



A $\sim 125^\circ$ post-early Serravallian counterclockwise rotation of the Gorgoglione Formation (Southern Apennines, Italy): New constraints for the formation of the Calabrian Arc

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ARTICLE INFO

Article history:

Received 28 February 2012

Received in revised form 3 January 2013

Accepted 8 January 2013

Available online 17 January 2013

Keywords:

Southern Apennines
Gorgoglione Formation
Paleomagnetism
Tectonics
Calabrian Arc
Biostratigraphy

ABSTRACT

The Southern Apennines, Calabro-Peloritane block, and Sicilian Maghrebides form a ~ 700 km long orogenic bend, known as Calabrian Arc (Cifelli et al., 2007). The bending of this orogenic system was realized progressively through opposite-sense rotation of the two limbs, counterclockwise (CCW) in the Southern Apennines and clockwise (CW) in the Sicilian Maghrebides, synchronous to the Miocene-to-Present opening of the Tyrrhenian Sea. Despite the wealth of paleomagnetic data from the Southern Apennines, the main Miocene rotational phase still remains poorly constrained in time and, more importantly, data from the most internal paleogeographic domains of the belt are completely lacking.

The Gorgoglione Formation, a middle Miocene piggy-back deposit of the Southern Apennines, unconformably resting over the internal Sicilide Unit, offers the unique opportunity to document the deformation pattern of the most internal units, and reconstruct the incipient tectonic phases leading to the formation of the Calabrian Arc. New paleomagnetic and biostratigraphic data from the Gorgoglione Fm. reveal a post-early Serravallian $\sim 125^\circ$ CCW rotation with respect to stable Africa. Such a large rotation, affecting the Gorgoglione Fm. (and consequently the underneath allochthonous Sicilide nappe) exceeds by $\sim 45^\circ$ the maximum mean CCW rotation previously reported for the Southern Apennines. We propose that the additional $\sim 45^\circ$ CCW rotation measured in the Sicilide Unit is the result of an earlier, late Miocene phase of deformation related to the onset of the Tyrrhenian Sea opening and affecting the most internal paleogeographic domains of the Southern Apennines. Our reconstructed tectonic scenario confirms and emphasizes the central role of the Ionian slab in the geodynamic evolution of the central Mediterranean.

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1. Introduction

The Cenozoic tectonic evolution of the central Mediterranean, and in particular the bending of the Alpine–Apenninic belt into an S-shaped orogen, was closely influenced by the geodynamic processes associated to the narrow Ionian oceanic seaway intervening between the European and African plates (Faccenna et al., 1997, 2001, 2007; Malinverno and Ryan, 1986; Rosenbaum et al., 2002). Slab roll-back of the Ionian lithosphere triggered, since the late Eocene, back-arc extension and progressive opening of the Liguro–Provençal basin and Tyrrhenian Sea (Faccenna et al., 1997; Kastens et al., 1988; Malinverno and Ryan, 1986). Subduction of the Ionian slab is testified by the Benioff plane deepening down to 300 km beneath the southern Tyrrhenian Sea (Fig. 1) (Chiarabba et al., 2008; Neri et

al., 2009). The evolution of the Tyrrhenian Sea started in the early Serravallian when the locus of the back-arc extension jumped from the eastern to the western margin of Sardinia, isolating an independent continental block (Calabro-Peloritane block (CPB), Fig. 1) (Faccenna et al., 1997; Mattei et al., 2002). During middle–late Miocene times the CPB detached completely from Sardinia and migrated \sim ESE-ward following the backward-retreat of the Ionian slab (Duermeijer et al., 1998; Faccenna et al., 1997, 2001; Kastens et al., 1988; Malinverno and Ryan, 1986; Patacca and Scandone, 1989; Patacca et al., 1990). This process was accompanied by opposite-sense vertical axis rotations in the adjacent orogenic domains, counterclockwise (CCW) in the Southern Apennines, and clockwise (CW) in the Sicilian Maghrebides (see Cifelli et al., 2007 for a comprehensive review). This protracted process eventually resulted into a ~ 700 km-long salient, namely the Calabrian Arc (Cifelli et al., 2007, 2008; Mattei et al., 2007) currently encircling the southern Tyrrhenian Sea. The regional rotation pattern of the Calabrian Arc is shown in Fig. 1.

