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Neogene and Quaternary geodynamic evolution of the Italian peninsula: the contribution of paleomagnetic data

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Abstract

Paleomagnetism has played an important role in the development of geodynamic models for the Italian peninsula. Paleomagnetic data from this area have been increasingly reported since the late 1960s, placing important constraints on geodynamics. A brief outline of the main concepts underlying a paleomagnetic study is provided in the first part of this paper. We also discuss the criteria for the assessment of the reliability of paleomagnetic data. Finally, the data collected over the past 25 years in peninsular and insular Italy are synthetically reviewed, discussing the main implications for the geodynamic evolution of the Tyrrhenian – Apennines – foreland system.

Key words *paleomagnetism – geodynamics – Italy*

1. Introduction

Paleomagnetism is a relatively young geophysical science that includes aspects of geomagnetism and rock magnetism. Advances in this discipline include a better understanding of the Earth's magnetic field, its generation and time evolution, improvements in solid state physics and the knowledge of the magnetization processes in minerals and rocks, and in the stability of magnetization components through geological time. Paleomagnetism has several applications over a wide variety of Earth science problems. Geodynamics is one of the best known applications of paleomagnetism and in fact paleomagnetic studies were crucially important in reviving interest in continental drift in the 1950s and early 1960s and have since been fundamental in geodynamic reconstruction at different scales. After Blackett, Runcorn, Irving, Creer and others in the late 1950s first showed with paleomagnetic measurements from Europe, North America, India and Australia that such continents underwent displacement and inferred the opening of the Atlantic Ocean, most work was carried out in stable continental areas to define motions of the cratonic parts of continents. The discovery of movements of these large crustal blocks led to the concept of Apparent Polar Wandering, APW (for a review of the historical background, see Le Grand, 1989; Opdyke, 1995).

In this framework another key result was the recognition that positive and negative lineated marine magnetic anomalies represented reversals of the Earth's magnetic field (see Glen, 1982). The following insertion in the plate tectonics scheme has enriched the results from continental rocks (see Gordon and Acton, 1989) and paleomagnetism still presently plays

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a fundamental role in global geodynamic models (*e.g.*, Gordon, 1995). Paleomagnetism holds a special place in geophysics also because it is not only concerned merely with the present Earth, as most branches of geophysics are, but with the history of the Earth's solid surface and deep interior over millions and millions of years (for the aspects concerning the history of the Earth's magnetic field the reader is referred to the comprehensive reviews by Merrill and McElhinny, 1983 and McFadden and Merrill, 1995).

In the last 20 years or so paleomagnetism has also played an increasing role in geodynamic studies on a more localized scale, dealing with the identification of rotations about the vertical axis of smaller crustal blocks and with the diffused deformation in the plate boundaries and orogenic belts (*e.g.*, Van der Voo and Channell, 1980; Lowrie and Hirt, 1986); this latest application is of particular concern in the Mediterranean area (*e.g.*, Morris and Tarling, 1996).

In this paper we briefly outline the basic concepts of paleomagnetism study applied to geodynamics and we present some criteria for assessing the reliability of paleomagnetic data (see the classical texts by McElhinny, 1973; Collinson, 1983; Tarling, 1983; Butler, 1991; Van der Voo, 1993). We then synthetically review the available paleomagnetic data for peninsular and insular Italy. The purpose of this review is to provide an up-to-date summary of the paleomagnetic studies carried out during the past 25 years and to assess their main geodynamic implications for the reconstruction of the main geodynamic events.

2. Natural Remanent Magnetization (NRM) of rocks and progressive stepwise demagnetization

Paleomagnetism is essentially the study of the remanent magnetization of rocks. Rocks acquire a natural remanent magnetization mainly by three processes:

– Thermoremanent Magnetization (TRM) – A remanence produced by cooling in a magnetic field from the Curie point to room temperature; TRM is typical of igneous rocks (deriving from consolidation of magma at any pressure). In the case of plutonic intrusions (low cooling rate), the remanence is acquired over a long time interval (paleomagnetic samples average out secular variation); in the case of volcanics (fast cooling rate), the remanence is acquired «instantaneously» (paleomagnetic samples record a spot-reading of the Earth's magnetic field).

– Depositional Remanent Magnetization (DRM) – A remanence acquired during or shortly after deposition of magnetic grains in water in the presence of a magnetic field. Typical of sediments. The sedimentation rate determines the extent to which secular variation is averaged out in a standard paleomagnetic sample (generally the secular variation is completely averaged in about 10^4 years).

– Chemical Remanent Magnetization (CRM) – A remanence acquired when a magnetic mineral either nucleates or grows through a critical size or grows at the expense of a parent magnetic phase in a magnetic field, at constant temperature ($T < T_{\text{curie}}$). Typical of alterations of pre-existing rocks (weathering, authigenesis, changes of T, P, ph....).

There are specific laboratory treatments on paleomagnetic specimens that aim at the recognition of all the magnetization components, particularly their direction and stability range. This is routinely achieved through a cycle of remanence measurements in progressive demagnetization steps. There are two demagnetization treatments that are commonly employed in paleomagnetic laboratories:

– Alternating Field (AF) demagnetization: demagnetization effected by a field of alternating polarity and smoothly decreasing amplitude; the peak field increases with each step of the demagnetization procedure. The contribution to the total remanence is gradually removed according to the coercivity spectra of the magnetic grains population in a standard paleomagnetic specimen.

– Thermal demagnetization: demagnetization effected by zero-field heating and cooling to room temperature; the peak temperature increases with each step of the procedure. The contribution to the total remanence is gradually removed according to the blocking temperature spectra of the magnetic grains population in a standard paleomagnetic specimen.

3. Uncertainties in paleomagnetic data

Paleomagnetic data have a statistical uncertainty about a mean direction. This uncertainty is particularly important when paleomagnetic data are employed to quantitatively evaluate crustal drifts and rotations and it places confidence limits on the obtained values. A short outline on the statistical grounds about paleomagnetic data is provided in the following.

3.1. *Fisher statistics*

Since paleomagnetic results can be thought of as directions penetrating a sphere of unit radius, it is common practice to use the properties of the Fisher (1953) distribution (assuming circularly distributed observations about a mean direction) for the scattering estimation.

The probability density distribution (P) of an ideal population of directions on a sphere is

$$P = \frac{\kappa}{4\pi \sinh \kappa} \exp\left(\kappa \cos \phi\right),$$

where κ is the precision parameter and ϕ is the angle between the direction of a sample and the true mean direction. For a finite number of observations, κ may be estimated by

$$\kappa = \frac{N-1}{N-R},$$

where N is the number of observations and R is the resultant sum of N vectorially added individual unit vectors.

An alternative, very common, way to express uncertainty of paleomagnetic data is by means of the parameter α_{95}, expressing the semi-angle of the cone of 95% of confidence about the mean direction:

$$\alpha_{95} = \cos^{-1}\left\{1 - \frac{N-R}{R}\left[20^{\left(\frac{1}{N-1}\right)} - 1\right]\right\}.$$

3.2. *Paleomagnetic directions and virtual geomagnetic poles*

The principal assumption in paleomagnetism is that the geomagnetic field, if considered on time scales of the order of 10^4 years or more, is dipolar and geocentric axial (GAD hypothesis). The geocentric hypothesis was confirmed by the analysis of paleomagnetic poles distribution for coeval samples coming from continental size distant areas. The GAD assumption was confirmed by the good agreement between paleomagnetic and paleogeographic determined poles; this was achieved by testing the alignment of the paleopoles and the geographical rotation axis in the geological past through the use of paleoclimatic indicators. For the last 100 Ma the GAD assumption is granted to within an allowable deviation of no more than 5°.

In paleomagnetism it is usual to derive the parameters of the geocentric dipole which would give rise to the observed magnetic field direction at a given latitude (λ) and longitude (ϕ). The geomagnetic pole of this imaginary dipole defines a Virtual Geomagnetic Pole (VGP). From spherical geometry VGP coordinates (λ', ϕ') can be determined given the coordinates of the sampling site (λ, ϕ) and its paleomagnetic direction, expressed in terms of declination and inclination (D, I) (fig. 1):

$$\lambda' = \sin^{-1}\left(\sin\lambda \cos p + \cos\lambda \sin p \cos D\right)$$

$$\phi' = \phi + \beta \quad \text{for} \quad \cos p \geq \sin\lambda \, \sin\lambda'$$

$$\phi' = \phi + \pi - \beta \quad \text{for} \quad \cos p < \sin\lambda \, \sin\lambda'$$

$$\beta = \sin^{-1}\left(\sin p \sin D / \cos\lambda'\right) \quad \text{for} \quad -\pi/2 \leq \beta \leq \pi/2,$$

where p is the magnetic colatitude (given by 2-cot $p = \tan I$), that is the great-circle distance from site to the pole, and β is the longitudinal difference between pole and site, positive toward the east. The fulfillment of these hypotheses, according to the above gives a precise paleogeographic meaning to D and I as recognized from paleomagnetic data.

