Paleomagnetic evidence for a post-Eocene 90° CCW rotation of internal Apennine units: A linkage with Corsica-Sardinia rotation?

J. Gattacceca, Chiara Caricchi, Francesca Cifelli, Leonardo Sagnotti, Federico Sani, Fabio Speranza, Massimo Mattei

► To cite this version:

J. Gattacceca, Chiara Caricchi, Francesca Cifelli, Leonardo Sagnotti, Federico Sani, et al.. Paleomagnetic evidence for a post-Eocene 90° CCW rotation of internal Apennine units: A linkage with Corsica-Sardinia rotation?. *Tectonics*, 2014, 33 (4), pp.374-392. 10.1002/2013TC003364 . hal-03036561

HAL Id: hal-03036561

<https://hal.science/hal-03036561>

Submitted on 12 Nov 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Copyright

RESEARCH ARTICLE

10.1002/2013TC003364

Key Points:

- Extensive paleomagnetic sampling in the inner sector of the Northern Apennines
- Large counterclockwise (CCW) rotations in the inner part
- A tectonic model of Central Mediterranean area is proposed

Correspondence to:

C. Caricchi,
chiara.caricchi@gmail.com

Citation:

Caricchi, C., F. Cifelli, L. Sagnotti, F. Sani, F. Speranza, and M. Mattei (2014), Paleomagnetic evidence for a post-Eocene 90° CCW rotation of internal Apennine units: A linkage with Corsica-Sardinia rotation?, *Tectonics*, 33, 374–392, doi:10.1002/2013TC003364.

Received 29 APR 2013

Accepted 18 FEB 2014

Accepted article online 24 FEB 2014

Published online 11 APR 2014

Paleomagnetic evidence for a post-Eocene 90° CCW rotation of internal Apennine units: A linkage with Corsica-Sardinia rotation?

Chiara Caricchi¹, Francesca Cifelli¹, Leonardo Sagnotti², Federico Sani³, Fabio Speranza², and Massimo Mattei¹
¹Dipartimento di Scienze, Università Roma TRE, Rome, Italy, ²Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy,

³Dipartimento di Scienze della Terra, Università degli Studi di Firenze, Firenze, Italy

Abstract We report on an extensive paleomagnetic study (36 sites) of the Tuscan Nappe succession from the Northern Apennines Arc, aimed to reconstruct the tectonic evolution of the internal sector of this chain. We analyzed Eocene pelagic foreland ramp deposits (Scaglia Toscana Formation) and Oligocene–lower Miocene siliciclastic turbidites (Macigno and Falterona Formations). Paleomagnetic results show that the internal sector of the Northern Apennines underwent large counterclockwise (CCW) rotations with respect to the Adria-Africa foreland. A decrease in the rotation magnitude was observed from the southern to the northern sector of the arc (from 91 to 36°). This trend is opposite to that observed in the more external units of Northern Apennines and demonstrates that the oroclinal bending model, which has been proposed for the external units of the chain, is not appropriate to explain the evolution of the internal sector of the arc. On the basis of the observed paleomagnetic pattern, we propose a new tectonic model in which the Tuscan and Falterona-Cervarola units in the southern area were first rotated CCW along with the Corsica-Sardinia block during its lower Miocene rotational drifting and were later involved in the main phases of rotational emplacement and translation toward the outermost sector (Umbria domain), thus yielding the final curved shape of the Northern Apennines chain. Data from this study represent the first paleomagnetic evidence of the influence of the Corsica-Sardinia CCW rotation in the Apennines orogenic wedge deformation, in the general framework of the geodynamic evolution of the Central Mediterranean subduction system.

1. Introduction

The peculiar tectonic feature of the Mediterranean region is given by the coexistence of curved mountain belts and back-arc basins, which developed synchronously, in a plate tectonics scenario dominated by the Africa-Eurasia convergence (Figure 1). Such arcs and related back-arc basins formed as a consequence of trench rollback of dense and narrow slabs, resulting from the progressive fragmentation of the subducting African Plate during Neogene and Quaternary [Malinverno and Ryan, 1986; Lonergan and White, 1997; Royden, 1993; Mattei et al., 2007]. In the Central Mediterranean, the northwest subduction of the Ionian Adriatic lithosphere underneath the Eurasian Plate, caused the progressive closure of the intervening Mesozoic oceanic basins of Tethyan domain and the formation of the Apennines-Maghrebide orogenic belt and Liguro-Provençal and Tyrrhenian extensional back-arc basins [Faccenna et al., 2004, and references therein].

Paleomagnetic data document that the curved shape of the Mediterranean orogenic arcs is the result of opposite rotations along the two arms of the arcs and that the opening of back-arc basins was related to drifting of rigid blocks and terranes around an Eulerian rotation pole (among others) [Kissel and Laj, 1988; Lonergan and White, 1997; Mattei et al., 2006; Cifelli et al., 2007, 2008; Maffione et al., 2013]. Vertical axis rotations in Central Mediterranean have been described as the result of two distinct events occurring at different times as a consequence of the progressive eastward retreat of the subducting Ionian-Adriatic lithosphere. The first episode occurred during the Oligocene–early (middle) Miocene and was responsible of the opening of the Liguro-Provençal back-arc basin and the CCW rotation of the Corsica-Sardinia block (see Speranza et al. [2002] and Gattacceca et al. [2007] for recent reviews). The second episode occurred after the late Miocene and was responsible of the opening of the Tyrrhenian back-arc basin and the curvature of the Northern Apennine Arc. This event was documented from the external domains of the Northern Apennines fold and thrust belt, where vertical axis rotations accommodated thrust activity (see Cifelli and Mattei [2010] for

Figure 1. Schematic map of the Northern Apennines and its location in the geodynamic framework of the Mediterranean Basin (inset). In the map, sites sampled in the Trasimeno Lake area (1), Chianti Mountains and Pratomagno (PM) area (2), and the Val di Lima (LV) and the Garfagnana (GF) area (3) are reported. MB = Mugello Basin.

a recent review). After decades of paleomagnetic research in the Central Mediterranean, few key issues are still outstanding. The amount and timing of the CCW rotation of the Corsica-Sardinia block is rather accurately known, whereas no constraints on their geographic extension to the east are available, even if it has been suggested that the Tertiary Piedmont Basin in Western Alps [Maffione *et al.*, 2008] and some internal units (Epiligurian clastic sediments) exposed in the external part of the Northern Apennines belt [Muttoni *et al.*, 2000] were also involved in the CCW rotation of the Corsica-Sardinia block. This uncertainty is due to the fact that most of the paleomagnetic data from the Northern Apennines come from the external portion of the chain portion of the chain that was thrust over the Adriatic foreland after the ending of the Corsica-Sardinia CCW rotations. Conversely, virtually no data were collected from preorogenic strata of the internal sector of the Northern Apennines, which experienced and recorded a continuous deformation history since the beginning of convergence in the Late Cretaceous, and which were already incorporated in the orogenic wedge during the Corsica-Sardinia rotation. Data from postorogenic Plio-Pleistocene sediments from Tuscany show no evidence of tectonic rotation [Mattei *et al.*, 1996], suggesting that rotations in the Northern Apennines were due to older orogenic episodes.

In order to provide new data for preorogenic and synorogenic rocks from the internal sector of the Northern Apennines Arc, an extensive paleomagnetic sampling was carried out in the Tuscan and Cervarola-Falterona (hereafter referred as TCF) units. Results show that these units underwent a larger amount of CCW rotations in the southern limb of the arc than in the northern one. This rotation pattern is at odds with that observed in the external units of Northern Apennines and is not compatible with a simple oroclinal-bending model. On this basis, we argue that the TCF units recorded a two-stage rotation phase: an early-middle Miocene phase linked to the Corsica-Sardinia rotation and a postlate Miocene related to thrust emplacement in the Northern Apennines.

2. Geological Setting

The curved Northern Apennines consists of several paleogeographic domains, organized in a fold and thrust belt forming a broad curved structure verging toward the Adriatic foreland (Figure 1). The curvature of the arc follows the Adriatic margin of the belt, with the orientation of the main structures ranging from NW-SE/MNW-ESE in the north to almost north-south in the south [e.g., *Elter, 1975; Boccaletti et al., 1980; Principi and Treves, 1984; Barchi et al., 1998a, 1998b*]. The uppermost nappes of the Northern Apennines are represented by oceanic units (Ligurian) characterized by the occurrence of Jurassic ophiolites and their Jurassic–Early Cretaceous sedimentary cover, overlain by Cretaceous–Oligocene flysch sequences. The Ligurian domain units overthrust eastward the Tuscan domain units, formed by Upper Triassic to Eocene marine carbonates and by Oligocene–lower Miocene foredeep sequences, which are deformed in an array of thrust sheets and ultimately thrust over the units of the Umbria-Marche-Romagna domain. The latter consists of sedimentary sequences deposited on a continental margin with basal Late Triassic evaporites, platform carbonates (Lias), and pelagic sequences (Jurassic–Eocene) enriched upward in terrigenous deposits (Paleogene) and flysch sequences (Miocene) (Figure 2).