The paleomagnetic data from the Southern Apennines in the northern limb of the Calabrian Arc, revealed an overall post-middle

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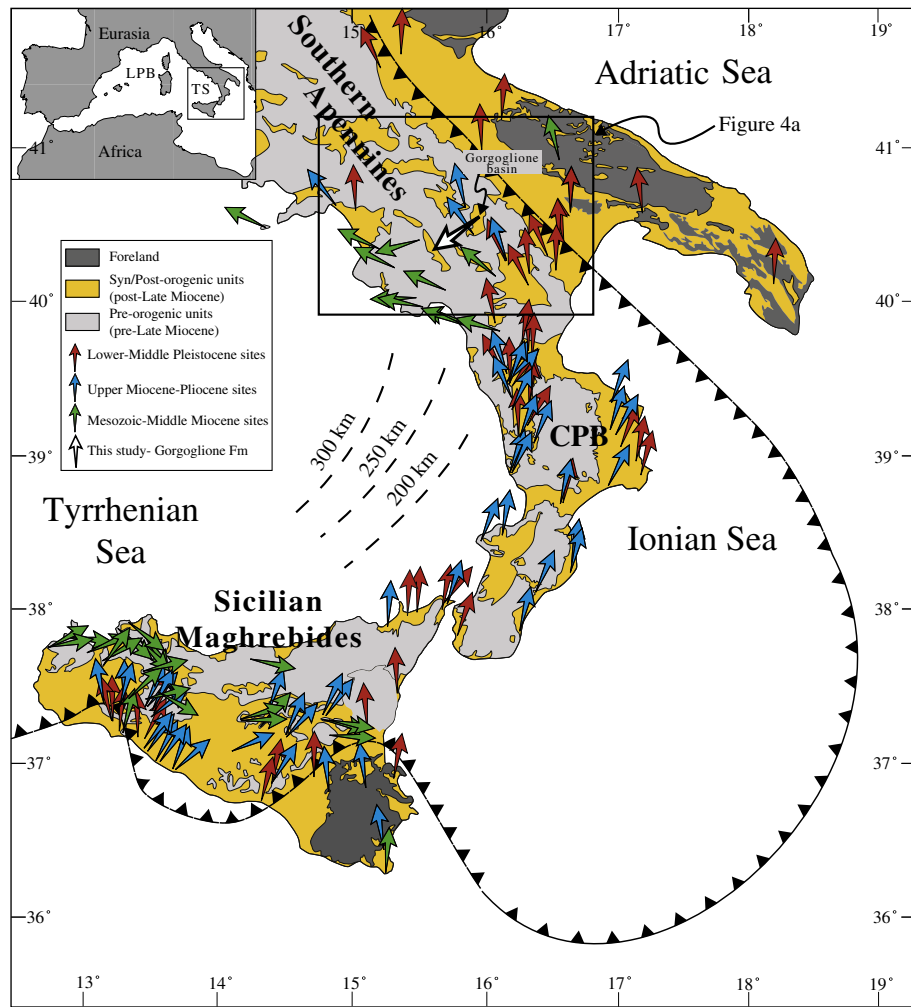


Fig. 1. Geological map of the Calabrian Arc showing the estimated tectonic rotations (colored arrows) with respect to stable Africa computed by Cifelli et al. (2007). Dotted lines represent isolines of the top of the Ionian slab (after Chiarabba et al., 2008). CPB, Calabro-Peloritan block; LPB, Liguro-Provençal basin; TS, Tyrrhenian Sea.

Miocene $\sim 80^\circ$ CCW rotation, with local maximum values as large as 106° (Gattacceca and Speranza, 2002). Part of this rotation ($\sim 20^\circ$) occurred in the early Pleistocene, when the compressive fronts shifted eastward affecting more external domains (Mattei et al., 2004; Sagnotti, 1992; Scheepers, 1994; Scheepers and Langereis, 1994; Scheepers et al., 1993). The southern limb of the arc (the Sicilian Maghrebides) underwent an overall post-middle Miocene $\sim 100^\circ$ CW rotations (with local 134° CW rotation documented from the most internal paleogeographic domains). Here the rotation magnitude decreases progressively from the internal towards the external domains of the belt (Butler et al., 1992; Channell et al., 1980, 1990; Oldow et al., 1990; Speranza et al., 1999, 2003). Conversely, in the Southern Apennines it is not possible to assess a similar pattern on the basis of the available data. The main rotational phase ended in the middle Pleistocene in both the Southern Apennines and Sicilian Maghrebides.

Despite the extensive paleomagnetic dataset available for the Southern Apennines, the onset of the main rotational phase is still poorly constrained in time due to the limited number of sites (only two) from Miocene rocks (Gattacceca and Speranza, 2002). Furthermore, the rotational history of the most internal paleogeographic domains, currently resting at the top of the orogenic pile, is totally unknown. Relying on the available dataset, the Calabrian Arc displays a not truly symmetrical bending (Cifelli et al., 2008), with the southern limb showing larger rotations than the northern one. Furthermore, some authors invoke the Europe–Africa convergence as the only driving force for the bending of the Calabrian Arc (Johnston

and Mazzoli, 2009). Accordingly, a number of moot points are still present: What is the timing and magnitude of the rotations related to the earliest stage of deformation in the Southern Apennines? Was the bending of the Calabrian Arc symmetrical or asymmetrical? Is the Ionian slab the only driving mechanism for the bending of the Calabrian Arc, or the Europe–Africa convergence contributes to the regional deformation as well?