Uncertainties statistically combine according to the geometry of a geocentric axial dipo-

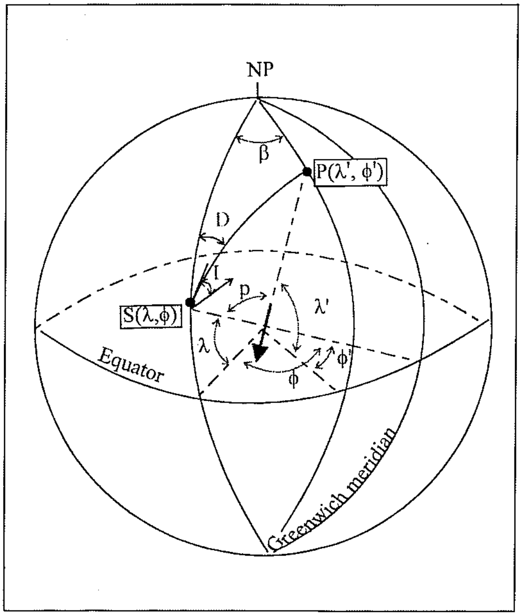

Fig. 1. Determination of magnetic pole position (P with coordinates λ', ϕ') from a paleomagnetic field direction (D, I) measured at a given site (S with coordinates λ, ϕ). The bold black arrow is the geocentric dipole that can account for the observed magnetic field direction.; p is the magnetic colatitude (angular distance from S to P) and β is the difference in longitude between the magnetic pole and the site. NP is the north geographic pole. Redrawn after McElhinny (1973).

lar magnetic field on the Earth surface, so that a circle of confidence about a mean paleomagnetic direction obtained for a given site produces an ellipse of confidence about the VGP computed by the same paleomagnetic data (fig. 2a). Such ellipse has semi-axes *dm* and *dp* given by

$$dm = \alpha_{95}\frac{\sin p}{\cos I} \qquad dp = 2\,\alpha_{95}\left(\frac{1}{1+3\cos^2 I}\right)$$

where p is the angle between the site and the pole (the colatitude) and I is the paleomagnetic inclination.

A circle of confidence about a mean paleomagnetic direction at a given site converts in two distinct uncertainties for paleomagnetic declination (D) and inclination (I) (*i.e.*, declination is badly defined at high latitudes, see fig 2b):

$$\Delta D = \sin^{-1}\left(\frac{\sin \alpha_{95}}{\cos I}\right) \qquad \Delta I = \alpha_{95}.$$

From a given VGP for a certain geological age an expected magnetic direction may be computed for each given site. Uncertainty on the VGP mean position (say A_{95} the α_{95} value computed on a population of VGPs) produces uncertainties on the expected paleomagnetic direction D_x and I_x:

$$\Delta D_x = \sin^{-1}\left(\frac{\sin A_{95}}{\sin p}\right) \qquad \Delta I_x = \frac{2A_{95}}{1+3\cos^2 p}.$$

4. The reliability of paleomagnetic data

Progress in rock magnetism analysis and data elaboration, has led in the past 40 years to an increase in the quality and significance of the paleomagnetic information; reliability criteria are however not generally codified and different requirements have been proposed by different authors (*e.g.*, Van der Voo, 1990; Besse and Courtillot, 1991). Moreover, the reliability of paleomagnetic data according to present standards depends on the aim of the analysis. In particular, for geodynamic purposes, the main requirements are synthetically listed in the following:

Sampling

- Collection of several *in-situ*-oriented samples from a single outcrop (site).
- Collection of samples at several geographically distributed sites.
- Well-determined rock age.
- Averaging out geomagnetic secular variations.
- Structural control and a presumption of tectonic coherence with crustal structure involved (that is to avoid strongly deformed rocks).

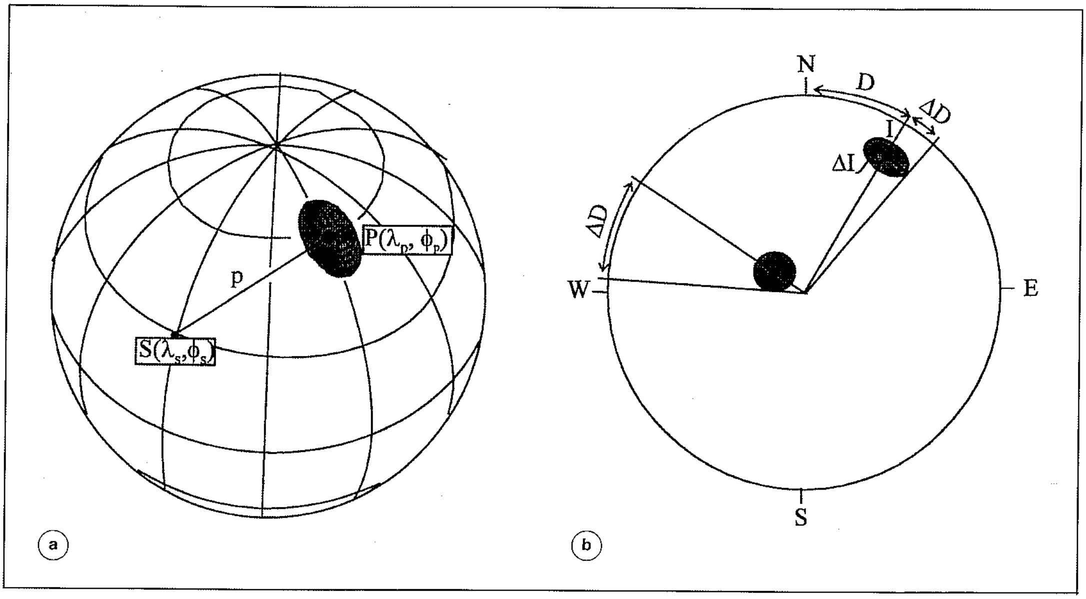

Fig. 2a,b. Uncertainties and confidence regions in paleomagnetic data. a) Ellipse of confidence about a VGP position (*P* with coordinates λ_p, ϕ_p). *dp* and *dm* are the semi-axes of the confidence ellipse. *S* is the sampling site with coordinates (λ_s, ϕ_s), *p* is the magnetic colatitude. Orthographic projection with latitude and longitude grid in 30° increments. b) Equal area projection of directions (*D* = paleomagnetic declination, *I* = paleomagnetic inclination) and attendant confidence limits (ΔD, ΔI) for two representative paleomagnetic data. Redrawn after Butler (1991).

Measurements

- Adequate (stepwise) demagnetization of all specimens.
- Rock magnetism analyses for identification of the magnetic carriers.

Data analysis

- Adequate analysis of the demagnetization data (Principal Component Analysis and best-fit to the demagnetization paths – evaluation of the Maximum Angular Dispersion).
- Statistically sufficient number of useful data for computation of paleomagnetic means.
- Field tests (*e.g.*, the fold test) that constrain the age of magnetization.
- Presence of reversals and antipodality of Normal and Reversed directions.
- No resemblance to paleopoles of younger ages.

5. Paleomagnetism and geodynamics

A quantitative estimate of the entity and the history of lithospheric and crustal deformation can be inferred from paleomagnetic data. More exactly paleomagnetism is used in geodynamic studies to assess vertical axis rotations (by means of paleomagnetic declinations) and latitudinal drifts (by means of paleomagnetic inclinations). The applicability of the method covers a broad range of scales and ranges from plates (*i.e.*, African plate), to microplates (*i.e.*, Corsica-Sardinia), terranes (*i.e.*, Wrangellia, along the Pacific coast of North America) and elementary geological structures (*i.e.*, a single fold). In the orogenic belts the applications are mostly finalized to three distinct topics:

1) to estimate the pattern of vertical axis rotations and latitudinal translations of tectonic units that underwent different amounts of orogenic transport;

2) to investigate the genesis of arcuate belts (that is testing the orocline hypothesis);

3) to reconstruct «true» orientation of stress and strain for deformational phases that affected rock units prior to rotation during orogenic transport.

However, some geodynamic problems cannot generally be solved easily by means of paleomagnetism. In particular, pure longitudinal translations are not directly resolvable from paleomagnetic data. Moreover, multiple phases of deformation may be actually superimposed on a measured paleomagnetic datum, so that what can be simply interpreted as a single vertical axis rotation may in reality be the resultant from the superposition of two (or more) distinct rotational phases. Finally, paleomagnetic data do not indicate directly the downward extent of the rotations found in the superficial cover.