The tectonic evolution of the Northern Apennines is characterized by the progressive migration of the orogenic front toward the Adriatic foreland, which is marked by the onset of siliciclastic deposits, which get progressively younger toward the Adriatic foreland. The onset of siliciclastic deposition in Northern Apennines occurred during Late Cretaceous in the oceanic Ligurian domain [*Treves, 1984; Carmignani et al., 1994*]. From Oligocene onward, foredeep basins migrated eastward and formed on top of sedimentary sequences belonging to the continental passive margin of Apulia (Figure 2). The incorporation of these two basins into the Apennines orogenic wedge marked the subduction of Adriatic continental lithosphere underneath Europe. During the Neogene, foredeep basins further moved toward the Apulia foreland in front of the migrating thrust nappes, as a consequence of eastward flexural retreat of the subducting Adriatic lithosphere [*Patacca et al., 1992*]. This process was particularly severe during Plio-Pleistocene times as evidenced by the presence, in the external part of the Apennines chain, of a foredeep basin system, which contains up to 8 km of Pliocene–Quaternary sedimentary rocks [*Royden et al., 1987*].

Classical interpretation of the internal sector of the Northern Apennines, characterized by crustal thinning, high heat flow and upraise of magmatic bodies, refers its evolution to an extensional tectonic regime developed since the middle Miocene in response to the back-arc Tyrrhenian basin development [*Jolivet et al., 1998; Collettini et al., 2006*, and references therein]. However, other authors suggested a more complex tectono-sedimentary evolution of this sector, suggesting compressional deformation affecting postorogenic sedimentary basins [*Boccaletti et al., 1999; Bonini et al., 1999; Bonini and Sani, 2002*]. In this interpretation the extensional tectonics currently affecting the basin fill developed later, since normal faults dissected the previous structures and did not control basin sedimentation. Active tectonic regime is represented by NW-SE trending normal faults, with a well-documented historical and recent seismicity, mostly located in the internal sector of the Umbria-Marche-Romagna region, at the edges of intramontane sedimentary basins (among others) [*Chiaraluca et al., 2004; Sani et al., 2009; Barchi and Ciaccio, 2009; Brozzetti et al., 2009*].

3. Paleomagnetic Sampling and Geological Setting of the Study Areas

In this study, paleomagnetic sampling was carried out in the internal sector of Northern Apennines. In particular, three main areas have been investigated: (1) the area around the Trasimeno Lake, (2) Chianti Mountains and Pratomagno area, and (3) the Val di Lima and Garfagnana area (Figure 1). Thirty-six sites were sampled (528 oriented cylindrical cores) using an ASC 280E petrol-powered portable drill with a water-cooled diamond bit. Cores were oriented in situ with a magnetic compass, corrected to account for a local $\sim 2^\circ$ E magnetic declination according to *Dominici et al. [2012]*.

3.1. Trasimeno Lake Area

This area is characterized by the presence of three major tectonic units, piled up during the Miocene. They are from west (top) to east (bottom): (i) the Ligurian units, consisting of Jurassic ophiolites; (ii) the Mount Cervarola-Falterona unit (Tuscan allochthon), an east verging imbricate thrust-stack made up of pelagites (Scaglia Toscana Formation) and siliciclastic turbidites (Macigno Formation) [*Plesi et al., 2002*]; and (iii) the Umbria unit, characterized by a Meso-Cenozoic carbonates succession followed by the foredeep turbidite succession of the Marnoso Arenacea Formation (early–middle Miocene) [*Mirabella et al., 2011*] (Figure 2).

Figure 2. Schematic stratigraphic sections and geometric relationships of the different tectonic units of Northern Apennines. TCF = Tuscan and Cervarola-Falterona units.

In this area, six sites (FT03, FT11–FT15) were sampled in the Scaglia Toscana Formation, consisting of calcareous marly turbidites and varicolored shales and marly shale layers (Ypresian-Lutetian). Moreover, seven sites (FT01, FT02, FT06–FT10) were sampled in the foredeep turbidite deposits of the upper part of the Macigno Formation, which consists of thick coarse-grained siliciclastic turbidites alternating with siliciclastic thin- and fine-grained beds (Aquitainian) (Figure 2).

Two continuous and well-exposed sections have been sampled in the Scaglia Toscana Formation (FT03 and FT15 sites). The first section is located in the Montanare Quarry north of Trasimeno Lake (site FT03 in Figure 1). The section is about 70 m thick and consists of alternating calcareous marls and marly shale layers. The lithofacies is characterized by limestone nut-brown strata, generally 5–40 cm thick with grey chert in nodules and lens. Forty-four samples were drilled throughout the sequence with a spacing ranging between 60 and 300 cm.

The second section is exposed south of the Trasimeno Lake, NW of Mount Solare in the Casilini Quarry (site FT15 in Figure 1). The section has a total thickness of about 50 m, and it is mainly made up of alternating calcareous and shale, marly shales layers, interbedded with thin varicolored shale and marly-shale. Fifty-three samples were drilled from calcareous strata, with an average sampling spacing ranging from 60 to 120 cm.

3.2. Chianti Mountains, Pratomagno, and Mugello Areas

The Chianti Mountains are mainly formed by Tuscan Nappe units forming an E-NE verging steeply to moderately dipping, overturned anticline, which exposes the Scaglia Toscana Formation (from Upper Cretaceous to lower Eocene members) at its core [Bonini *et al.*, 1999, 2012]. Referring to Sagri *et al.* [2012], the Tuscan Nappe in this sector overthrusts the more external Mount Cervarola-Falterona unit. The Falterona succession, cropping out in the Pratomagno Ridge, consists of Rupelian-Chattian varicolored clays alternating with mudstone layers (Villore Marls), followed by silicoclastic turbidites of the Falterona Formation, (Chattian-Burdigalian) [Bortolotti *et al.*, 2009]. The succession ends with thrust-top deposits of the Marne di Vicchio Formation mainly cropping out in the Mugello Basin area. This formation consists of gray marls and silty marls, interbedded by thin sandstone layers with calcareous component.

In this area four sites (FT16–FT19) were sampled in the pelagic and ramp deposits of the Scaglia Toscana Formation, five sites (FT20–FT24) were sampled in the foredeep turbidite deposits of the Falterona Formation, and three sites were taken from the Burdigalian thrust-top deposits of the Marne di Vicchio Formation (FT25–FT27) (Figure 1).

3.3. Val di Lima and Garfagnana

In the Val di Lima and Garfagnana areas the Tuscan Nappe Mesozoic units outcrop in the core of an east verging recumbent fold, intersected by NW-SE and E-W normal faults, which represent the tectonic boundary with the Oligocene siliciclastic turbidites (Macigno Formation) [Fazzuoli *et al.*, 1994, 1998]. The compressional deformation started in Eocene and culminated during late Oligocene–late Miocene, when the Ligurian unit thrust onto the more external domain and the Falda Toscana underwent internal imbrication [Boccaletti and Coli, 1982; Carmignani *et al.*, 1978].

In this area we sampled nine sites from the pelagic carbonates of the Scaglia Toscana Formation (Upper Cretaceous-Eocene). In Val di Lima three sites (FT28-FT29-FT30) were sampled in the Mesozoic core south of Lucchio village (LV in Figure 1) and one site (FT36) in the northernmost part of the Mesozoic core, whereas in the Garfagnana area three sites (FT33-34-35) were sampled in the Corfino Mesozoic core and two sites (FT31-32) were sampled near Sassorosso village (Figure 1, GF).

4. Paleomagnetic Methods and Results

Paleomagnetic and rock magnetic analyses were carried out at the paleomagnetic laboratory of the Istituto Nazionale di Geofisica e Vulcanologia (Rome, Italy). The natural remanent magnetization (NRM) of standard cylindrical specimens was measured using a 2-G Enterprises magnetometer equipped with DC superconducting quantum interference device coils within a magnetically shielded room. In order to identify the main magnetic minerals in the study sediments, we carried out a series of rock magnetic analyses on selected specimens representative of the different sampled units. The measurements included (1) Isothermal remanent magnetization (IRM) acquisition curves, carried out on 38 samples, and (2) stepwise thermal demagnetization of a three-component IRM [Lowrie, 1990], carried out on 58 samples. The IRM was analyzed

Figure 3. Results from magnetic mineralogy analyses. IRM acquisition curves showing the prevalence of (a) high-coercivity minerals in the Scaglia Toscana Formation and (b) of low-coercivity minerals in the Macigno, Falterona, and Marne di Vicchio Formations. Thermal demagnetization curves of a three-component (hard, medium, soft) IRM [Lowrie, 1990] are shown for Scaglia Toscana formation (Figures 3c–3e), Macigno Formation (Figure 3f), Cervarola-Falterona Formation (Figure 3g), and Marne di Vicchio Formation (Figure 3h).

by applying a stepwise increasing magnetic field (0–900 mT) along the z axis sample with a pulse magnetizer and by measuring the remanent magnetization after each step with a 2-G cryogenic magnetometer. The three-component IRM was produced by sequential application of pulsed magnetic fields of 2.7 T, 0.6 T, and 0.12 T along z, y, and x sample axes, respectively.

4.1. Magnetic Mineralogy

In the Scaglia Toscana Formation specimens, both low-coercivity and high-coercivity ferromagnetic minerals were identified. IRM curves show that most of the samples do not saturate at the maximum applied field (Figure 3a). For these samples, the maximum unblocking temperature of the intermediate- and high-coercivity IRM components is ~680°C indicating the presence of hematite (Figure 3c). Some specimens are almost saturated at 0.4 T (Figure 3a), indicating the occurrence of low-coercivity minerals. For these specimens, the maximum unblocking temperature of the IRM components is ~580°C or (rarely) 320°C, suggesting the presence of magnetite and (in rare cases) iron sulfides, respectively (Figures 3d and 3e). Some other samples show an intermediate behavior, suggesting the presence of both high- and low-coercivity minerals (Figure 3a).