We tried to address these questions carrying out an integrated paleomagnetic and biostratigraphic study of the Gorgoglione Fm., a middle Miocene piggy-back deposit of the Southern Apennines (Boenzi and Ciaranfi, 1970; Boiano, 1993, 1997; Cocco et al., 1972; Critelli and Le Pera, 1994; Critelli and Loiacono, 1988; Patacca et al., 1990; Pescatore et al., 1980, 1999) resting in unconformable contact above a unit (i.e., the Varicolored Clays, interpreted as part of the Sicilide Unit) of internal paleogeographic provenance (Cinque et al., 1993; Critelli, 1999; Lentini et al., 2002; Monaco and Tortorici, 1995; Patacca and Scandone, 2007). Because of these features the Gorgoglione Fm. offers a unique chance to investigate on the rotation history of the most internal paleogeographic domains of the Southern Apennines, and reconstruct in more detail its geodynamic evolution in the framework of the Calabrian Arc formation.

2. Geological setting

The Southern Apennines are a fold-and-thrust belt composed of both autochthonous and allochthonous marine sedimentary units

juxtaposed in a complex structure displaying a combination of thin- and thick-skinned features (Casero et al., 1988; Cello and Mazzoli, 1999; Cello et al., 1989; Lentini et al., 2002; Mazzoli et al., 2000; Menardi-Noguera and Rea, 2000; Mostardini and Merlini, 1986; Patacca and Scandone, 2007). The upper part of the orogenic wedge consists of NE-verging, rootless nappes derived from basinal and platform domains (Sicilide–Liguride Units, Apenninic platform, and Lagonegro Unit), transported over an autochthonous carbonatic platform (Apulian platform), which in turn is arranged into a deep-seated duplex system known as “buried Apulian belt” (e.g., Cello et al., 1989). The present boundary between the allochthonous and autochthonous units is marked by a low-angle, large-displacement thrust fault penetrated by numerous oil wells (Mazzoli et al., 2000).

The paleogeographic distribution of the tectono-stratigraphic domains of the Southern Apennines (Fig. 2) is described, from the internal towards the external sectors, by a deep basin (probably part of the Alpine Tethys) carrying ophiolite-bearing units (the Liguride and Sicilide Units; Ogniben, 1969; Patacca and Scandone, 2007), an internal carbonate platform (the Apenninic platform; Argnani, 2000; Mostardini and Merlini, 1986), an external basin (Lagonegro basin; Mostardini and Merlini, 1986; Ogniben, 1969), commonly interpreted as the cover of the Ionian Sea, and an external carbonate platform (the Apulian platform; Ricchetti et al., 1988). The undeformed part of the Apulia platform currently constitutes the Apulian foreland.

According to Patacca and Scandone (2007), tectonic events leading to the current setting of the Southern Apennines started in the middle Miocene times (Burdigalian–Langhian boundary, ~16 Ma), when the Sicilide–Liguride Units detached from their substratum and thrust over the western border of the Apenninic platform, which at that time was already experiencing internal deformation. During Langhian–Serravallian times (~16–12 Ma) the Sicilide–Liguride Units and Apenninic platform were emplaced over the Lagonegro Unit. In the early Tortonian times an out-of-sequence (e.g., Morley, 1988) thrusting event affected the internal Sicilide Unit resulting in its complete superposition above the Apenninic platform. Between the end of the Miocene (Tortonian) and the early Pliocene (Zanclean) the entire orogenic wedge was detached from its basement and transported over the Apulian platform by at least 100 km through a low-angle thrust fault. Finally, in the late Pliocene–early Pleistocene times the orogenic wedge and the underneath Apulian platform was stacked along younger reverse faults possibly involving the basement. The current

relative position of the different tectono-stratigraphic units of the southern Apennines is shown in Fig. 3.

The Gorgoglione Fm. in the southern part of the Southern Apennines (Fig. 4) is a ~1500 m-thick piggy-back deposit consisting of coarse sandy turbidites and mudstone intervals (Boenzi and Ciaranfi, 1970; Boiano, 1993, 1997; Cocco et al., 1972; Critelli and Le Pera, 1994; Critelli and Loiacono, 1988; Patacca et al., 1990; Pescatore et al., 1980, 1999). The base of the sequence is composed of turbidites sourced from crystalline basement terranes of the westernmost sectors of the belt and showing immature compositions and textures as consequence of the syn-sedimentary tectonics of the basin margins (Critelli and Loiacono, 1988). Pelitic horizons, which appear sporadically in the lower and middle turbidite systems, become predominant in the upper turbidite system (Fig. 4C) (Boiano, 1997).