Geodynamic applications of paleomagnetic data from relatively old sequences (*e.g.*, Paleozoic or Mesozoic) in orogenic belts require the knowledge of a reliable reference paleomagnetic direction for an adjacent stable plate as a function of geologic time.

There are two possible approaches to compute vertical axis rotations and latitudinal drifts from paleomagnetic data:

1) Direction space approach, based on the comparison of the observed paleomagnetic direction with that expected from the nearby stable plate for a given period at the study locality (fig. 3a)

$R = D_0 - D_x$ vertical axis rotation, positive clockwise;

$F = I_x - I_0$ flattening, or latitudinal drift.

2) Pole space approach, based on the comparison of the VGP computed by the observed

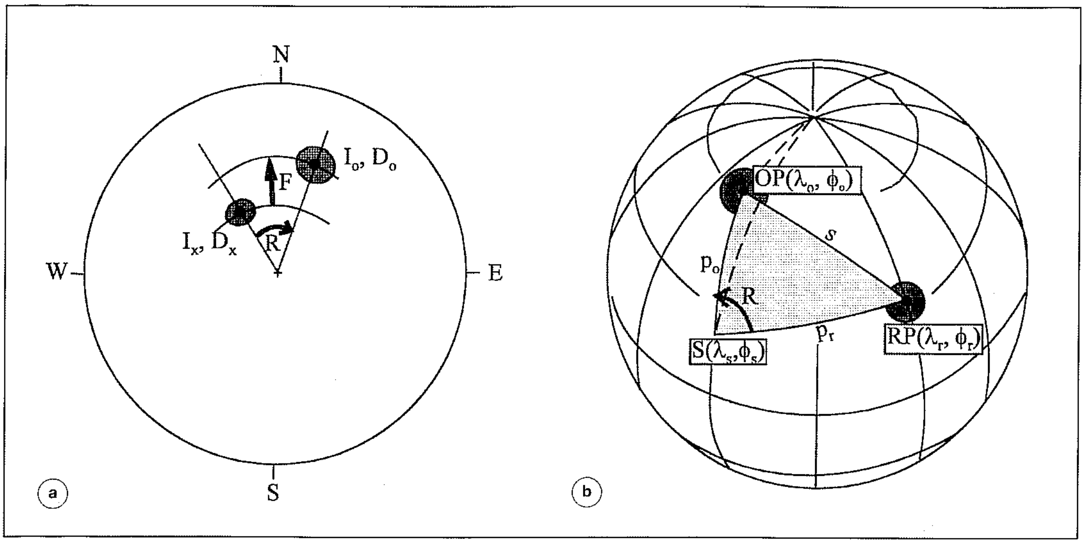

Fig. 3a,b. Estimates of vertical axis rotations and latitudinal drifts from paleomagnetic data. a) Directions space approach. Equal area projection, I_0 and D_0 are the observed paleomagnetic inclination and declination, I_x and D_x are the expected inclination and declination. R is the vertical axis rotation, F is the latitudinal transport; b) Pole space approach. RP is the reference paleomagnetic pole at (λ_r, ϕ_r), OP is the observed paleomagnetic pole at (λ_0, ϕ_0), S is the site location at (λ_s, ϕ_s). The light stippled region is a spherical triangle with apices S, OP and RP and sides s, p_0 and p_r. R is the vertical axis rotation. The poleward transport p is given by $p = p_0 - p_r$. Orthographic projection with latitude and longitude grid in 30° increments. Redrawn after Butler (1991).

paleomagnetic data with that expected from the Apparent Polar Wander Path (APWP) of adjacent stable plates (estimate of angles on a spherical surface, see fig. 3b).

The uncertainties related to the observed and reference paleomagnetic data produce uncertainties in the quantitative estimates of rotations and translations given by

$$\Delta R = 0.8\sqrt{\Delta D_0^2 + \Delta D_x^2} \quad \Delta F = 0.8\sqrt{\Delta I_0^2 + \Delta I_x^2}.$$

6. A critical review of the available paleomagnetic data in the Italian peninsula and islands

The application of paleomagnetism to the study of the geodynamic evolution of the Italian peninsula has markedly evolved during the past 20 years. Most early studies concerned Mesozoic - lower Tertiary sequences and most of the early geodynamic concepts derived from paleomagnetic studies were drastically modified by the recent study of Neogene and Quaternary sequences throughout the peninsula. This was in part due to the advantages deriving from studying sequences contemporary to the main geodynamic events (table I).

This review has been organized into nine sections, separately taking into account the main Italian tectonic provinces (fig. 4). In particular, we will discuss the paleomagnetic data from the Corsica-Sardinia block (section 6.1), the Northern Apennines (6.2), the Tyrrhenian margin (6.3), the Central Apennines (6.4), the Southern Apennines (6.5), the Calabro-Peloritan block (6.6), the Sicilian belt (6.7), with a synthesis for the entire peri-Tyrrhenian arc (6.8) and the Adriatic and Iblean foreland (6.9).

The data from Mesozoic - lower Tertiary sequences were compared to coeval reference data extrapolated from the most recent versions of the European and African APWP (Besse and Courtillot, 1991; Van der Voo, 1993); indeed, the amounts of rotation recorded in these sequences remain controversial, since they critically depend on the nearby reference plate APWPs (*e.g.*, Morris and Tarling, 1996; Channell, 1996). Moreover, the paleomagnetic data from the translated structures of the Apennines and the Sicilian belt were compared to the coeval data from the Adriatic and Iblean foreland. We emphasize that the amount of rotation experienced by the Adriatic block with respect to Africa is still debated (*e.g.*, Lowrie, 1986; Van der Voo, 1993; Marton and Nardi, 1994;

Table I. A comparison between paleomagnetic data from «young» and «old» rocks in the Italian peninsula, with reference to the geodynamic applications.

	Young rocks (Neogene-Quaternary)	Old rocks (Mesozoic-Paleogene)
Age relationships with the main geodynamic events	Coeval	Older
Extensive remagnetizations	Unlikely (fold test can rule out)	Likely (fold test cannot rule out)
Multiple phases of rotation	Unlikely	Likely
Reference direction for the geodynamic interpretation of the paleomagnetic data	From GAD Earth's magnetic field (precisely known)	From coeval pole in the African APWP (not yet well established)
Conclusion	Geodynamic interpretation relatively straightforward	Geodynamic interpretation relatively ambiguous

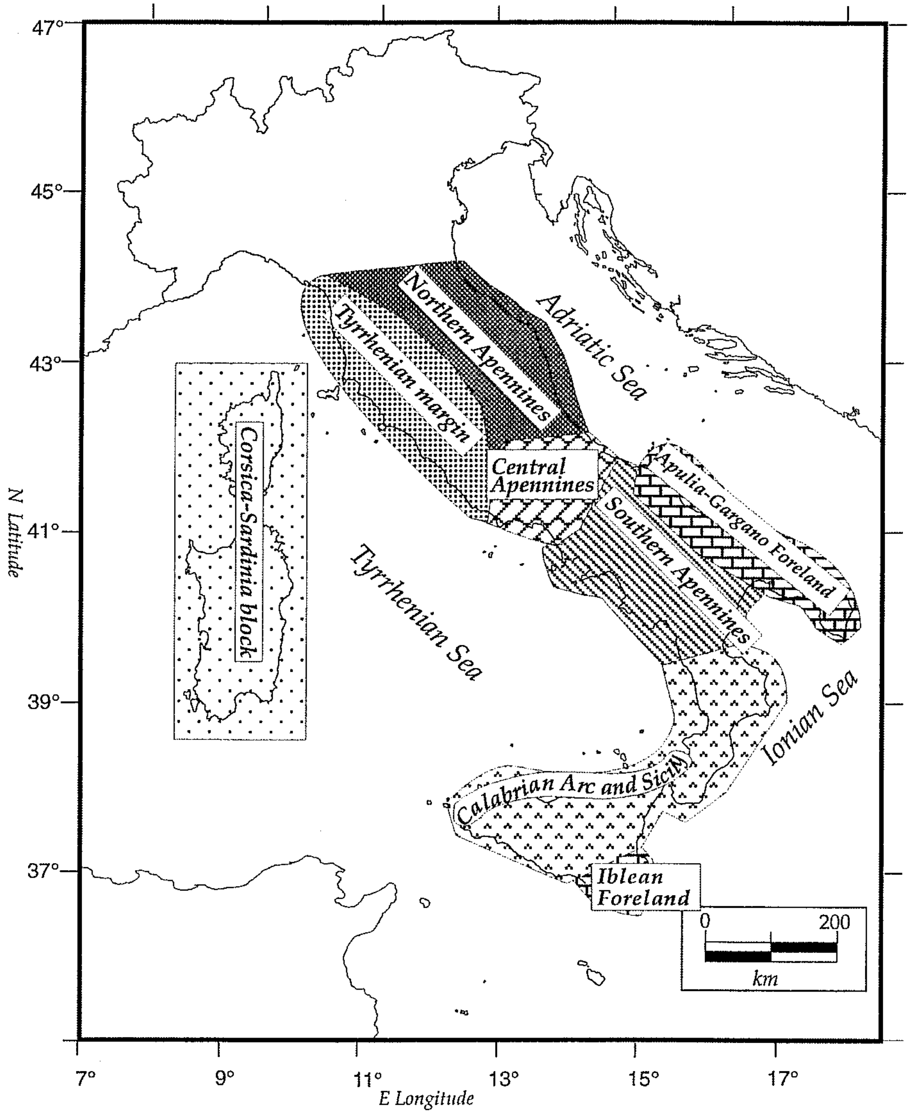

Fig. 4. Outline of the main tectonic provinces discussed in this review.

