), which belong to a crustal block that extends off shore and is known as the Danois block. On land this block is separated from the remaining Cantabrian Cordillera by major faults. The city of Villaviciosa (SVI) lies on this block surrounded by Permo-Triassic sediments, which have yielded very interesting paleomagnetic results. All samples were thermally demagnetized and showed very stable magnetization components (see Fig. 6c).
The presence of two polarities in the sampled section indicates an Early Triassic age (McElhinny and Burek, 1971). Also because of the presence of a level with reversed polarities little doubt can exist about the primary origin of the magnetization. The inclinations of the characteristic magnetization components have values that are characteristic for the Triassic. The more interesting becomes the position of the paleomagnetic pole (see Fig. 9), which shows no major offset relative to the European Triassic poles.
The samples from Late Jurassic mudstones collected along the beach of Lastres (SLA) have yielded paleomagnetic directions deviating from European as well as from other Iberian paleomagnetic data. These were rejected from further consideration.
The samples from the Late Jurassic sandy marls of Tazones (STA) could be cleaned sufficiently by thermal demagnetization and only had to be corrected for a minor dip of the strata. The mean result is plotted in Figure 8 and is close to the

corresponding European Jurassic poles. This result confirms the absence of major rotations with respect to Europe of the crustal block to which the sampled Permo-Triassic and Upper Jurassic rocks belong.

DISCUSSION

The paleomagnetic results from stable Iberia presented in this paper have given a new and younger lower limit Barremian-Aptian, for the timing of the rotation and further confirm the results of earlier studies. The results from the Bilbao synclinorium and from northwestern Cantabria, however, are puzzling. Le Pichon et al. (1970) have proposed a rather simple movement scheme for the Iberian peninsula around the "Paris-pole of rotation". They supposed the North Pyrenean fault to be the fundamental boundary between Iberia and Europe. Accordingly its western extension should pass Biaritz and follow the North Gascony ridge (see Fig. 10, solid line marked N.P.F.Z.). Seismic studies have shown the presence of oceanic basement directly west of it, at 5° EL 45° NL (Limond et al., 1974). It seems therefore very likely, indeed, that a fundamental boundary is located there. One must realize, however, that the rotation started "Mid-Cretaceous" and that the anomalies 33-31 only specify the very final stage.

A hypothesis for the Iberia-Europe plate boundary configuration, that reconciles all arguments can be proposed. When the Iberian peninsula moved away from Europe accordingly the history proposed by Williams (1975), the plate boundary was situated west and south of the Danois block, along the present coast of Cantabria, through the Bilbao synclinorium, south of the Cinco-Vilas massif and than eastwards following the North Pyrenean fault (as given in Fig. 1). This line is a circle of a rotation pole that is hardly differing from the Paris-pole of rotation. Slightly after or contemporaneous anomaly 33 (Fig. 10) the plate boundary jumped more inland (towards Europe) and the configuration proposed by Le Pichon et al. (1970) became effective. So the crustal fragment (stippled area in Fig. 10), containing the present Danois block, the Bilbao synclinorium and the Cinco-Vilas massif, became part of Iberia and separated from the European continent when the spreading axis branched into the European continent. Anomaly 32-31 came into existence. In Figure 11 this is further elucidated in a schematic way. The amount of separation (100-200 km) of the Danois block from the European continent is not detectable by paleomagnetic means and paleomagnetic data coming from this separated block (stippled in Fig. 10) will therefore reveal European-like poles. The later northward compressive phase (40-45 My) has obscured the plate boundaries : the sediments were thrust towards the South forming the Cantabrian Cordillera. Moreover, to the north and west of the Danois block the North Pyrenean through developed and presumably reduced the initial amount of separation.

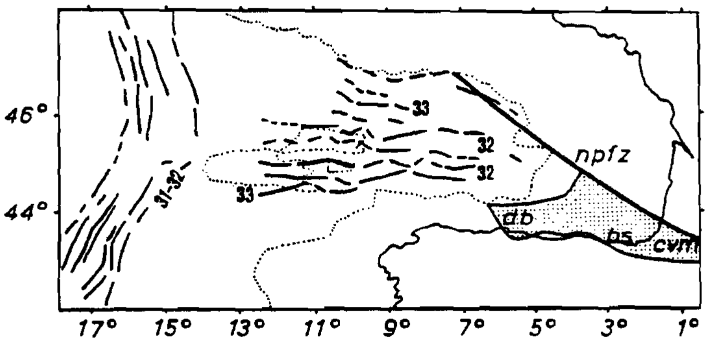

Figure 10. Magnetic anomalies in the Bay of Biscay, after Williams (1975). Also is indicated the extension of the North Pyrenean fault zone (NPFZ), according to LePichon et al., 1970. DB = Danois Block; BS = Bilbao Synclinorium; CVM = Cinco-Vilas Massif.

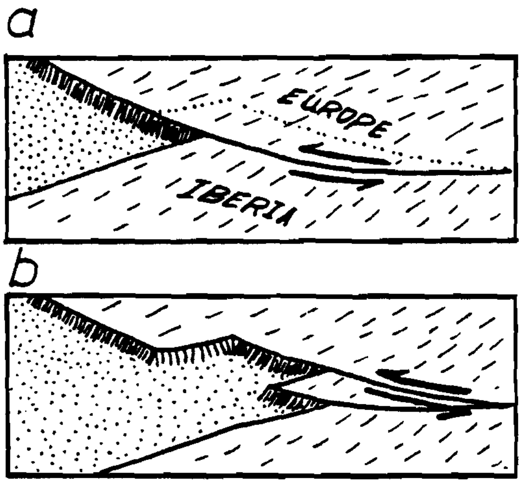

Figure 11. Schematic block diagram showing the possible changing plate boundary configuration and development in the Bay of Biscay, during the final stage of the movement of Iberia.

CONCLUSIONS

The rotation of the Iberian Peninsula had not commenced or was in a very early stage in Barremian-Aptian times.
Mesozoic paleomagnetic data from areas along the coast of Cantabria are not showing any difference with coeval data from the European plate and presumably prove the existence of a shifting fault system, along which the rotational movement of Iberia was achieved.
The magnetostratigraphic study of Late Santonian and Early Campanian limestones revealed that the concurrent range of Elevata and Carinata falls entirely within the lowermost part of the Gubbio "A" reversed interval.

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CURRICULUM VITAE

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