The totality of the samples from Macigno Formation, Falterona Formation, and Marne di Vicchio Formation saturate at 0.3 T (Figure 3b), indicating that the high-coercivity minerals are not present in significant concentration in these sediments. The stepwise thermal demagnetization of a three-component IRM in these samples show that the low-coercivity component is removed at 580°C, suggesting that the magnetic mineralogy is dominated by magnetite (Figures 3f–3h).

4.2. Demagnetization of the Natural Remanent Magnetization and Vector Analysis

The natural remanent magnetization (NRM) of the studied samples was analyzed through both stepwise thermal and alternating field (AF) demagnetization. The NRM intensities range mostly between 2×10^{-5} and 6×10^{-3} A/m. Demagnetization diagrams indicate a stable paleomagnetic behavior, with vector end points aligned along linear paths directed toward the origin of orthogonal demagnetization diagrams, after the removal of a viscous low coercivity remanence component at 120°–180°C or 10–15 mT (Figure 4). However, some of the studied samples were too weakly magnetized (NRM values of about 1×10^{-5} A/m) to allow reliable complete stepwise demagnetization or gave unstable directions during stepwise demagnetization. Such samples were discarded from further analyses. Demagnetization data were plotted using orthogonal vector diagrams [Zijderveld, 1967] and the characteristic remanent magnetization (ChRM) was determined by principal component analysis [Kirschvink, 1980] for 292 specimens. Most of these specimens yield a maximum angular deviation (MAD) <15°. Of these, the 70% show a MAD <10°. All the samples yielding MAD >17° were rejected and not considered in further analyses.

Most of the Scaglia Toscana Formation samples are characterized by a stable magnetization component. The characteristic remanent magnetization was generally isolated at temperature ranging from 300°C to 650–700°C suggesting the presence of hematite as main magnetic carrier. These samples, generally, show a reverse polarity (Figures 4a–4c). In some samples the natural magnetization was completely demagnetized at 550–600°C, indicating the presence of magnetite (Figures 4d–4e). When AF treatment is used, these samples show a linear decay toward the origin up to 80–100 mT and do not show acquisition of a gyromagnetic remanent magnetization (GRM) at high AF (Figure 4j). Other few samples define a cluster of directions at temperatures higher than 320°C (Figure 4f). Samples from Macigno Formation, Falterona Formation, and Marne di Vicchio Formation were completely demagnetized both in the range 480–530°C and between 320 and 360°C, likely due to the presence of magnetite (Figures 4g and 4h) and iron sulfides (Figure 4i), respectively. In most of the AF demagnetized samples from the Macigno Formation, the ChRM was completely demagnetized at 60–80 mT (Figure 4k), whereas few samples show the acquisition of a gyromagnetic remanence at AF peaks higher than 30 mT, suggesting the presence of iron sulfides, as greigite (Figure 4l) [Snowball, 1997; Sagnotti and Winkler, 1999; Stephenson and Snowball, 2001].

4.3. Paleomagnetic Mean Directions

Site mean directions and relative statistics parameters are listed in Table 1. The obtained ChRM directions were analyzed using Fisher's [1953] statistic. In 17 sites the data are too dispersed to determine a well-defined ChRM. In 15 sites the mean directions are well defined ($\alpha_{95} < 15^\circ$), whereas in four sites the scattering of the data allows only a rough estimate of the ChRM orientation, with α_{95} values between 16° and 24.5°. Paleomagnetic rotations for each site and for each sampled areas were evaluated by comparing paleomagnetic direction to coeval expected directions calculated for African poles from Besse and Courtillot [2002] as the Tuscan Nappe units were deposited onto the Adriatic lithosphere, and African poles are routinely used as proxy of Adria poles [e.g., Van der Voo, 1993; Channell, 1996; Channell et al., 1992; Muttoni et al., 2001]. Rotation values and associated 95% confidence limits were calculated according to the method of Demarest [1983] and are reported in Table 1.

4.3.1. Trasimeno Lake Area

In the area around the Trasimeno Lake (Figure 1. area 1), reliable paleomagnetic results have been obtained from eight out of the 15 sampled sites. Sites from Scaglia Toscana Formation show reverse polarity (FT12, FT15) and both normal and reverse polarities (FT03). Sites from Macigno Formation show both normal (FT02, FT07, FT09, FT10) and reverse polarities (FT01) (Table 1). In all the sites from Macigno and Scaglia Formations, the ChRM directions are strongly deviated CCW respect to the expected geocentric axial dipole (GAD) magnetic field for normal and reverse polarity, despite their different age and magnetic mineralogy. It is worth to note that in site FT03 the normal and reverse polarities are not antipodal (negative bootstrap reversal test of Tauxe et al. [1991]; Figure 5a), bearing the reverse polarity directions a larger amount of CCW

Figure 4. Orthogonal vector diagrams (after tectonic correction) for the progressive (a–i) thermal demagnetization and (j–n) AF of representative samples. Demagnetization step values are in degrees Celsius and mT, respectively. Open and solid symbols represent projection on the vertical and horizontal planes, respectively.

Table 1. Paleomagnetic Directions and Rotations From TCF Units^a

Site	Coordinates (Latitude-Longitude)	Lithology	Formation	Age	n/N	S ₀	D _{BTC}	I _{BTC}	k _{BTC}	α _{95BTC}	D _{ATC}	I _{ATC}	k _{ATC}	α _{95ATC}	Rotation (± Error)	Flattening (± Error)
<i>Trasimeno Lake Area: Scaglia Toscana Formation</i>																
FT03	r/n 43° 14' 32.3'; 12° 04' 54.9'	Mudstone	Scaglia Toscana	Eocene	29/45	229, 26	322.0	53.5	22.6	5.8	290.4	47.4	22.6	5.8	-67.7 (8.2)	4.4 (6.3)
r	16/45						131.1	-60.8	30.5	6.6	96.5	-49.1	34.6	6.4	-81.6 (9.0)	2.7 (6.6)
n	13/45						331.1	43.6	35.0	7.1	305.8	43.3	35.0	7.1	-52.3 (9.0)	8.5 (7.0)
FT12	43° 04' 17.7'; 12° 11' 22.6'	Mudstone	Scaglia Toscana	Eocene	6/16	245, 43	87.1	-60.4	28.3	12.8	76.3	-18.9	28.3	12.8	-103.1 (11.8)	33.5 (11.1)
FT15	43° 02' 38.7'; 12° 08' 52.7'	Mudstone	Scaglia Toscana	Eocene	34/68	220, 79	182.3	-68.8	20.5	5.6	80.5	-27.9	20.5	5.6	-97.6 (6.9)	23.7 (6.2)
Mean					3		314.1	65.7	13.7	34.7	266.8	32.2	15.3	32.6	-91.3 ± 31.2	19.5 ± 25.8
<i>Trasimeno Lake Area: Macigno Formation</i>																
FT01	43° 20' 48.3'; 12° 02' 09.2'	Sandstone-	Macigno	Aquitanian	8/14	263, 42	76.7	-75.6	24.7	11.4	81.2	-33.2	24.7	11.4	-103.6 (11.6)	21.5 (9.5)
		Limestone														
FT02	43° 14' 49.4'; 12° 06' 28.1'	Sandstone-	Macigno	Aquitanian	8/11	246, 30	351.5	42.8	15.3	14.6	322.5	43.4	15.3	14.6	-42.4 (16.4)	11.8 (11.9)
		Limestone														
FT07	43° 17' 57.2'; 12° 02' 30.4'	Sandstone-	Macigno	Aquitanian	7/13	235, 30	336.7	35.1	29.8	11.2	314.8	35.5	29.8	11.2	-49.7 (12.5)	19.7 (11.6)
		Limestone														
FT09	43° 27' 34.6'; 12° 08' 12.2'	Mudstone	Macigno	Aquitanian	11/14	230, 21	332.6	50.5	11.3	14.2	306.7	50.3	11.3	14.2	-57.8 (18.1)	5.09 (10.1)
FT10	43° 27' 46.8'; 12° 07' 40.3'	Mudstone	Macigno	Aquitanian	10/15	160, 11	314.6	41.6	16.1	12.4	309.1	51.3	16.1	12.4	-55.4 (16.2)	4.09 (10.3)
Mean					5		329.1	51.4	12.6	22.4	302.4	45.1	16.8	19.2	-62.1 ± 22.1	10.2 ± 15.4
<i>Mount Chianti Area: Scaglia Toscana Formation</i>																
FT16	43° 32' 19.8'; 11° 24' 32.9'	Mudstone	Scaglia Toscana	Eocene-	7/8	248, 09	66.2	-60.2	24.2	12.5	66.6	-51.2	24.2	12.5	-111.3 (16.5)	0.9 (10.7)
				Oligocene												
FT17	43° 35' 58.2'; 11° 22' 02.1'	Mudstone	Scaglia Toscana	Eocene-	9/10	73, 17	297.8	6.5	40.6	8.2	300.5	18.3	40.4	8.2	-57.4 (8.3)	33.9 (7.71)
				Oligocene												
FT18	43° 36' 09.0'; 11° 22' 21.2'	Mudstone	Scaglia Toscana	Eocene-	6/7	24, 23	259.6	37.3	10.8	21.3	278.9	47.2	10.8	21.3	-79.0 (25.7)	5.0 (10.3)
				Oligocene												
FT19	43° 32' 06.3'; 11° 22' 41.0'	Mudstone	Scaglia Toscana	Eocene-	7/7	220, 22	325.3	64.2	31.8	10.9	281.1	61.4	31.9	10.9	-55.4 (16.2)	4.1 (17.2)
				Oligocene												
Mean					4		281.4	45.9	5.6	42.7	279.6	46.5	11.2	28.8	-81.3 ± 34.9	5.4 ± 22.9
<i>Garfagnana and Val di Lima Area: Scaglia Toscana Formation</i>																
FT28 ^c	44° 01' 53.1'; 10° 43' 04.1'	Mudstone	Scaglia Toscana	Middle Eocene	8/9	28, 50 ^b	160.0	-69.6	12.7	16.7	191.4	-25.0	12.7	16.2	25.9 (14.3)	4.1 (10.3)
FT30	44° 01' 14.9'; 10° 43' 07.2'	Mudstone	Scaglia Toscana	U. Cretaceous-	8/9	283, 22	157.8	-46.2	50.2	7.9	144.4	-31.3	50.3	7.9	-21.1 (7.9)	17.4 (7.0)
				Paleocene												
FT31	44° 10' 52.6'; 10° 24' 28.6'	Mudstone	Scaglia Toscana	U. Cretaceous-	10/11	211, 31 ^b	138.5	-19.4	31.1	8.8	125.6	-25.5	31.1	8.8	-39.8 (8.3)	23.4 (7.6)
				Paleocene												
FT33	44° 11' 02.5'; 10° 24' 17.0'	Mudstone	Scaglia Toscana	U. Cretaceous-	9	263, 37 ^b	165.3	-71.4	36.5	8.6	110.7	-47.0	36.5	8.6	-54.7 (10.4)	2.0 (7.4)
				Paleocene												
FT34	44° 12' 50.5'; 10° 22' 19.6'	Mudstone	Scaglia Toscana	U. Cretaceous-	10/10	283, 36 ^b	161.3	-63.9	24.7	9.9	130.7	-36.2	24.7	9.9	-34.7 (10.1)	12.8 (8.4)
				Paleocene												
FT35 ^c	44° 12' 44.9'; 10° 24' 43.1'	Mudstone	Scaglia Toscana	U. Cretaceous-	10/10	39, 29 ^b	86.3	13.3	9.4	16.6	85.1	-6.8	9.4	16.6	-80.3 (13.4)	42.1 (13.3)
				Paleocene												
FT36 ^c	44° 04' 27.8'; 10° 35' 28.5'	Mudstone	Scaglia Toscana	Middle Eocene	9	284, 26 ^b	61.4	6.7	5.4	24.5	56.0	25.2	5.4	24.5	58.2 (21.8)	27.5 (19.6)
Mean					4		151.9	-51.0	11.2	28.7	128.7	-35.6	32.4	16.4	-36.7 ± 16.1	13.3 ± 13.2