Channell, 1996). This implies that the rotation amounts in the Apennines with respect to the foreland are liable to revisions; however, we regret that the comparison of Mesozoic paleomagnetic data from Italy relatively to the African APWP is neglected even in very recent regional reviews (*e.g.*, VanDijk and Scheepers, 1995).

Several geodynamic questions on the timing and the amount of rotation for the main structural provinces are still unsolved, notwithstanding the rich and reliable paleomagnetic data set; some answers may be found extending the paleomagnetic research and integrating evidence from different branches of the Earth sciences.

6.1. *Corsica-Sardinia*

A first paleogeographic reconstruction in which the Corso-Sardinia block lies adjacent to Southern France was proposed by Emile Argand already in 1924. Different geological evidence was then found to support this hypothesis, which was subsequently accepted by many geologists, who proposed that the drifting of the Corsica-Sardinia block should imply a counter-clockwise (CCW) rotation of the two islands. These considerations obviously incited the production of paleomagnetic data; indeed, the Corsica-Sardinia block was the first paleomagnetically investigated area in Italy and was the object of several studies in the 1968-1981 years (see table II). These studies concerned mainly Permian volcanics, Oligo-Miocene calc-alkaline sequences and Plio-Pleistocene basalts, whilst only a few studies (Horner and Lowrie, 1981; Vigliotti and Kent, 1990; Vigliotti and Langenheim, 1995) reported paleomagnetic results from sedimentary sequences (Mesozoic and Tertiary).

The paleomagnetic data, when compared with coeval reference directions from the European APWP, indicate a large CCW (60°-70° in average) rotation of Corsica-Sardinia, roughly

Table II. Synthesis of paleomagnetic results from the Corsica-Sardinia block.

Rock type and age	CCW rotation with respect to Europe	References	Notes
Permian volcanics and sediments	40°-90° (60°-70° in average)	Nairn and Westphal (1968) Zijderveld *et al.* (1970) Westphal *et al.* (1976) Storetvedt and Petersen (1976) Storetvedt and Markhus (1978) Edel *et al.* (1981) Vigliotti *et al.* (1990)	No rotation between Corsica and Northern Sardinia (Vigliotti *et al.*, 1990) Late Hercynian block rotations in Sardinia? (Edel *et al.*, 1981)
Mesozoic carbonate sequences	~ 90° after Trias ~70°(??) after Jurassic	Horner and Lowrie, 1981	
Oligo-Miocene volcanics	0°-60° (30° in average)	De Jong *et al.* (1969) Bobier and Coulon (1970) De Jong *et al.* (1973) Bobier (1974) Coulon *et al.* (1974) Manzoni (1974) Edel and Lortscher (1977) Edel (1979) Montigny *et al.* (1981) Vigliotti and Langenheim (1995)	Highly scattered data Rotation occurred during early-middle Miocene?
Tertiary sediments	~30° after Eocene (1 site, Corsica), 0°-10°(?) after Burdigalian-Serravallian (Sardinia)	Vigliotti and Kent (1990) Vigliotti and Langenheim (1995)	
Plio-Pleistocene basalts	0°	Bobier and Coulon (1970) Manzoni *et al.* (1972) Alvarez *et al.* (1973) Coulon *et al.* (1974)	

30° of which presumably occurred during late Mesozoic - early Tertiary, and the other 30° during Oligo-Miocene. Most of the authors proposed that the former rotational episode occurred together with the Cretaceous 30° CCW rotation of Iberia. In this case, the Corsica-Sardinia block was previously located to the south of the present Pyrenean belt, adjacent to the Northern Catalan coast, and the geological similarities found with the Provençal coast (Westphal *et al.*, 1976) may be purely fortuitous.

Montigny *et al.* (1981) reviewed all the then available Oligo-Miocene paleomagnetic data, concluding that the rotation of the Corsica-Sardinia block was extremely rapid and mostly occurred in the Burdigalian, between 20.5 and 19 Ma ago. This apparently decisive conclusion has recently been critically revised by Todesco and Vigliotti (1993) and new paleomagnetic data from Northern Sardinia volcanics and sediments dated at 20.5-18.5 Ma (Vigliotti and Langenheim, 1995) confirm that the exact timing of the Oligo-Miocene rotational event is not completely understood.

Finally, early paleomagnetic works suggested a differential Tertiary rotation of a decoupled Corsica-Sardinia block (Westphal *et al.*, 1976), but recent paleomagnetic data suggest that the Corsica-Northern Sardinia block rotated as a whole (Vigliotti *et al.*, 1990).

6.2. *Northern Apennines*

The Mesozoic - early Tertiary Scaglia Formation from the Umbria-Marche Apennines is, both for paleomagnetism and magnetostratigraphy, one of the most studied sedimentary sequences in the world, providing a long-standing influence on the development of most of the geodynamic models for the whole Italian peninsula and the «Adria» microplate. Indeed, the concepts of CCW «rotation of the Italian peninsula» and «African affinity» of Adria and its margins were born from the earliest paleomagnetic studies (Lowrie and Alvarez, 1974, 1975; Klootwijk and VandenBerg, 1975; VandenBerg and Wonders, 1976; VandenBerg *et al.*, 1978) in this area. All these authors considered the Umbria-Marche units as «autochthonous» and assumed a large extrapolation of the vertical axis rotations there found to the whole Italian peninsula. However, the geodynamic interpretation of the paleomagnetic data from this region underwent substantial modifications (see table III), following the improvements in the knowledge of the general Apennine tectonics and of the major plate motion since the Mesozoic. Gradually the concept of «rotation of the Italian peninsula» was dismissed and the age of the rotation has considerably rejuvenated.

The origin of the arcuate shape of the Umbria-Marche Apennines represents a further long debated subject, that has been repeatedly tested by paleomagnetism. A mechanism of «oroclinal» bending (when the amount of rotation throughout the chain is structurally dependent) was first confirmed and then rejected according to different data sets from Mesozoic - lower Tertiary sediments in the internal (Umbria-Marche) domain (Channell *et al.*, 1978; Eldredge *et al.*, 1985; Hirt and Lowrie, 1988). New data from Messinian sediments along the external (Marche-Romagna) domain suggest that at least the external arc is properly an «orocline», supporting the existence, during the Messinian, of a straight belt-foredeep system roughly oriented N320°. It was found that vertical axis rotations are related to the Neogene-Quaternary emplacement of the Apennine thrust sheets (Speranza *et al.*, 1997); nevertheless, the exact timing of the rotations after the early Pliocene, the driving geodynamic mechanism and the depth of the structures involved in this rotation are still unclear.

6.3. *Tyrrhenian margin*

The first paleomagnetic studies of the Tyrrhenian margin were carried out mainly to define the spatial and temporal extent of the vertical axis rotations already detected in the Apennines, considering the Tyrrhenian margin and Northern Apennines as a single structural province. The first data in this region were collected in the Triassic Verrucano Formation in Tuscany (VandenBerg and Wonders, 1976), inferring that the whole Italian peninsula

Table III. Compendium of the main geodynamic interpretations for the paleomagnetic data from the Northern Apennines.