The Gorgoglione Fm. is deformed into a broad syncline with NNW–SSE-axis (Catalano et al., 1993; Pescatore et al., 1980), and rests in both tectonic and stratigraphic (unconformable) contacts over the Varicolored Clays (Fig. 4C). The Varicolored Clays is a Cretaceous–Paleogene chaotic mélange composed of pelitic, highly sheared matrix enclosing large, undeformed olistoliths made of younger rocks (Ogniben, 1969). The Varicolored Clays are commonly considered as the lowermost stratigraphic interval of the internal Liguride–Sicilide Units (Cinque et al., 1993; Critelli, 1999; Lentini et al., 2002; Monaco and Tortorici, 1995; Patacca and Scandone, 2007), although some authors proposed a more external paleogeographic origin (i.e., the Lagonegro basin; Casero et al., 1988; Cello and Mazzoli, 1999; Mostardini and Merlini, 1986; Pescatore, 1988; Pescatore et al., 1999). The age of the Gorgoglione Fm. is still debated as different biostratigraphic studies indicated a Langhian–late Serravallian (Giannandrea et al., 2009; Lentini et al., 2002), Langhian–early Tortonian (Boenzi and Ciaranfi, 1970; Patacca and Scandone, 2007), Tortonian (Boiano, 1997; Di Nocera et al., 2011; Sgroso, 1998), and late Tortonian (Patacca et al., 1990) age.

3. Sampling and methods

A total of 349 samples were collected from the clay-rich upper turbidite system of the Gorgoglione Fm. at 30 sites distributed between the villages of Castelmezzano and Gorgoglione (Fig. 4C). Cores were drilled by using a petrol-powered portable drill cooled by water (oriented hand samples were gathered at one site only). At each site 5–32 cores (11 on average) were collected, within a 2–3 m-thick stratigraphic

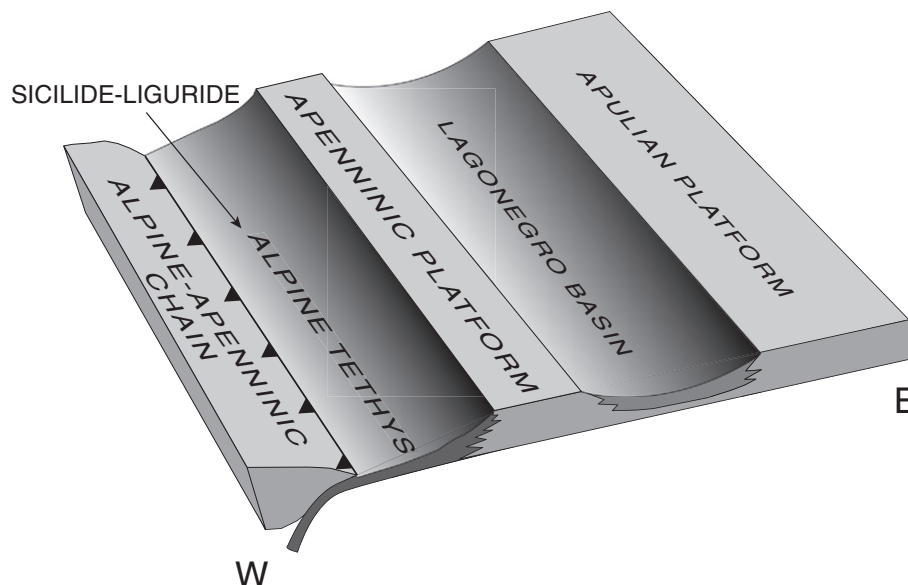


Fig. 2. Paleogeographic distribution of the Southern Apennines depositional realms during the early Miocene after Mostardini and Merlini (1986).

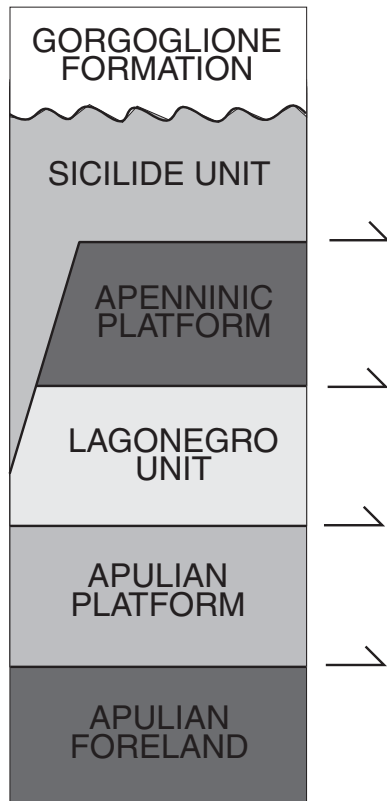


Fig. 3. Schematic log showing the current relationships between the different tectono-stratigraphic units of the Southern Apennines. Undulate line indicates unconformable contact of the Gorgoglione Formation above the Sicilide Unit.

interval in order to average out secular variation of the geomagnetic field. Cores were oriented in situ by a magnetic compass, corrected to account for a local $\sim 2^\circ$ magnetic declination (according to Istituto Nazionale di Geofisica e Vulcanologia, 2007).