^aThe n/N number of great circles/total number of studied samples at a site; D and I are site-mean declinations and inclinations calculated before (D_{BTC}, I_{BTC}) and after (D_{ATC}, I_{ATC}) tectonic correction; k and α₉₅ are statistical parameters after Fisher (1953); S₀ is bedding attitude (azimuth of the dip and dip values).

^bDeduced by anisotropy of magnetic susceptibility orientation; r/n indicates sites characterized both by samples with reversal and normal polarity.

^cSites not considered in further tectonic interpretation.

Figure 5. (a) Equal area projection of sample characteristic remanent magnetization (ChRM) directions and 95% confidence ellipse from the FT03 site. Full (empty) circles represent projection on the lower (upper) hemisphere. (b) Bootstraps reversal test. The graphics represent the cumulative distribution of Cartesian coordinates of data represented in Figure 5a. The reverse polarity mode has been flipped to its antipode. The intervals containing 95% level of confidence of each set of components are also drawn (vertical line). The bootstraps reversal test [Tauxe *et al.*, 1991] is negative, as the 95% confidence intervals for the normal and reverse antipodes, overlap for Y and Z but not for X.

rotation (Figure 5b and Table 1). This suggests that in this site data population is affected by a recent magnetic overprint that was not completely removed during stepwise demagnetization. On this basis the paleomagnetic rotation calculated for site FT03 has to be considered as a minimum value of rotation as the ChRM directions are deflected toward the north by a recent magnetic overprint. When we consider together results from the three sites from Scaglia Toscana Formation, with all site directions flipped to normal polarity, the mean paleomagnetic direction after tectonic correction is $D = 266.8^\circ$, $I = 32.2^\circ$ ($k = 15.3$, $\alpha_{95\%} = 32.6$), in normal polarity coordinates. This mean direction is better grouped than before tectonic correction ($D = 314.1^\circ$, $I = 65.7^\circ$, $k = 13.7$, $\alpha_{95\%} = 34.7$), although the bootstrap fold test [Tauxe *et al.*, 1991] is inconclusive. We also note that before tectonic correction the mean paleomagnetic direction is far from the geocentric axial dipole (GAD) magnetic field expected for the sampling localities (Figure 6a). Both these observations strongly suggest that the isolated ChRM for the Scaglia Toscana Formation has been acquired before folding and is probably of primary (syndepositional) origin. When the mean ChRM direction is compared with the direction expected at the sampling site from the coeval (45 Ma) African paleopole (λ ($^\circ$ N) = 79.1 ; φ ($^\circ$ E) = 200.6 , $A_{95} = 5.2$) a mean value of $91.3^\circ \pm 31.2^\circ$ counterclockwise (CCW) rotation ($F = 19.5 \pm 25.8$) is obtained.

The site mean ChRM direction for the five Macigno Formation sites is also better grouped after ($D = 302.4^\circ$, $I = 45.1^\circ$, $k = 16.8$, $\alpha_{95\%} = 19.2$) than before tectonic correction ($D = 329.1^\circ$, $I = 51.4^\circ$, $k = 12.6$, $\alpha_{95\%} = 22.4$) (Figure 6c and Table 1). In this case the bootstrap fold test [Tauxe *et al.*, 1991] is positive, showing that the degree of unfolding to produce the maximum τ_1 is included between 49 and 97% (Figure 6b), suggesting that the ChRM for the Macigno Formation has been acquired before folding and that directions can be used for tectonic interpretations. When the mean ChRM direction for the Macigno Formation sites is compared with that expected from the coeval (20 Ma) African paleopole (λ ($^\circ$ N) = 81.7 ; φ ($^\circ$ E) = 165.7 , $A_{95} = 4.5$), the value of rotation is $62.1^\circ \pm 22.1^\circ$ CCW ($F = 10.2 \pm 15.4$).

4.3.2. Chianti Mountains and Pratomagno Areas

In the Chianti Mountains and Pratomagno areas reliable paleomagnetic results have been obtained from all the four sampled sites from the Scaglia Toscana Formation, whereas the seven sites from Falterona and Marne di Vicchio Formations did not give reliable results. In the Scaglia Toscana Formation, one site (FT16) shows a reverse polarity, one site has a normal polarity (FT17) and two sites have both normal and reverse polarity components (FT18, FT19). In all the sites the ChRM directions are strongly deviated CCW respect to the expected GAD magnetic field. If we consider together the sites with reverse and normal polarities, the site-mean directions are better grouped after ($D = 279.6^\circ$, $I = 46.5^\circ$, $K = 11.2$, $\alpha_{95\%} = 28.8$), than before tectonic correction ($D = 281.4^\circ$, $I = 45.9^\circ$, $K = 5.6$, $\alpha_{95\%} = 42.7$) (Table 1 and Figure 6e). The bootstrap fold test [Tauxe *et al.*, 1991] is positive showing that the degree of unfolding to produce the maximum τ_1 is included between 120 and 149 % (Figure 6d). These results suggest a primary origin for ChRM for the Scaglia Toscana Formation in the Chianti area allowing using the obtained directions for tectonic interpretations. When the mean ChRM

Figure 6. Equal area projection of the site-mean directions from (a, c) Scaglia Toscana Formation and Macigno Formation of Trasimeno Lake area, (e) from Scaglia Toscana Formation of Mount Chianti and Pratomagno area, and (f) from Scaglia Toscana Formation of the Val di Lima and Garfagnana area. White and black symbols represent projection onto upper and lower hemisphere, respectively. Ellipses are the projections of the α_{95} cone about the mean directions (the star is the mean for the area and the dotted ellipse the related α_{95} cone projection). Bootstrap fold tests (b) for Macigno Formation of Trasimeno Lake area, (d) for Scaglia Toscana Formation of Mount Chianti and Pratomagno area, and (f) for Scaglia Toscana Formation of the Val di Lima and Garfagnana area. Red dashed lines: trends of the largest eigenvalues (τ_1 s) of the orientation matrices from representative data as they evolve during untilting. The directions are adjusted for tilt incrementally from -20% to 160% .

direction is compared with the direction expected at the sampling site from the coeval (45 Ma) African paleopole (λ (°N) = 79.1°; φ (°E) = 200.6°, A_{95} = 5.2), the rotation is $R = -81.3^\circ \pm 34.9^\circ$ ($F = 5.4 \pm 22.9$) (Table 1).

4.3.3. Val di Lima and Garfagnana Areas

In the Val di Lima and Garfagnana areas, well-defined directions have been obtained from seven out of the eight sampled sites from Scaglia Toscana Formation. All the sites have a reverse polarity, except site FT36 that has a normal polarity. Among the seven sites, four (FT30–31, FT33–34) show very well defined mean site directions ($\alpha_{95} < 10.0^\circ$) and are consistently rotated CCW. Conversely the other three sites (FT28, FT35, and FT36) show poorly defined site mean directions ($\alpha_{95} > 16.2^\circ$), which are far from the other four sites, being rotated clockwise (CW) (FT28 and FT36) or showing very large amount of CCW rotations (FT35) (Table 1). For these reasons, these sites have been not further considered for tectonic interpretations.