Areal extent of the rotation	
Italian peninsula	Lowrie and Alvarez (1974, 1975) Klootwijk and VandenBerg (1975) VandenBerg and Wonders (1976) VandenBerg *et al.* (1978) VandenBerg and Zijderveld (1982)
Northern Apennines	Channell and Tarling (1975)
Structural dependence through the belt (local tectonics and differential decollement)	Channell (1977) Channell *et al.* (1978) Van der Voo and Channell (1980) Hirt and Lowrie (1988) Channell (1992) Speranza *et al.* (1997)
Age of the rotation	
Late Cretaceous (with respect to Africa)	Klootwijk and VandenBerg (1975)
2 phases of CCW rotation Cretaceous (45°) and Eocene (25°) (with respect to Europe)	Lowrie and Alvarez (1974, 1975)
Coherence with Africa up to late Cretaceous, followed by relative CCW rotation (25°) during early Tertiary	VandenBerg and Wonders (1976) VandenBerg *et al.* (1978)
Late Tertiary	Channell *et al.* (1978) Lowrie (1986) Hirt and Lowrie (1988)
Neogene	Channell (1992)
Plio-Pleistocene	Speranza *et al.* (1997)

was part of the African plate until the early Tertiary and subsequently it underwent a 25° CCW rotation with respect to Africa and 15° relatively to the Southern Alps. This conclusion was later rejected by Kligfield and Channell (1979) who stated that paleomagnetic data from the allochthonous Verrucano Formation «cannot be used to establish the autochthony of Umbria or the applicability of the Umbrian data to autochthonous Italy». Paleomagnetic data from this region were then used to assess that any rotation in the Umbria-Marche region should have been completed by the early Pliocene (Lowrie and Alvarez, 1979).

Recent studies (Sagnotti *et al.*, 1994; Mattei *et al.*, 1996a) on the Messinian-Pleistocene neo-autochthonous cycle sediments indicated no rotation for the Tyrrhenian margin since late Pliocene (fig. 5) and remarked that the Tyrrhenian margin and Northern Apennines actually are two distinct rotational domains. The new data show that (Mattei *et al.*, 1996b): 1) the severe extensional, rifting and spreading processes which have occurred in the Tyrrhe-

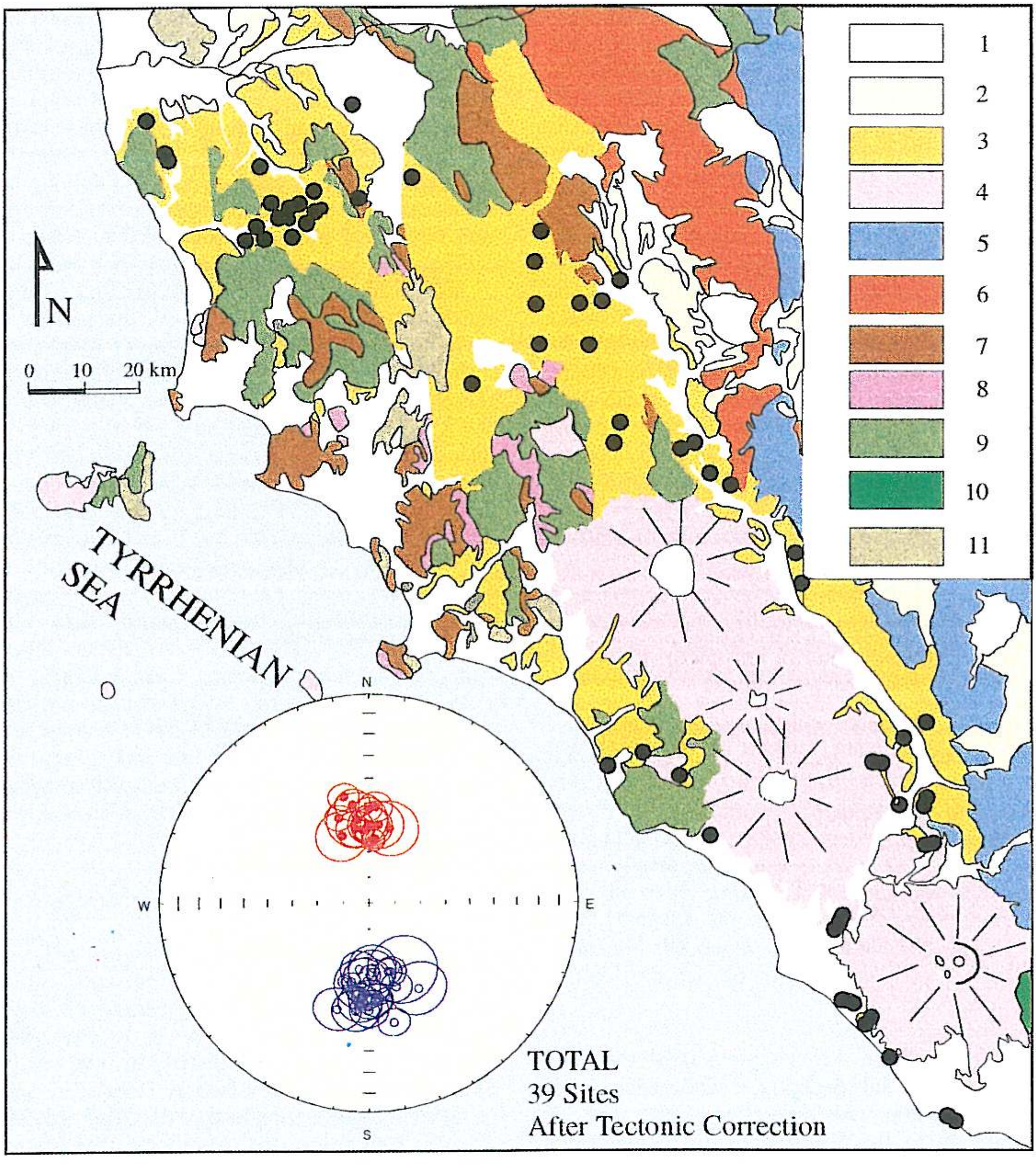

Fig. 5. Paleomagnetic sampling sites in the neo-autochthonous sequences of the Tuscan-Latium Tyrrhenian margin and equal-area projection of the paleomagnetic site mean directions. 1) Quaternary sediments; 2) Villafranchian sediments; 3) Miocene - Pliocene sediments; 4) Igneous rocks; 5) Umbria-Marche units; 6) Cervarola unit; 7) Tuscan unit; 8) Sub-Liguride units; 9) Liguride units; 10) Latium carbonate platform; 11) Metamorphic basement. Paleomagnetic data: open (blue) circle – reverse polarity; closed (red) circles – normal polarity. Redrawn after Sagnotti *et al.* (1994) and Mattei *et al.* (1996a).

nian Sea since Messinian did not cause any tectonic rotation in the Northern-Central Tyrrhenian margin of the Italian peninsula; 2) the processes that produced shortening and large rotations in the Apennine thrust sheets were followed by an irrotational late-orogenic collapse.

6.4. *Central Apennines*

Paleomagnetic studies of the Central Apennines have been performed only in the past few years and they propose a complex, structure-dependent, pattern of vertical axis rotations.

The results from the Cretaceous limestones of the Monte Maiella (Jackson, 1990) and Monte Greco-Monte Genzana (Marton and D'Andrea, 1992) structures, in the Eastern Abruzzi range, were interpreted in terms of a 25°-40° clockwise (CW) rotation relatively to the Apulia foreland. However, lower Cretaceous data from these structures are not statistically distinct from the coeval reference direction estimated by the recentmost African APWPs and from coeval data from Gargano (see section 6.9).

Extensive sampling was carried out in Tertiary sediments along different structures (Dela Pierre *et al.*, 1992; Mattei *et al.*, 1995). The results point out that the observed wide variability in the structural trends is a consequence of a widespread and composite pattern of vertical axis rotations. The data from the late Cretaceous-Eocene Scaglia Formation in the Gran Sasso range (Dela Pierre *et al.*, 1992) were interpreted as indicative of a differential CCW rotation (up to 90° in the eastern sector) over the underlying, not rotated, Monti della Laga structures.

Two distinct rotational phases were identified in the other structures of the Central Apennines (Mattei *et al.*, 1995). The first is a CCW rotation recorded in Eocene-Oligocene sediments; the second produced post-late Miocene differential block rotations according to different domains: CW rotations for the Southern Sabina, CCW rotations for the Latium-Abruzzi carbonate platform and CW rotations for the Marsica. This rotational pattern is referred to strike-slip faults and out-of-sequence thrust activity. Also in this case the exact timing of this rotational phase is unknown. Paleomagnetic evidence suggests that at the end of the Miocene the Central Apennines belt-foredeep system was roughly straight and oriented N320°.

The first paleomagnetic data from continental Plio-Pleistocene sediments in the intermontane basins of the Central Apennines (Alfonsi *et al.*, 1995) have been heavily affected by the presence of a strong viscous magnetization, and therefore they are not suitable for geodynamic interpretations.

6.5. *Southern Apennines*

The first paleomagnetic data from the Southern Apennines were collected over 20 years ago. This region has since been the focus of several paleomagnetic studies aimed at the reconstruction of the geodynamic evolution from the Jurassic to the Present, and in particular a better understanding of the Apennine mountain-building processes. The first studies concerned paleomagnetic results from Mesozoic (mainly sedimentary) rocks (Channell and Tarling, 1975; Manzoni, 1975; Incoronato, 1983; Incoronato *et al.*, 1985; Incoronato, 1988; Incoronato *et al.*, 1988; Iorio and Nardi, 1988; Jackson, 1990; Gialanella *et al.*, 1991).