Paleomagnetic measurements were carried out in the Paleomagnetism Laboratory of the Istituto Nazionale di Geofisica e Vulcanologia (INGV, Rome, Italy). Thermal demagnetization of a three-component isothermal remanent magnetization (IRM) was carried out on one sample per site in order to characterize the main magnetic carriers (Lowrie, 1990). Fields of 2.7, 0.6 and 0.12 T were imparted on the z, y, and x sample axes, respectively, by using a Pulse Magnetizer (Model 660, 2G Enterprises).

The natural remanent magnetization (NRM) of the sampled specimens was removed via 11–12 thermal steps (with variable temperature increments) in a magnetically shielded oven. Residual magnetization was measured at each step with a superconducting cryogenic magnetometer (2G Enterprises, USA). One representative specimen per site was also demagnetized with alternating field (AF) technique. Demagnetization data were plotted on orthogonal diagrams (Zijderveld, 1967), and the magnetization components were isolated via principal component analysis (Kirschvink, 1980) using Remasoft 3.0 software (Chadima and Hrouda, 2006). Only computed directions showing a maximum angle of deviation (MAD, Kirschvink (1980)) smaller than 15° were considered for this study. Site-mean directions were evaluated by using a Fisherian statistics (Fisher, 1953) of virtual geomagnetic poles (VGPs) corresponding to the characteristic remanent magnetizations (ChRMs), adopting a fixed (45°) cut-off (e.g., Johnson et al., 2008). The use of VGPs rather than paleomagnetic directions for the computation of the site mean values was preferred as it allows a more realistic error estimate on the declination and inclination values (e.g., Deenen et al., 2011).

Ad-hoc biostratigraphic sampling was carried out contextually to paleomagnetic sampling (at the same locations, Fig. 4C) in order to constrain precisely the age of the sampled stratigraphic interval. At each

site three samples have been collected at one-meter distance from each other. Biostratigraphy relied on calcareous nannofossil content analysis of 37 samples from the 22 sites whose relative position within the stratigraphic sequence was clearly constrained (see Supplementary data). The abundance of nannofossils was estimated as the number of specimens for field of view, according to the following abundance categories: Total abundance – Presence (1 specimen/ >100 fields), Rare (1 specimen/ $10\text{--}100$ fields), Few (1 to 10 specimens/field), Common (10 to 30 specimens/field) and Abundant (>30 specimens/field); Relative abundance – Presence (1 specimen/ >100 fields), Rare (1 specimen/ $10\text{--}100$ fields), Few (1 specimen/ $2\text{--}10$ fields), Common (1 specimen/ $1\text{--}2$ fields) and Abundant (>1 specimen/field). A quantitative analysis of nannofossils was performed adopting the methodology described by Backman and Shackleton (1983) and Rio et al. (1990), extensively used in the Mediterranean and extra-Mediterranean studies (Di Stefano et al., 2008, and references therein). A counting of 30–50 sphenoliths was performed to evaluate the abundance of *Sphenolithus heteromorphus*, while the *Helicosphaera* species were counted in 50–100 helicoliths. The biozone attribution is according to Sprovieri et al. (2002) and Di Stefano et al. (2008) for the Mediterranean middle Miocene. The adopted age of Langhian/Serravallian boundary (13.82 Ma) is that established by Hilgen et al. (2009).

4. Results

4.1. Paleomagnetism and rock magnetism

About 30% of the sampled specimens (115 out of 349) belonging to 10 sites (Table 1) showed a weak (0.06–0.91 mA/m) but stable and measurable remanence, the remaining samples carrying a noisy, uninterpretable magnetic signal characterized by lower intensities (0.02–0.09 mA/m) (Fig. 5). Additional 63 specimens (out of 115) were disregarded due to the poor quality of the estimated directions (i.e., $\text{MAD} > 15^\circ$). Characteristic remanent magnetizations (ChRMs) of the remaining 52 specimens showed blocking temperatures in the range of 275–325 $^\circ\text{C}$, except for two sites (PP04 and PP19) characterized by higher (420–540 $^\circ\text{C}$) values (Fig. 5). The AF demagnetization revealed to be unsuitable for our samples as only 50–60% of the NRM was removed at maximum applied fields of 70 mT. Thermal demagnetization of a three-component IRM (Fig. 6) pointed out to the presence of a medium-soft mineralogical fraction (coercivity < 0.12 T) which was completely demagnetized at ~ 580 $^\circ\text{C}$ (Curie temperature of magnetite; Dunlop and Özdemir (1997)), whereas a hard fraction (coercivity > 0.12 T) was virtually absent.