For the four sites we consider, the mean site direction is better grouped after ($D = 128.7^\circ$, $I = -35.6^\circ$, $K = 32.3$, $\alpha_{95\%} = 16.4$) than before ($D = 151.9^\circ$, $I = -51.0^\circ$, $K = 11.2$, $\alpha_{95\%} = 28.7$) tectonic correction (Figure 6g), and the bootstrap fold test [Tauxe *et al.*, 1991] is positive (Figure 6f), suggesting that the ChRM has a primary (syndimentary) origin. When the mean paleomagnetic directions are compared with the directions computed from the African paleopole at 65 Ma (λ (°N) = 71.6°; φ (°E) = 234.2°, A_{95} = 3.6), a rotation $R = -36.7^\circ \pm 16.1^\circ$ ($F = 13.3 \pm 13.2$) is obtained (Table 1).

5. Discussion

5.1. Distribution of Paleomagnetic Rotations Along the Northern Apennines Arc

Paleomagnetic rotations calculated for each site are reported in Figure 7a, together with the overall set of paleomagnetic rotations already published in Northern Apennines and recalculated by Cifelli and Mattei [2010]. The complete paleomagnetic data set is analyzed and discussed taking into account the spatial distribution of paleomagnetic declinations along the length of the arc and along two different profiles oriented orthogonal to the main structural axes of the chain (Figures 7b and 7c). We then compare the amount of rotation displayed by paleomagnetic declinations with the change in strike of the structural trends (oroclinal test according to Schwartz and Van der Voo [1983]).

Three different rotational domains can be recognized from the external toward the internal portion of the arc. The first domain is represented by the external sector of the Northern Apennines, where a large amount of paleomagnetic data has been collected from the Oligocene–lower Miocene Epiligurian units, the Jurassic–Oligocene Umbria–Marche domain and the upper Miocene–lower Pliocene Umbria–Marche foredeep units. Along this sector of the arc, a progressive increase of CCW paleomagnetic rotations can be observed moving from the north-south oriented southern portion of the arc, toward the WNW-ESE oriented, northern sector of the arc, where up to 52° of CCW rotations have been measured in the Oligocene–lower Miocene Epiligurian units [Muttoni *et al.*, 1998]. The second sector is represented by the TCF units, which form the more internal domain of the Northern Apennines. In this area our results confirm the general trend of CCW rotations already measured in preorogenic and synorogenic units from the external Northern Apennines. However, the distribution of CCW rotation in the internal units shows a peculiar trend in comparison with data from the more external sector of the chain. In fact, in the Tuscan Domain units, the amount of CCW vertical axis rotations decreases from the southern sector of the arc (Trasimeno Lake and Chianti-Pratomagno areas), where we have measured a very large amount of CCW rotations in the Eocene Scaglia Toscana Formation ($R = -91.3^\circ \pm 31.2^\circ$ and $R = -81.3^\circ \pm 34.9^\circ$, respectively) and in the lower Miocene Macigno Formation ($R = -62.1^\circ \pm 22.1^\circ$), toward the northern part of the arc (Val di Lima area), where the mean rotation is $R = -36.7^\circ \pm 16.1^\circ$ (Table 1). The third sector is represented by the western Tyrrhenian margin, where the upper Miocene–lower Pleistocene postorogenic units show no significant vertical axis rotations [Mattei *et al.*, 1996].

Paleomagnetic rotations along two profiles orthogonal to the main structural trend of the arc were projected in order to analyze the distribution of paleomagnetic rotations from the internal to the external sectors of the Northern Apennines (Figures 7b and 7c), assuming that moving away from the Tyrrhenian coast to the east we progressively move from the more internal deformed sectors of the chain to the more external and less deformed ones. In the southern profile, CCW rotations measured in the orogenic units decrease significantly from the internal to the external sector of the chain (Figure 7c). In particular, whereas CCW rotations up to 100° have been measured in the Tuscan domain in the Trasimeno Lake and Chianti areas, CCW rotations

Figure 7. (a) Paleomagnetic declinations and relative confidence limits from this study and from previous published results on the Tuscan Nappe. Rotations and confidence limits were calculated by comparing paleodirections to the coeval reference directions from the coeval expected African paleopole from Besse and Courtillot [2002] according to Demarest [1983]. (b) Paleomagnetic declinations north of line A were projected along this line, whereas (c) paleomagnetic declinations south of line A were projected along line B.

measured in the more external Umbria-Marche units decrease to about 20°. These different paleomagnetic rotations are not related to the different age of the sampled sequences, as both preorogenic and synorogenic units are systematically more rotated CCW in the TCF than in the Umbria-Marche units. On the other side, the boundary between these two different rotational domains is very sharp and corresponds with the tectonic boundary between the TCF and the Umbria-Marche units, suggesting that the larger amount of CCW rotations measured in the TCF units could be related to a geodynamic event that does not involve the more external units of the Northern Apennines. This event occurred before the upper Miocene as the post orogenic units of the western Tyrrhenian margin are not rotated.

Figure 8. Oroclinal test for the Tuscan Nappe considering rotations directly compared with (a) bedding strike direction at each site, and (b) the fold axis direction for each site, deduced by AMS analyses. Dashed line represents a regression line of our data; m represents the angular coefficient of the correlation between rotation and bedding strike or fold axes.

In the northern profile (Figure 7b) we observe a different distribution of paleomagnetic rotations with respect to the southern one. In fact, the different tectonic units of the Apennine orogenic wedge show a comparable amount of paleomagnetic rotations, which is on average between 25° and 50° CCW. In particular, with regards to the internal TCF units, we measured a mean paleomagnetic rotation of about 35° CCW, which is comparable with the amount of CCW rotation measured in the middle Jurassic units of the Tuscan Nappe [Aiello and Hagstrum, 2001] and is similar to the paleomagnetic rotations measured in Oligocene to Miocene sites from the Epiligurian units (about 50° CCW) and from the upper Miocene sites from the more external Umbria-Marche units (about 35° CCW). Also in this area paleomagnetic results collected from the western Tyrrhenian margin of Northern Apennines prove that CCW paleomagnetic rotations measured in the internal sector of the chain occurred before late Miocene.

5.2. The Oroclinal Bending of the Northern Apennines

The origin of the Northern Apennine Arc has been debated since Channell *et al.*

[1978] observed that the increase in CCW rotations measured in the Cretaceous-Eocene “Scaglia” Formation, from southern toward northern Umbria, probably reflected the oroclinal bending of an originally straight fold belt. This mechanism was first confirmed [Eldredge *et al.*, 1985] and then rejected [Van der Voo and Channell, 1980; Lowrie and Hirt, 1986; Hirt and Lowrie, 1988] on the basis of different data sets from Mesozoic–lower Tertiary sediments in the Umbria-Marche domain of the chain. Later on, from the study of Messinian foredeep sediments of the external Umbria-Marche domain, Speranza *et al.* [1997] indicated that the present-day shape of the external part of the Northern Apennines Arc is related to the oroclinal bending of an originally N320° trending straight belt. These authors suggested that vertical axis rotations accompanied the migration of the main thrust front toward the Adriatic foreland and characterized also the development of second-order curved thrust fronts in the Apennines. In order to test a possible oroclinal origin for the curved shape of the TCF unit structures, we carried out an oroclinal test based on results from this work (Figure 8). The relationship between paleomagnetic declinations and structural directions was investigated using the method originally proposed by Schwartz and Van der Voo [1983] for the Appalachians and later applied in different curved orogenic systems, including the Northern Apennines [Eldredge *et al.*, 1985; Lowrie and Hirt, 1986; Speranza *et al.*, 1997]. The reference rotation is $R_r = 315^\circ$, as most of our results show large counterclockwise rotations, and the reference structural direction is $S_r = 315^\circ$, representative of the main orientation of the Northern Apennines tectonic structures. It is worth noting that the chosen references values (declinations and structural directions) are not critical for this type of diagram, but it is important that this value is kept constant in the analysis. As site structural direction (that must be considered as axis of the thrust-related folds in the Tuscan units) we used the direction of the bedding strike (Figure 8a) or the mean direction of the magnetic lineation of tectonic origin observed by AMS data (Figure 8b), according to Speranza *et al.*, (1997).

The oroclinal test calculated for the Cretaceous-Eocene Scaglia Toscana Formation shows that paleomagnetic rotation and bedding strike orientation are poorly correlated ($r^2 = 0.21$) (Figure 8a). The quality of the correlation decreases even more ($r^2 = 0.01$) if we calculate paleomagnetic rotation versus fold axis orientation

Figure 9. Schematic cartoon of the tectonic evolution of the Northern Apennines with different stages of drifting and rotation of the Corsica-Sardinia block. LD = Ligurian domain; TD = Tuscan domain; UD = Umbrian domain. (GR = Garfagnana area; CH = Chianti Mountains; TL = Trasimeno Lake).

(Figure 8b). Furthermore, the t test calculated comparing our results with the data distribution for zero slope gives negative results both at the 99% and 95% level of confidence. In both cases the t value is 0.27. These results indicate that the oroclinal test is negative and that there is no significant correlation between the orientation of tectonic structures and the measured paleomagnetic rotations. Therefore a different model is required to explain the distribution of paleomagnetic rotations in the Tuscan units.