The sampled rocks were collected in allochthonous structures and the paleomagnetic data have been used to infer the amount of vertical axis rotations that accompanied the tectonic transport towards the Adriatic foreland. The paleomagnetic data from Mesozoic sediments are scarce and often of low-quality and indicate very different amounts of CCW rotation with respect to the coeval reference direction from the African APWP and the Adriatic foreland (fig. 6).

Some old paleomagnetic results have recently been re-evaluated in light of more rigorous analyses of the demagnetization data (Incoronato, 1988) suggesting that some structures possibly underwent a complex deformation history and multiple phases of rotations. Mesozoic paleomagnetic data were also re-

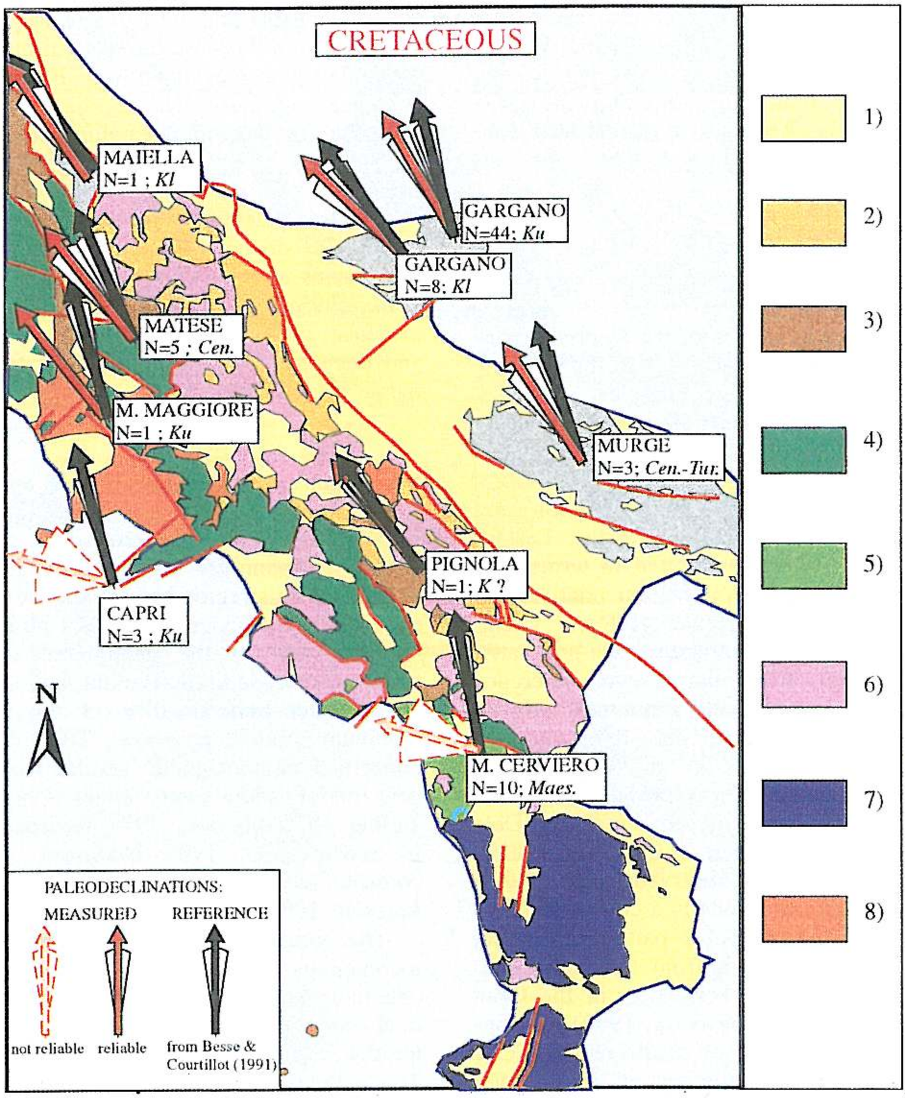

Fig. 6. Cretaceous paleomagnetic data from sediments in the Southern Apennines and the Apulian foreland. Kl = lower Cretaceous; Ku = upper Cretaceous; Cen. = Cenomanian; Tur. = Turonian; Maes. = Maestrichtian. Red dashed arrows and cones indicate paleomagnetic data (M. Cerviero, Capri) obtained by laboratory treatments not reliable according to present standards or highly scattered results. Black arrows represent the directions expected at each site location, when considered fixed to the African plate. Reference African directions and their confidence cones at each site were computed from the African pole list in the paper by Besse and Courtillot (1991), using the formulas shown in section 3.2. We emphasize that data collected from a single locality (M. Maiella, M. Maggiore, Pignola) are hardly representative of a whole structure. Schematic geologic map from Funiciello *et al.*, 1981: 1) post-orogenic sedimentary sequences; 2) late orogenic flysch; 3) Mesozoic - early Tertiary basinal sequences; 4) Mesozoic - early Tertiary carbonatic platform sequences; 5) Verbicaro unit; 6) Allochthonous Liguride and Sicilide complexes; 7) Alpine units of the Calabride complex; 8) Pleistocene volcanics.

cently interpreted as representative of local movements between adjacent structures, more than regional rotations (Gialanella *et al.*, 1991). Finally, detailed rock magnetism analyses integrated with magnetic anisotropy studies pointed out that «anomalous» paleomagnetic data from Mesozoic carbonates may result from peculiar magnetic fabrics, probably related to internal strain and/or chemical remagnetization during the Tertiary main deformation events (Gialanella *et al.*, 1994). This should explain the origin of too steep paleo-inclinations characterizing some paleomagnetic results from Mesozoic limestones (*e.g.*, paleomagnetic data from Lagonegro in Incoronato *et al.*, 1985 and from Monte Raparo in Jackson, 1990), which are difficult to understand in terms of simple tectonic deformations.

Only in the past few years were data obtained from Neogene and Quaternary terrigenous clayey sediments proving that large vertical axis rotations in the Southern Apennines (and also the Calabrian arc and Sicily, see next sections) occurred during Pliocene and Pleistocene times. These data outline a pattern of rotations that appears of regional significance (fig. 7).

Considerable CCW rotations (≈ 24°) occurred after the early Pleistocene in some basins of the Southern Apennines (Sagnotti, 1992; Sagnotti and Meloni, 1993; Scheepers and Langereis, 1994), whereas no rotation is recorded in the post-orogenic sediments of the Bradano cycle (Scheepers, 1992; Scheepers *et al.*, 1993). A middle Pliocene - lower Pleistocene regional phase of about 15° CCW rota-