Site-level dispersion of paleomagnetic directions for eight out of ten sites reflects the scatter induced by paleosecular variation (PSV) of the geomagnetic field, being the cone of 95% confidence around the site mean VGP (A95) within the maximum and minimum values (A95max–A95min) expected for a PSV-induced scatter according to Deenen et al. (2011) (Table 1). At site PP19 PSV is overestimated (A95 > A95max), implying that an additional source of error (sampling?) is responsible (together with PSV) for the increase of dispersion of paleomagnetic directions. Conversely, at site PP13 PSV is underestimated (A95 < A95min) possibly due to a late stage magnetic overprint.

Fig. 7 shows the computed site mean directions arranged in two distinct clusters, NE- and SW-oriented (in tilt corrected coordinates). The NE-directed cluster (sites PP01, PP04, PP17, PP19, PP26, PP27, PP28) shows a prevailing reverse magnetic polarity except for one site. In situ directions for this cluster are not statistically consistent with a present geocentric axial dipole (GAD) field direction ($D = 0^\circ$, $I = 61^\circ$; Fig. 7). On the other hand, in situ directions for the SW-oriented cluster (sites PP12, PP13, PP14) are close to the reverse direction of the present GAD field ($D = 180^\circ$, $I = -61^\circ$; Fig. 7). A fold test (McFadden, 1990) performed on sites PP12, PP13 and PP14 resulted negative ($\xi_{(\text{in situ})} = 0.616$, $\xi_{(\text{unfolded})} = 2.535$, $\xi_{95\%} = 2.076$) at the 95% confidence level, pointing out to a post-tilting magnetization.