5.3. Paleomagnetic Rotations of the Northern Apennines in the Framework of Cenozoic Evolution of the Central Mediterranean

Paleomagnetic results from the internal Tuscan units of the Northern Apennines show a distribution of CCW rotations along the arc that cannot be explained using the oroclinal bending model, which has been successfully proposed for the evolution of the external portion of the arc [Speranza *et al.*, 1997]. On this base we propose a different model to explain the distribution of paleomagnetic rotation in the internal part of the Northern Apennines, which integrates in a single evolutionary model the Oligo-Miocene drifting and CCW rotation of the Corsica-Sardinia block and the curvature of the Northern Apennines Arc (Figure 9). The tectonic model takes into account (1) the predrift paleogeography of the Corsica-Sardinia block, (2) the timing of deformation of the different tectonic units of Northern Apennines, (3) the overall paleomagnetic data from Northern Apennines, and in particular, the very large amount of CCW rotations measured in the southern portion of the TCF units, when compared to the more external Umbria-Marche units.

The paleogeography of the Northern Apennines and Corsica-Sardinia block at the predrift stage (Chattian) is shown in Figure 9a. At that time the more internal units (Ligurian oceanic domain), which were incorporated in the Apennine chain during the Late Cretaceous, formed a double verging orogenic wedge, related to northeastward subduction of the Adriatic-Ionian lithosphere. The proposed position of the Corsica-Sardinia block, located adjacent to southern France, was originally suggested by Argand [1924] and has been later confirmed by a large amount of geological, geophysical, and paleomagnetic evidences [De Jong and Manzoni, 1968; De Jong *et al.*, 1969; Zijdeveld *et al.*, 1970; Alvarez, 1972; Alvarez *et al.*, 1973; De Jong *et al.*, 1973; Westphal *et al.*, 1973; Montigny *et al.*, 1981; Burrus, 1984; Edel, 1980; Vigliotti *et al.*, 1990; Speranza *et al.*, 2002; Gattacceca *et al.*, 2007].

The Oligocene–lower Miocene drifting and CCW rotation of the Corsica-Sardinia block, and its influence on Northern Apennines units, are shown in Figures 9b and 9c. In this reconstruction the paleogeography of the Corsica-Sardinia block and the precise timing and amount of CCW rotations have been defined by the recent paleomagnetic results [Gattacceca *et al.*, 2007]. These authors, on the basis of integrated paleomagnetic and geochronology investigations of Miocene volcanic sequences, have proven that 45° CCW rotation with respect to stable Europe occurred after 21 Myr (Aquitainian), of which 30° CCW rotation occurred between 20.5 and 18 Myr, during the maximum volcanic events in Sardinia. At the same time, paleomagnetic analyses from sedimentary units from Corsica and from volcanic successions in Sardinia concur to demonstrate that the rotation was completed around 15 Myr ago (Langhian) [Vigliotti and Kent, 1990; Speranza *et al.*, 2002; Gattacceca *et al.*, 2007]. These results are fully compatible with a predrift palinspastic reconstruction where the Corsica-Sardinia block is located adjacent to the coast of Southern France (Figure 9a), as deduced from morphological fit of the continental margins, oceanic crust extension defined by tectonic subsidence analysis [Pasquale *et al.*, 1995], and compatible with 3-D gravity inversion [Chamot-Rooke *et al.*, 1999], and define a rotation pole during the drifting of the Corsica-Sardinia block located in the Ligurian Sea around 43.5°N, 9.5°E. [Gattacceca *et al.*, 2007]

The Corsica-Sardinia CCW rotation has been coeval with the incorporation of the Tuscan domain succession in the Apennine orogenic wedge (Figures 9a and 9b). Both these processes were induced by the westward subduction and eastward slab rollback of the Adriatic-Ionian lithosphere. During the early Miocene the trench was located to the east of the TCF units, and this tectonic domain represented the external front of the Northern Apennines thrust and fold belt. Therefore, the TCF units, together with the Corsica-Sardinia block, formed the upper plate of the subducting system, while the Umbria-Marche units still represented the undeformed foreland domain. In this framework it appears reasonable that the CCW rotation of the Corsica-Sardinia block also extended to the TCF units, which was also located in the upper plate in the subducting system. In this tectonic interpretation, the Corsica-Sardinia CCW rotation was recorded only by the southern part of the TCF units (Trasimeno Lake and Chianti areas) that is in the area located to the south of the Corsica-Sardinia pole of rotation (43.5°N, 9.5°E) (Figures 9b and 9c). Conversely, the Northern Apennines units located to the north of the rotation pole (Val di Lima area) were not affected by this tectonic process and did not rotate. This interpretation explains the significant decreases of CCW rotations from the southern to the northern part of the TCF units. The significant difference in the amount of CCW rotation between the Tuscan and the Umbria Marche units also demonstrates that the latter were not involved in the Corsica-Sardinia rotation. This is not surprising as, during the lower Miocene, the Umbria-Marche units still represented the foreland of the Apennines orogeny and were located in the lower plate of the Adriatic-Ionian subducting system (Figures 9b and 9c). It is worth to note that the amount of Corsica-Sardinia CCW rotation (about 45–50°) is not enough to explain the entire CCW rotation measured in the Tuscan units (which reaches 80°–90°). Therefore, we suggest that, in analogy with what has been observed in the more external part of the northern Apennine, a portion of CCW rotations that we measured in the Tuscan units is related to local deformation and the stacking of Tuscan units over the Umbria-Marche domain during the early–middle Miocene. As a consequence, the huge CCW rotations ($\approx 80^\circ$ – 90°) measured in the southern part of the TCF units (Trasimeno Lake and Chianti Mountains) are related to two different processes: the Corsica-Sardinia CCW ($\approx 50^\circ$) and the curvature of the Apennine Arc ($\approx 30^\circ$ – 40°). The latter is also responsible of the entire CCW rotations measured in the northern TCF units (Val di Lima), which was not involved in the Corsica-Sardinia CCW rotation.

During the late Miocene and Pliocene vertical axis rotations accompanied thrust emplacement of the tectono-stratigraphic units located in the external sector of the Northern Apennines as a consequence of slab rollback of the subducting Adriatic lithosphere [Speranza *et al.*, 1997; Muttoni *et al.*, 1998] (Figure 9d). These rotations did not involve the internal Tuscan units. In fact the late Miocene-Pleistocene postorogenic sequences that deposited on top of the deformed internal Apennines units during the rifting of the Tyrrhenian Sea basin did not undergo vertical axis rotations [Sagnotti *et al.*, 1994; Mattei *et al.*, 1996] (Figure 9d).

6. Conclusions

The tectonic evolution of Central Mediterranean has been mainly characterized by two coeval processes, which occurred during the progressive slab rollback of the subducting Adriatic-Ionian lithosphere. These processes are the drifting and CCW rotation of the Corsica-Sardinia block and the progressive curvature of the Northern Apennines chain. Classically, these two events have been considered distinct and occurring at

different times, mostly because there was no paleomagnetic evidence of the Corsica-Sardinia CCW rotation in the Apenninic orogenic wedge. The new paleomagnetic data from the Tuscan and Cervarola-Falterona units, located in the internal portion of the Northern Apennines, provide the first paleomagnetic evidence of the link between the two processes and reveal a huge post-Eocene CCW rotation of approximately 90° with respect to the Adriatic foreland. We suggest that during the Corsica-Sardinia drifting the Northern Apennines orogenic wedge also rotated CCW, implying a coherent CCW rotation of the whole upper plate of the Central Mediterranean subduction system during the opening of the Liguro-Provençal Basin, in response to the Adriatic-Ionian subduction slab rollback. This scenario changed during the middle Miocene, with the end of the Corsica-Sardinia drifting and CCW rotation, when back-arc extensional processes were transferred to the Tyrrhenian Basin. Since that time the vertical axis rotations occurred in the external part of the Apennines orogenic wedge, which progressively acquired its present-day curvature as a consequence of the rollback of the subducting Adriatic slab. At the same time, the postorogenic basins located along the northern Tyrrhenian Basin did not rotate. The difference between the rotational patterns associated to the opening of the Liguro-Provençal and the northern Tyrrhenian Basins is probably related to their different style of lithospheric extension and back-arc opening. The evolution of the Liguro-Provençal Basin was characterized by drifting and oceanic crust spreading, with a large CCW rotation of the whole upper plate above the subducting lithosphere, whereas during the opening of the northern Tyrrhenian Sea the postorogenic basins developed without rotations and extensional tectonics never evolved from the rifting to the drifting stage.

Acknowledgments

We are grateful to F. Botti for the fruitful discussions on to Tuscan Nappe succession. Thanks also to A. Winkler for his help and useful suggestions during the laboratory phase and to S. Lucifora for her help during laboratory analyses. This research has been funded by Italian MIUR through Cofin_2010-2011 (project 2010TT22SC_003) grants.