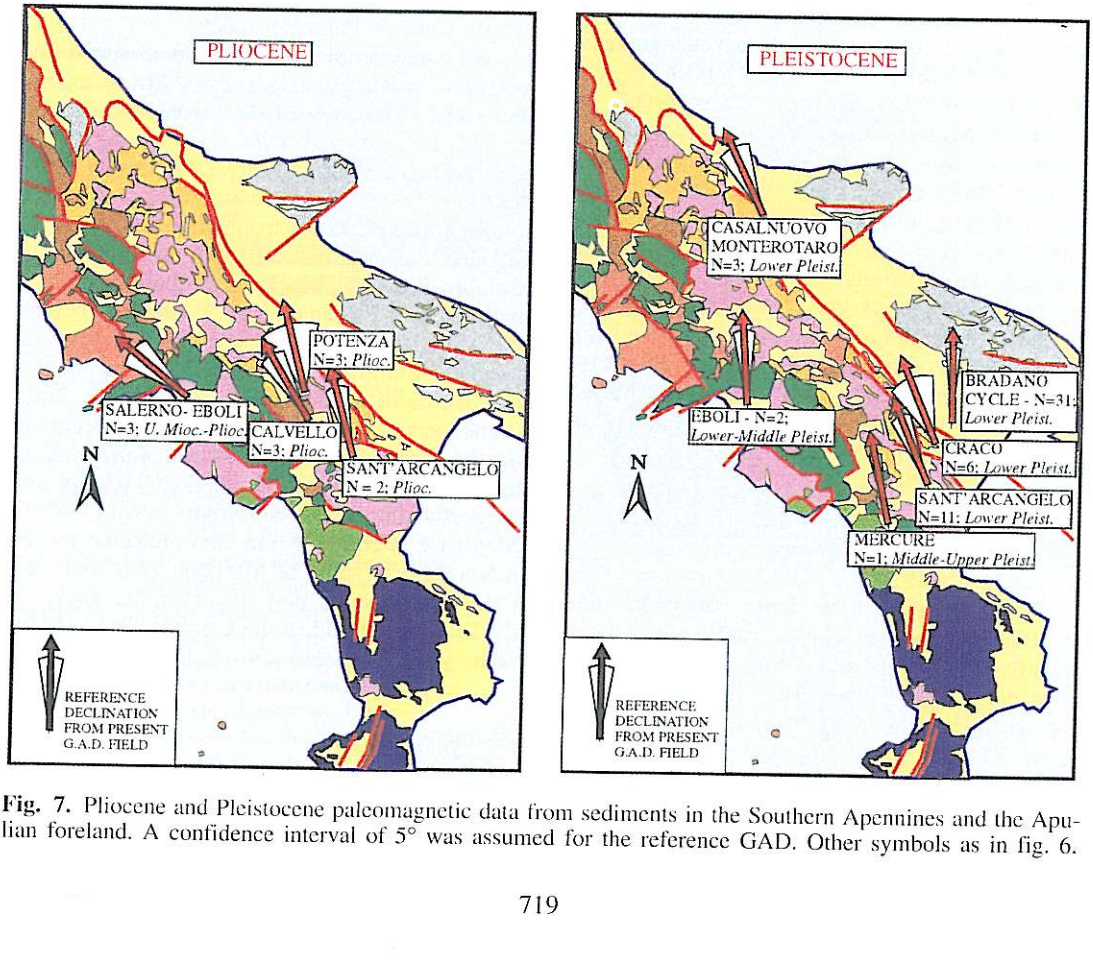

Fig. 7. Pliocene and Pleistocene paleomagnetic data from sediments in the Southern Apennines and the Apulian foreland. A confidence interval of 5° was assumed for the reference GAD. Other symbols as in fig. 6.

tion was suggested by Scheepers and Langereis (1994), on the basis of the comparison of paleomagnetic data from sediments of late Messinian to late Pleistocene age, from different structures. However, this hypothetic phase is not substantiated by paleomagnetic data from the Sant'Arcangelo basin (Sagnotti, 1992; Sagnotti and Meloni, 1993), where it appears that all the recorded CCW rotations occurred after the deposition of the lower Pleistocene clays. On the other hand, in this basin different amounts of CCW rotations are recorded in sediments of the same age from sites geographically distributed in the eastern flank of the basin in an apparently regular trend increasing from north to south (Sagnotti, 1992; Scheepers *et al.*, 1993). Paleomagnetic data for middle-late Pleistocene sediments are currently available for 4 sites only at two distinct localities (Scheepers and Langereis, 1994) showing no coherent rotational patterns: in the Eboli area no significant rotation was observed, whereas in the Rotonda area, in the Mercure basin, about 12° of CCW rotation are recorded in continental lagoonal sediments of middle-late Pleistocene age.

The whole set of data currently available shows that the rotations detected in Mesozoic formations may, in some structures, reflect complex deformations resulting from competing and diachronous geodynamic phenomena. Further investigations are clearly needed to clarify the geographic and temporal distribution of tectonic rotations in the Southern Apennines and to better understand the dynamics of the deformation in this belt.

6.6. *Calabro-Peloritan block*

Paleomagnetic data from several sites in Plio-Pleistocene clayey sediments have recently been reported (Aïfa *et al.*, 1988; Scheepers, 1994; Scheepers *et al.*, 1994); relying on such data, a uniform CW rotation of about 15° has been proposed for the whole Calabro-Peloritan block (Scheepers *et al.*, 1994), taking place in an extremely short time interval, between 1 and 0.7 Ma (VanDijk and Scheepers, 1995). However, the observed widespread records for CW rotation (with values actually ranging from 0° to 40°) depend strongly on the structural position of the sites as well as on the age of the studied sequences. This aspect deserves some additional comments; in particular, the data from Northern Calabria (Scheepers, 1994) show that the sites of the west flank of the Crati basin record relatively large CW rotations, whereas the coeval sites on the east flank of the basin appear essentially not rotated. Moreover, two sections containing the Jaramillo subchron (dated at 0.990-1.070 Ma; Cande and Kent, 1995) provided very different results: one of them, on the west side of the Crati basin (San Marco Argentano) is rotated about 40° CW, the other, on the north of the basin (Firmo) is not rotated. It is noteworthy that the Firmo and the east Crati sites constitute the «evidence» for placing an upper limit on the age of the rotation of the whole Calabro-Peloritan block!

We conclude that, though a generalized CW rotation during Pleistocene of the Calabro-Peloritan block is well established, more data should be obtained before assuming robust conclusions concerning the actual timing of the rotation throughout the whole block.

Preliminary results from Miocene sediments suggest that rotations were not uniform for the Calabro-Peloritan block (Scheepers, 1994). A major CCW rotation (~ 90°) episode in middle-Miocene was suggested on the basis of magnetostratigraphic analyses carried out at the Basilicoi section, in the Crotone basin (Scheepers, 1994), but this early interpretation has been very recently dismissed, following an integrated study of paleomagnetic results and magnetic fabrics (Duermeijer *et al.*, 1996). Major CCW rotations are also indicated by the paleomagnetic study of Mesozoic sediments and Paleozoic igneous and metamorphic rocks in the Sila massif and in the Coastal Chain (Manzoni, 1979; Manzoni and Vigliotti, 1983).

6.7. *Sicilian belt*

Several paleomagnetic data are available for the Northern Sicilian chain and the Caltanissetta basin. The data from the Mesozoic - lower Tertiary sediments in the West Sicilian fold and thrust belt collected over the past 20 years indicated large-scale CW rotations for the different paleogeographic units (Catalano *et al.*, 1976; Schult, 1976; Channell *et al.*, 1980; Nairn *et al.*, 1985; Channell *et al.*, 1990). The magnitude of the CW rotations detected in these studies decreases stepwise from over 120° in the upper sheets (paleogeographically internal Panormide units) to almost no rotation in the frontal portion of the belt (external part of the Saccense unit) (fig. 8). These rotations have been related to thrusting and to changes in the direction of tectonic transport from easterly to southerly (Oldow *et al.*, 1990).

The paleomagnetic data recently reported for some magnetostratigraphic sections in

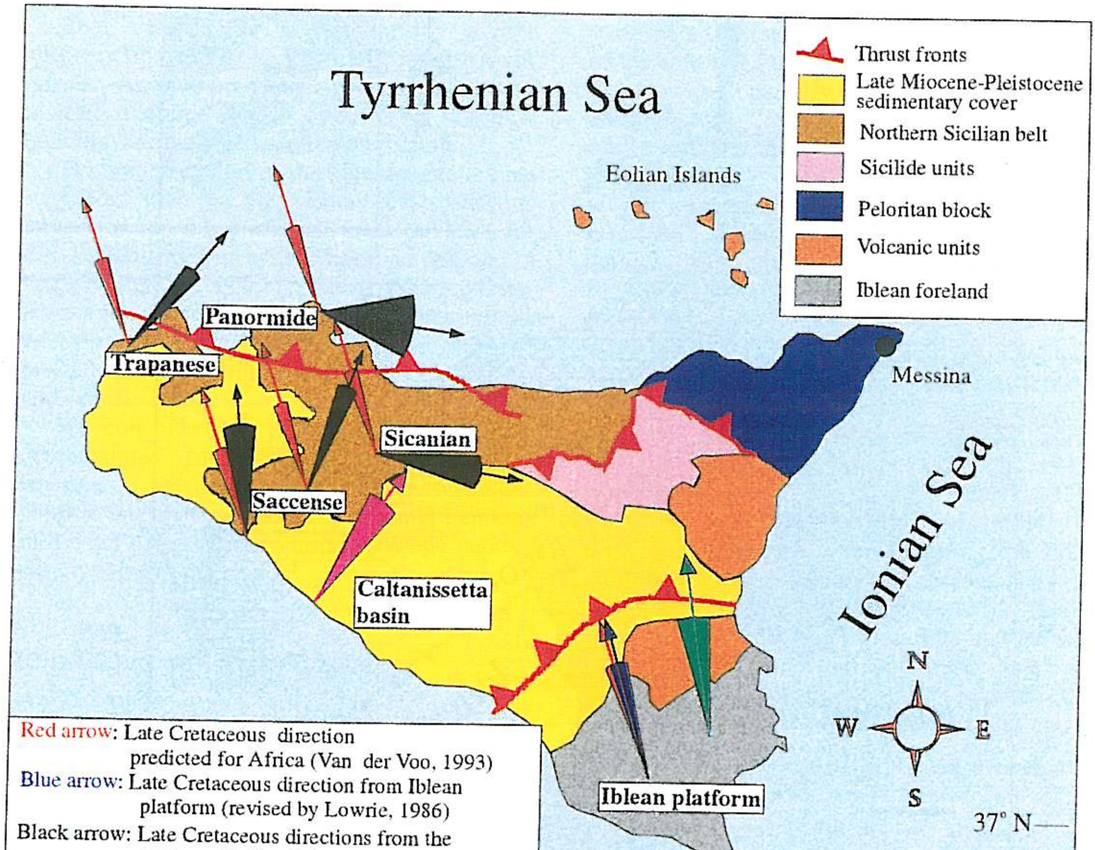

Fig. 8. Late Cretaceous and Pliocene paleomagnetic data from the Sicilian belt and the Iblean foreland.