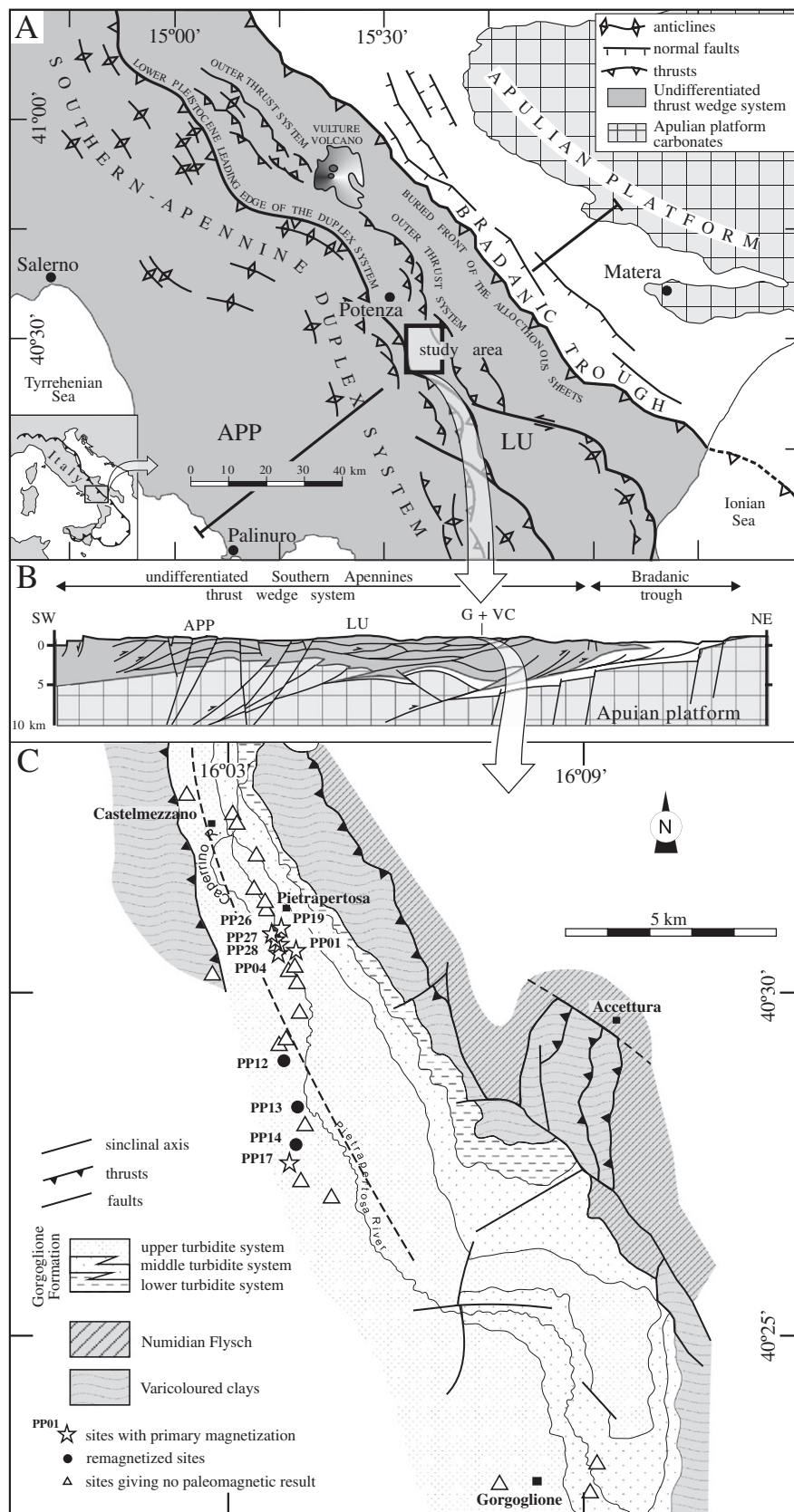


Fig. 4. Simplified tectonic map (A) and geological cross-section (B) of the Southern Apennines, redrawn after [Piedilato and Prosser \(2005\)](#); APP, Apenninic platform; LU, Lagonegro Unit; G, Gorgoglione Formation; VC, Varicolored Clays. (C) Geological map of the Gorgoglione basin redrawn after [Boiano \(1997\)](#) showing the sampling sites and the main tectonic features.

Table 1
Paleomagnetic results from the Gorgoglione Formation.

Site	Coordinates		Polarity chron	Bedding	In situ		Tilt corrected		k	α_{95}	K	A95	A95 _{min}	A95 _{max}	N
	Latitude (N)	Longitude (E)			D(°)	I(°)	D(°)	I(°)							
PP01	40°30'03.2"	16°04'04.2"	C5ABn	230/32	218.2	74.9	225.8	43.1	23.1	14.2	16.8	16.8	8.3	26.5	6
PP04	40°29'59.7"	16°03'42.2"	C5AAr	225/46	243.3	−69.0	30.5	−63.3	19.2	11.3	10.5	15.6	6.8	19.2	10
PP17	40°27'24.3"	16°03'29.7"	C5AAr	70/55	90.7	−10.9	112.9	−59.4	14.2	21.1	7.8	29.2	8.9	29.7	5
PP19	40°30'17.0"	16°03'56.5"	C5ABr	237/32	135.0	−67.1	91.3	−47.6	8.3	24.7	6.3	28.9	8.3	26.5	6
PP26	40°30'15.7"	16°03'44.6"	C5ABr	237/32	62.3	−63.4	59.8	−31.5	20.5	15.1	30.0	12.4	8.3	26.5	6
PP27	40°30'14.8"	16°03'45.1"	C5ABr	240/33	52.4	−62.6	56.0	−29.7	15.0	10.6	16.8	10.0	5.9	15.6	14
PP28	40°30'12.3"	16°03'48.4"	C5ABr	245/25	51.9	−59.9	57.0	−35.3	13.0	22.0	19.2	17.9	8.9	29.7	5
Whole dataset							56.9	−42.6	10.9	6.5	9.8	6.9	3.6	7.2	48
<i>Remagnetized sites</i>															
PP12	40°28'21.0"	16°03'31.2"	–	66/17	196.6	−79.0	226.4	−64.5	98.1	7.8	44.1	11.6	8.9	29.7	5
PP13	40°27'57.4"	16°03'51.0"	–	50/18	191.9	−71.7	209.9	−55.8	204.0	4.2	128.3	5.3	7.8	24.1	7
PP14	40°27'38.5"	16°03'35.9"	–	70/25	188.4	−80.1	232.8	−59.1	24.5	18.9	17.9	22.3	9.8	34.2	4

Magnetic polarity chrons are referred to the GPTS of Gradstein et al. (2004). Bedding is expressed in dip azimuth/dip values. D and I are site mean declination and inclination calculated before and after tilt correction, respectively. k and α_{95} are the Fisherian (Fisher, 1953) dispersion (or precision) parameter and cone of 95% confidence around the mean paleomagnetic direction, respectively. K and A95 are precision parameter determined from the mean virtual geomagnetic pole (VGP) direction and cone of 95% confidence around the virtual geomagnetic pole (VGP) mean direction, respectively. A95min and A95max are the minimum and maximum cones of confidence expected for a paleosecular variation (PSV)-induced scatter for the given distribution (Deenen et al., 2011). N is the number of samples used for the statistics having a maximum angle of deviation (MAD) < 15°, and included within the 45° cut-off of the VGPs latitude.

A post-tilting magnetization of site PP13 is also supported by the low dispersion of its VGPs at site level ($A95 < A95_{min}$, Table 1), commonly observed in remagnetized sites (e.g., Meijers et al., 2011). Consequently, sites PP12, PP13 and PP14 were disregarded from further analysis.