References

- Aiello, I. W., and J. T. Hagstrum (2001), Paleomagnetism and paleogeography of Jurassic radiolarian cherts from the Northern Apennines of Italy, *Geol. Soc. Am. Bull.*, **113**, 469–481.
- Alvarez, W. (1972), Rotation of the Corsica-Sardinia microplate, *Nature*, **235**, 103–105.
- Alvarez, W., F. G. Franks, and A. E. M. Nairn (1973), Paleomagnetism of Plio-Pleistocene basalts from NW Sardinia, *Nature*, **243**, 10–11.
- Argand, E. (1924), *La Tectonique de l'Asie*, vol. 1, pp. 171–372 Extrait du Compte-rendu du XIIIe Congrès géologique international 1922, Liège.
- Barchi, M. R., A. De Feyter, B. Magnani, G. Minelli, G. Piali, and B. Sotera (1998a), The structural style of the Umbria-Marche fold and thrust belt, *Mem. Soc. Geol. Ital.*, **52**, 557–578.
- Barchi, M. R., A. De Feyter, B. Magnani, G. Minelli, G. Piali, and B. Sotera (1998b), Extensional tectonics in the Northern Apennines (Italy): Evidence from the CROP3 deep seismic reflection line, *Mem. Soc. Geol. Ital.*, **52**, 528–538.
- Barchi, M. R., and M. G. Ciccio (2009), Seismic images of an extensional basin, generated at the hanging-wall of a low-angle normal fault: The case of the Sansepolcro Basin (Central Italy), *Tectonophysics*, **479**, 285–293.
- Besse, J. and V. Courtillot (2002), Apparent and true polar wander and the geometry of the geomagnetic field over the last 200 Myr, *J. Geophys. Res.*, **107**(B11), 2300, doi:10.1029/2000JB000050.
- Boccaletti, M., M. Coli, F. A. Decandia, E. Giannini, and A. Lazzarotto (1980), Evoluzione dell'Appennino Settentrionale secondo un nuovo modello strutturale, *Mem. Soc. Geol. Ital.*, **21**, 359–373.
- Boccaletti, M. and M. Coli (1982), Carta strutturale dell'Appennino Settentrionale 1:250.000, CNR Progetto Finalizzato Geodinamica, SELCA, Firenze.
- Boccaletti, M., M. Bonini, G. Moratti, and F. Sani (1999), Compressive Neogene-Quaternary tectonics in the hinterland area of the Northern Apennines, *J. Pet. Geol.*, **22**, 37–60.
- Bonini, M., G. Moratti, and F. Sani (1999), Evolution and depocenter migration in thrust-top basins: Inferences from the Messinian Velona Basin (Northern Apennines, Italy), *Tectonophysics*, **304**, 95–108.
- Bonini, M. and F. Sani (2002), Extension and compression in the Northern Apennines (Italy) hinterland: Evidence from the Late Miocene-Pliocene Siena-Radicofani Basin and relations with basement structures, *Tectonics*, **21**(3), 1010, doi:10.1029/2001TC900024.
- Bonini, M., G. Moratti, F. Sani, and M. L. Balestrieri (2012), Compression-to-extension record in the late Pliocene-Pleistocene Upper Valdarno Basin (Northern Apennines, Italy): Structural and thermochronological constraints, *Ital. J. Geosci.*, **131**(1), 54–80, doi:10.3301/IJG.2011.18.
- Bortolotti, V., C. Poccianti, G. Principi, F. Sani, M. Benvenuti, R. Catanzariti, S. Moretti and V. Reale (2009), Note Illustrative della Carta Geologica d'Italia alla scala 1:50.000. Foglio 264 Borgo San Lorenzo, Servizio Geologico d'Italia, Roma, in press.
- Brozzetti, F., P. Boncio, G. La Vecchia, and B. Pace (2009), Present activity and seismogenic potential of a low-angle normal fault system (Citta' di Castello, Italy): Constraints from surface geology, seismic reflection data and seismicity, *Tectonophysics*, **463**, 31–46.
- Burrus, J. (1984), Contribution to a geodynamic synthesis of the Provençal Basin (north-western Mediterranean), *Mar. Geol.*, **55**, 247–269.
- Carmignani, L., G. Giglia, and R. Kligfield (1978), Structural evolution of the Apuane Alps: An example of continental margin deformation, *J. Geol.*, **86**, 487–504.
- Carmignani, L., R. Carosi, A. Di Pisa, M. Gattiglio, G. Musumeci, G. Oggiano, and P. C. Pertusati (1994), The Hercynian chain in Sardinia (Italy), *Geodinamica Acta*, **7**(1), 31–47.
- Channell, J. E. T. (1996), Paleomagnetism and paleogeography of Adria, in *Paleomagnetism and Tectonics of the Mediterranean Region*, Geological Society Special Publications, vol. 1, edited by A. Morris and D. H. Tarling, pp. 119–132, Geological Society of London, London.
- Channell, J. E. T., W. Lowrie, F. Medizza, and W. Alvarez (1978), Paleomagnetism and tectonics in Umbria Italy, *Earth Planet. Sci. Lett.*, **39**, 199–210.
- Channell, J. E. T., R. Brandner, A. Spieler, and J. S. Stoner (1992), Paleomagnetism and paleogeography of the Northern Calcareous Alps (Austria), *Tectonics*, **11**, 792–810.
- Chamot-Rooke N., J.-M. Gaulier, and F. Jestin (1999), Constraints on Moho depth and crustal thickness in the Liguro-Provençal Basin from a 3D gravity inversion: Geodynamic implications, in *The Mediterranean Basins: Tertiary Extension Within the Alpine Orogen*, Geological Society London Special Publications, vol. 156, edited by B. Durand et al. pp. 37–61, Geological Society, London.
- Chiaraluce, L., et al. (2004), Complex normal faulting in the Apennines thrust-and-fold belt: The 1997 seismic sequence in central Italy, *Bull. Seismol. Soc. Am.*, **94**, 99–116.