Pliocene sequences from the Caltanissetta basin near Eraclea Minoa (Scheepers and Langereis, 1993) indicate about 35° of CW rotation since early Pliocene, 24° of which younger than the Gauss/Matuyama boundary (~ 2.6 Ma) and 10° during approximately Kaena times (~ 3.05 Ma). This latter conclusion is not in agreement with the evidence for no rotation with respect to the Iblean platform found in the nearby Mesozoic sediments of the Saccense unit near Sciacca (Channell *et al.*, 1990). We conclude that the overall pattern and timing of Neogene and Quaternary vertical axis rotations in allochthonous Sicily are not yet completely clarified and certainly merit to be further investigated.

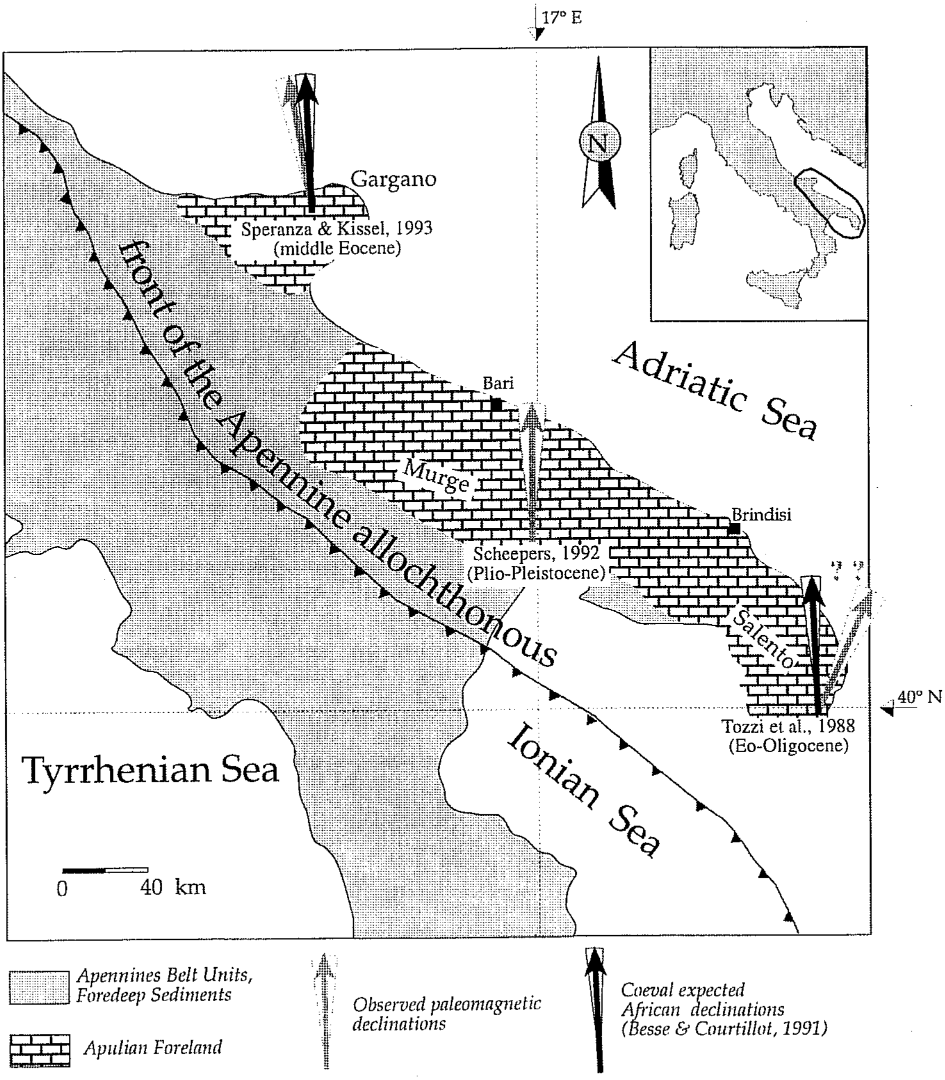

Fig. 9. Eocene - Pleistocene paleomagnetic data from the Apulia-Gargano foreland.

6.8. *The peri-Tyrrhenian arc (Southern Apennines, Calabro-Peloritan block and Sicilian belt)*

Paleomagnetism was considered essential to unravel two main geodynamic features of the peri-Tyrrhenian arc:

1) to estimate the pattern of vertical axis rotations through tectono-stratigraphic units that belonged to different (internal to external) paleogeographic domains and underwent different amounts of orogenic transport toward the foreland;

2) to establish if the present-day arcuate shape of the arc is an original feature of the African-Adriatic continental margin or if it was instead acquired by a process of oroclinal bending during the Apenninic orogeny.

The interpretation of the paleomagnetic data suggested that (1) the amount of rotation is larger for the more internal units (at least for the Sicilian belt), which have undergone a large amount of tectonic transport (*e.g.*, Catalano *et al.*, 1976) and that (2) the ancient continental margin was much less arched than the present peri-Tyrrhenian arc (*e.g.*, Incoronato and Nardi, 1989).

We conclude that point (1) is not clearly demonstrated for the Southern Apennines, whereas it is more evident in the Sicilian nappes, and that most of the oroclinal bending in the arc (2) is due to Plio-Pleistocene geodynamic events.

6.9. *Adriatic and Iblean foreland*

The Adriatic foreland has been subjected to broad paleomagnetic analyses since the mid seventies to test the geodynamical evolution of the whole Adriatic block.

Data from early and late Cretaceous carbonatic platform sequences from Gargano and Murge (Channell and Tarling, 1975, Channell, 1977; VandenBerg, 1983; Lowrie, 1986; Marton and Nardi, 1994) show, when compared to the most recent African APWPs, a slight (~ 10°-15°) CCW rotation which is significant. Data from VandenBerg (1983) for the Gargano promontory were recently recomputed (Van der Voo, 1993). At present the existence of a (slight) post-Cretaceous CCW rotation of the backbone of «Adria» with respect to the African plate is still controversial (fig. 9).

Paleomagnetic data from Eocene limestones in the Gargano promontory (Speranza and Kissel, 1993) can be interpreted either in terms of remagnetization or as evidence for no post-Eocene rotation of Gargano with respect to Africa. The data from the Eocene-Oligocene sediments in the Salento peninsula were interpreted as evidence for a CW rotation (Tozzi *et al.*, 1988) but they are probably affected by widespread remagnetization (the significance of the fold test for the paleomagnetic data from Salento was critically reviewed by Bazhenov and Shipunov, 1991) and therefore they are not easily applicable to geodynamic reconstructions. Finally, data from Plio-Pleistocene clayey units in the Apulian foreland (Scheepers, 1992) show that no rotation has occurred since Late Pliocene (fig. 9).

The Iblean foreland in Sicily has been the focus of extensive paleomagnetic investigations since the seventies. The paleomagnetic data from Cretaceous, Neogene and Quaternary sediments and volcanics are not statistically different from the reference directions computed by the African APWP (Schult, 1973; Barberi *et al.*, 1974; Gregor *et al.*, 1975; Grasso *et al.*, 1983; Besse *et al.*, 1984). A slight (~ 10°) CCW rotation during the Plio-Pleistocene was attributed to extensional processes in the Pelagian Sea (Besse *et al.*, 1984). Again, the uncertainties in the reference APWP for Africa and the usual confidence intervals related to paleomagnetic data hamper the sound identification of such slight rotations.

7. Conclusions

Paleomagnetism played a fundamental role in the development of models of Central Mediterranean geodynamic evolution. From the early simplex concept of «rotation of the Italian peninsula», thought of as a rigid block movement, the data gradually outlined a far more complex pattern of varied rotations that occurred mostly during the Neogene and Quaternary (that is they are coeval with the main geodynamic events) and differ for the various provinces distinguished on a geological basis. Differential vertical axis rotations are widespread in the region and were important for the genesis of present arcuate structures.

The available paleomagnetic data were critically reviewed in nine distinct sections: a comprehensive synthesis was not attempted since several geodynamic problems remain open and a regional link between the paleomagnetically detected vertical axis rotations and the main geodynamic events, as pointed out by classical geology, has yet to be soundly established.

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