- Cifelli, F., M. Mattei, and F. Rossetti (2007), Tectonic evolution of arcuate mountain belts on top of a retreating subduction slab: The example of the Calabrian Arc, *J. Geophys. Res.*, **112**, B09101, doi:10.1029/2006JB004848.
- Cifelli, F., M. Mattei, and M. Della Seta (2008), Calabrian Arc oroclinal bending: The role of subduction, *Tectonics*, **27**, TC5001, doi:10.1029/2008TC002272.
- Cifelli, F. and M. Mattei (2010), Curved orogenic systems in the Italian Peninsula: A paleomagnetic review, in *The Geology of Italy: Tectonics and Life Along Plate Margins*, vol. 36 edited by M. Beltrando, et al., 17pp. Journal of the Virtual Explorer, Roma, Italy doi:10.3809/jvirtex.2010.00239.
- Collettini, C., N. De Paola, H. R. Holdsworth, and M. R. Barchi (2006), The development and behaviour of low-angle normal faults during Cenozoic asymmetric extension in the Northern Apennines Italy, *J. Struct. Geol.*, **28**, 333–352.
- De Jong, K. A., and M. Manzoni (1968), Paleomagnetismo e cronologia delle collate basaltiche di orosei, *Boll. Soc. Geol. Ital.*, **87**, 713–717.
- De Jong, K. A., M. Manzoni, and J. D. A. Zijderfeld (1969), Paleomagnetism of the Alghero Trachyandesites, *Nature*, **224**, 67–69.
- De Jong, K. A., M. Manzoni, T. Stavenga, F. Van Dijk, R. Van der Voo, and J. D. A. Zijderfeld (1973), Palaeomagnetic evidence for rotation of Sardinia during the early Miocene, *Nature*, **243**, 281–283.
- Demarest, H. H. (1983), Error analysis for the determination of tectonic rotation from paleomagnetic data, *J. Geophys. Res.*, **88**, 4321–4328.
- Dominici, G., A. Meloni, A. Di Ponzio and M. Miconi (2012), Italian Magnetic Network and magnetic reference fields at 2010.0, *Ann. Geophys.*, **55**(6), 2012; doi:10.4401/ag-5411.
- Edel, J. B. (1980), Etude paléomagnétique en Sardaigne. Conséquences pour la géodynamique de la Méditerranée occidentale, PhD thesis, Institut de Physique du Globe, Université Louis Pasteur, Strasbourg (France).
- Eldredge, S., V. Bachtadse, and V. Van der Voo (1985), Paleomagnetism and the orocline hypothesis, *Tectonophysics*, **119**, 153–179.
- Elter, P. (1975), L'ensemble ligure, *Bull. Soc. Geol. Fr.*, **17**, 984–997.
- Faccenna, C., C. Piromallo, A. Crespo-Blanc, L. Jolivet, and F. Rossetti (2004), Lateral slab deformation and the origin of the western Mediterranean Arcs, *Tectonics*, **23**, TC1012, doi:10.1029/2002TC001488.
- Fazzuoli, M., S. Becarelli, G. Burchietti, G. Ferrini, C. A. Garzonio, G. Mannori, F. Sani, and G. Sguazzoni (1994), A short outline of the geology of the Mesozoic inlier in the Lima Valley Northern Apennines, *Mem. Soc. Geol. Ital.*, **48**, 79–85.
- Fazzuoli, M., et al. (1998), Geologia del nucleo mesozoico della Val di Lima (province Pistoia e Lucca, Appennino Settentrionale), Note illustrative della carta geologica (scala 1:25.000), *Boll. Soc. Geol. Ital.*, **117**, 479–535.
- Fisher, R. A. (1953), Dispersion on a sphere, *Proc. R. Soc. A*, **217**, 295–305.
- Gattacceca, J., A. Deino, R. Rizzo, D. S. Jones, B. Henry, B. Beaudoin, and F. Vadeboin (2007), Miocene rotation of Sardinia: New paleomagnetic and geochronological constraints and geodynamic implications, *Earth Planet. Sci. Lett.*, **258**(3–4), 359–377.
- Hirt, A. M., and A. Lowrie (1988), Paleomagnetism of the Umbrian-Marches orogenic belt, *Tectonophysics*, **146**, 91–103.
- Jolivet, L., et al. (1998), Midcrustal shear zones in postorogenic extension: Example from the northern Tyrrhenian Sea, *J. Geophys. Res.*, **103**, 12,123–12,160.
- Kissel, C., and C. Laj (1988), The Tertiary geodynamical evolution of the Aegean Arc: A paleomagnetic reconstruction, *Tectonophysics*, **146**(1–4), 183–201.
- Kirschvink, J. L. (1980), The last-square line and plane and the analysis of paleomagnetic data, *Geophys. J. R. Astron. Soc.*, **62**, 699–718.
- Loneragan, L., and N. White (1997), Origin of the Betic-Rif mountain belt, *Tectonics*, **16**, 504–522.
- Lowrie, W., and A. M. Hirt (1986), Paleomagnetism in arcuate mountain belts, in *The Origin of the Arcs*, edited by F. C. Wezel, pp. 141–158, Elsevier, New York.
- Lowrie, W. (1990), Identification of ferromagnetic minerals in a rock by coercivity and unblocking temperature properties, *Geophys. Res. Lett.*, **17**, 159–162.
- Maffione, M., F. Speranza, C. Faccenna, A. Cascella, G. Vignaroli, and L. Sagnotti (2008), A synchronous Alpine and Corsica-Sardinia rotation, *J. Geophys. Res.*, **113**, B03104, doi:10.1029/2007JB005214.
- Maffione, M., F. Speranza, A. Cascella, S. G. Longhitano, and D. Chiarella (2013), A ~125° post-early Serravallian counterclockwise rotation of the Gorgoglione Formation (Southern Apennines, Italy): New constraints for the formation of the Calabrian Arc, *Tectonophysics*, **450**, 1–27, doi:10.1016/j.tecto.2013.01.005.
- Malinverno, A., and W. B. F. Ryan (1986), Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the lithosphere, *Tectonics*, **5**, 227–245.
- Mattei, M., C. Kissel, and R. Funicello (1996), No tectonic rotation of the Tuscan margin (Italy) since upper Messinian: Structural and geodynamical implications, *J. Geophys. Res.*, **101**, 2835–2845.
- Mattei, M., F. Cifelli, I. Martín Rojas, A. Crespo Blanc, M. Comas, C. Faccenna, and M. Porreca (2006), Neogene tectonic evolution of the Gibraltar Arc: New paleomagnetic constrains from the Betic chain, *Earth Planet. Sci. Lett.*, **250**, 522–540, doi:10.1016/j.epsl.2006.08.012.
- Mattei, M., F. Cifelli, and N. D'Agostino (2007), The evolution of the Calabrian Arc: Evidence from paleomagnetic and GPS observations, *Earth Planet. Sci. Lett.*, **263**, 259–274, doi:10.1016/j.epsl.2007.08.034.
- Mirabella, F., F. Brozzetti, A. Lupattelli, and M. R. Barchi (2011), Tectonic evolution of a low-angle extensional fault system from restored cross-sections in the Northern Apennines (Italy), *Tectonics*, **30**, TC6002, doi:10.1029/2011TC002890.
- Montigny, R., J. B. Edel, and R. Thuzat (1981), Oligo-Miocene rotation of Sardinia: K-Ar ages and paleomagnetic data of Tertiary volcanic, *Earth Planet. Sci. Lett.*, **54**, 261–271.
- Muttoni, G., A. Argnani, D. V. Kent, N. Abrahamsen, and U. Cibin (1998), Paleomagnetic evidence for Neogene tectonic rotations in the Northern Apennines Italy, *Earth Planet. Sci. Lett.*, **154**, 25–40.
- Muttoni, G., L. Lanci, A. Argnani, A. M. Hirt, U. Cibin, N. Abrahamsen, and W. Lowrie (2000), Paleomagnetic evidence for a Neogene two-phase counterclockwise tectonic rotation in the Northern Apennines (Italy), *Tectonophysics*, **326**, 241–253.
- Muttoni, G., E. Garzanti, L. Alfonsi, S. Cirilli, D. Germani, and W. Lowrie (2001), Motion of Africa and Adria since the Permian: Paleomagnetic and paleoclimatic constraints from northern Libya, *Earth Planet. Sci. Lett.*, **192**, 159–174.
- Pasquale, V., M. Verdoya, and P. Chiozzi (1995), Rifting and thermal evolution of the northwestern Mediterranean, *Ann. Geofis.*, **XXXVIII**(1), doi:10.4401/ag-4131.
- Patacca, E., R. Sartori, and P. Scandone (1992), Tyrrhenian Basin and Apenninic arcs: Kinematics relations since Late Tortonian times, *Mem. Soc. Geol. Ital.*, **45**, 425–451.
- Plesi, G., et al. (2002), The Tuscan successions of the high Tiber Valley (Foglio 289–Città di Castello): Biostratigraphic, petrographic and structural features, regional correlations, *Boll. Soc. Geol. Ital. Vol. Spec.*, **1**, 425–436.
- Principi, G., and B. Treves (1984), Il sistema Corso-Appenninico come prisma di accezione. Riflessi sul problema generale del limite Alpi–Appennini, *Mem. Soc. Geol. Ital.*, **28**, 549–576.
- Royden, L. H. (1993), Evolution of retreating subduction boundaries formed during continental collision, *Tectonics*, **12**, 629–638.

- Royden, L. E., E. Patacca, and P. Scandone (1987), Segmentation and configuration of subducted lithosphere in Italy: An important control on thrust-belt and foredeep-basin evolution, *Geology*, *15*, 714–717.
- Sagnotti, L., M. Mattei, C. Faccenna, and R. Funicello (1994), Paleomagnetic evidence for no tectonic rotation of the central Italy Tyrrhenian margin since upper Pliocene, *Geophys. Res. Lett.*, *21*, 481–484.
- Sagnotti, L., and A. Winkler (1999), Rock magnetism and palaeomagnetism of greigite-bearing mudstones in the Italian peninsula, *Earth Planet. Sci. Lett.*, *165*, 67–80.
- Sagri, M., P. Bruni, M. Bertini, A. Cecchi, N. Cipriani, M. Fazzuoli, M. Magi, M. Mazza, P. Pandeli, and F. Sani (2012), Note illustrative della carta geologica d'Italia 1:50000, Figline Valdarno, sheet 276, scale 1:50,000, Ist. Super. per la Prot. e la Ric. 1123 1124 Rome.
- Sani, F., et al. (2009), Late Pliocene–Quaternary evolution of outermost hinterland basins of the Northern Apennines (Italy), and their relevance to active tectonics. Special Issue “Ten years after the Umbria-Marche Earthquake, Central Italy”. E. Tondi, L. Chiaraluce, and G. Roberts Editors, *Tectonophysics*, *476*(1–2), 336–356, doi:10.1016/j.tecto.2008.12.012.
- Schwartz, S. Y., and R. Van der Voo (1983), Paleomagnetic evaluation of the orocline hypothesis in the central and southern Appalachians, *Geophys. Res. Lett.*, *10*, 505–508.
- Snowball, I. F. (1997), Gyromagnetic magnetization (GRM) and the magnetic properties of greigite bearing clays in southern Sweden, *Geophys. J. Int.*, *129*, 624–636.
- Speranza, F., L. Sagnotti, and M. Mattei (1997), Tectonics of the Umbria- Marche-Romagna Arc (central Northern Apennines, Italy): New paleomagnetic constraints, *J. Geophys. Res.*, *102*, 3153–3166.
- Speranza, F., I. M. Villa, L. Sagnotti, F. Florindo, D. Cosentino, P. Cipollari, and M. Mattei (2002), Age of the Corsica-Sardinia rotation and Liguro-Provençal Basin spreading: New paleomagnetic and Ar/Ar evidences, *Tectonophysics*, *347*, 231–251.
- Stephenson, A., and I. Snowball (2001), A large gyromagnetic effect in greigite, *Geophys. J. Int.*, *145*, 570–575.
- Tauxe, L., N. Kylstra, and C. Constable (1991), Bootstrap statistics for paleomagnetic data, *J. Geophys. Res.*, *96*, 11,723–740.
- Treves, B. (1984), Orogenic belts as accretionary prisms: The example of the Northern Apennines, *Ofioliti*, *9*, 577–618.
- Van der Voo, R., and J. E. T. Channell (1980), Paleomagnetism in orogenic belts, *Rev. Geophys. Space Phys.*, *18*, 455–481.
- Van der Voo, R. (1993), *Paleomagnetism of the Atlantic, Tethys, and Iapetus Oceans*, vol. 411, Cambridge Univ. Press, New York.
- Vigliotti, L., and D. V. Kent (1990), Paleomagnetic results of Tertiary sediments from Corsica: Evidence of post-Eocene rotation, *Phys. Earth Planet. Inter.*, *62*, 97–108.
- Vigliotti, L., W. Alvarez, and M. McWilliams (1990), No relative rotation detected between Corsica and Sardinia, *Earth Planet. Sci. Lett.*, *98*, 313–318.
- Westphal, M., C. Bardon, A. Bossert, and R. Hamzeh (1973), A computer fit for Corsica and Sardinia against Southern France, *Earth Planet. Sci. Lett.*, *18*, 137–140.
- Zijderveld, J. D. A. (1967), A.C. demagnetization of rocks: Analysis of results, in *Methods in Palaeomagnetism*, edited by D. W. Collinson, K. M. Creer, and S. K. Runcorn, pp. 254–286, Elsevier, New York.
- Zijderveld, J. D. A., K. A. De Jong, and R. Van der Voo (1970), Rotation of Sardinia: Palaeomagnetic evidence from Permian rocks, *Nature*, *226*, 933–934.