Besides calculating site mean values, we applied a Fisherian statistics of VGPs corresponding to all the 52 individual directions from the seven sites from the NE-oriented cluster. The dispersion of 48 directions is representative of PSV alone being the $A95_{min} < A95 < A95_{max}$ (Fig. 8a, Table 1). The remaining four directions that exceed the expected PSV-induced scatter belong to three different sites (one from site

PP04, one from PP19 and two from PP17) and are probably affected by the external sources of scattering (i.e., sampling or instrumental errors). A mean direction for the Gorgoglione Fm. based on the 48 paleomagnetic directions has $D = 56.9^\circ \pm 7.6^\circ$, $I = -42.6^\circ \pm 9.1^\circ$, $k = 10.9$, $\alpha_{95} = 6.5^\circ$, $K = 9.8$, $A95 = 6.9$ (Table 1, Fig. 8b).

As a confirmation for the primary origin of these directions, the non parametric fold test (Tauxe and Watson, 1994) that was performed on the dataset constituted by the 48 directions resulted positive, showing a maximum grouping (highest τ_1) close to full (100%) unfolding and indicating a pre-tilting magnetization (Fig. 9).

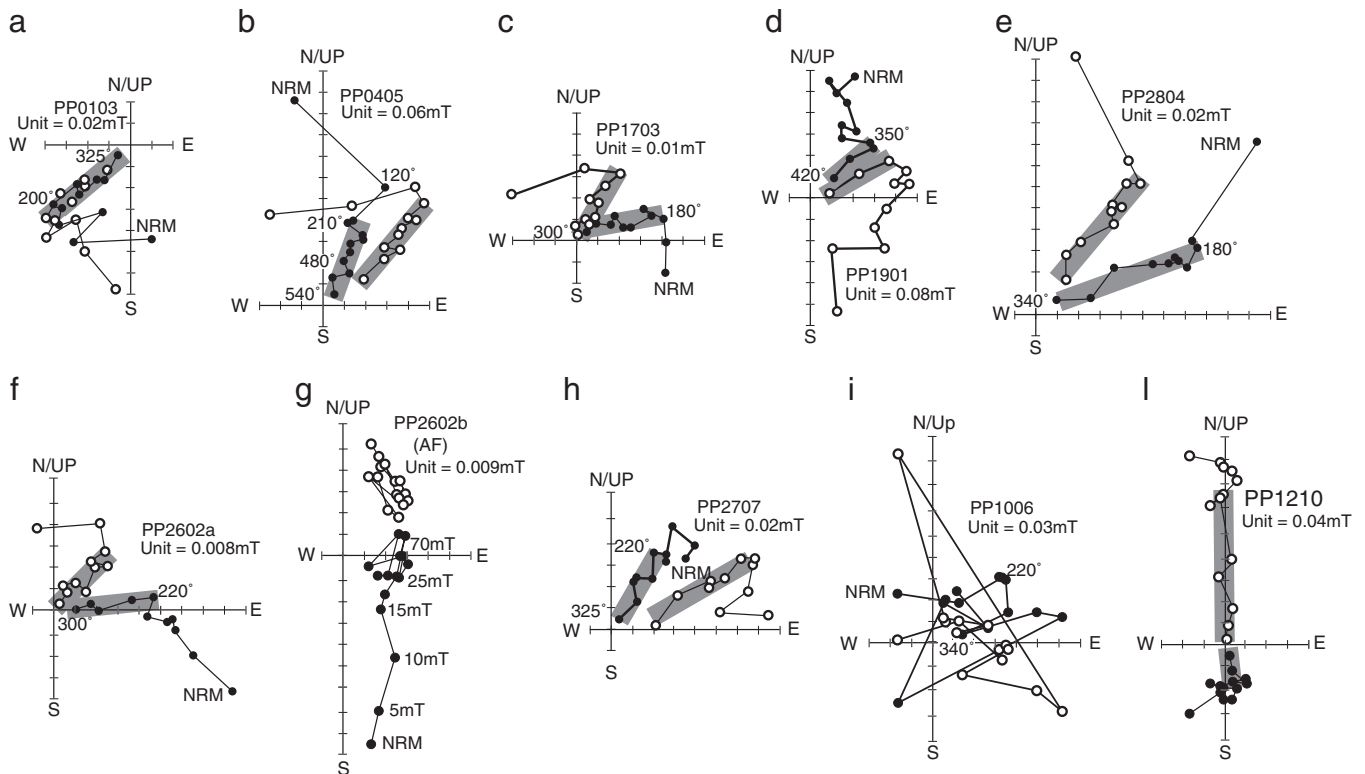


Fig. 5. Zijderveld diagrams (in tilt corrected coordinates) for representative samples carrying a (a–h) pre-tilting magnetization including a twin specimen demagnetized with AF technique (g), (i) uninterpretable remanence, and (l) post-tilting magnetization. Solid and open dots represent projection on the horizontal and vertical planes, respectively. Demagnetization step values are in °C. Shaded gray lines indicate the interpreted ChRMs.

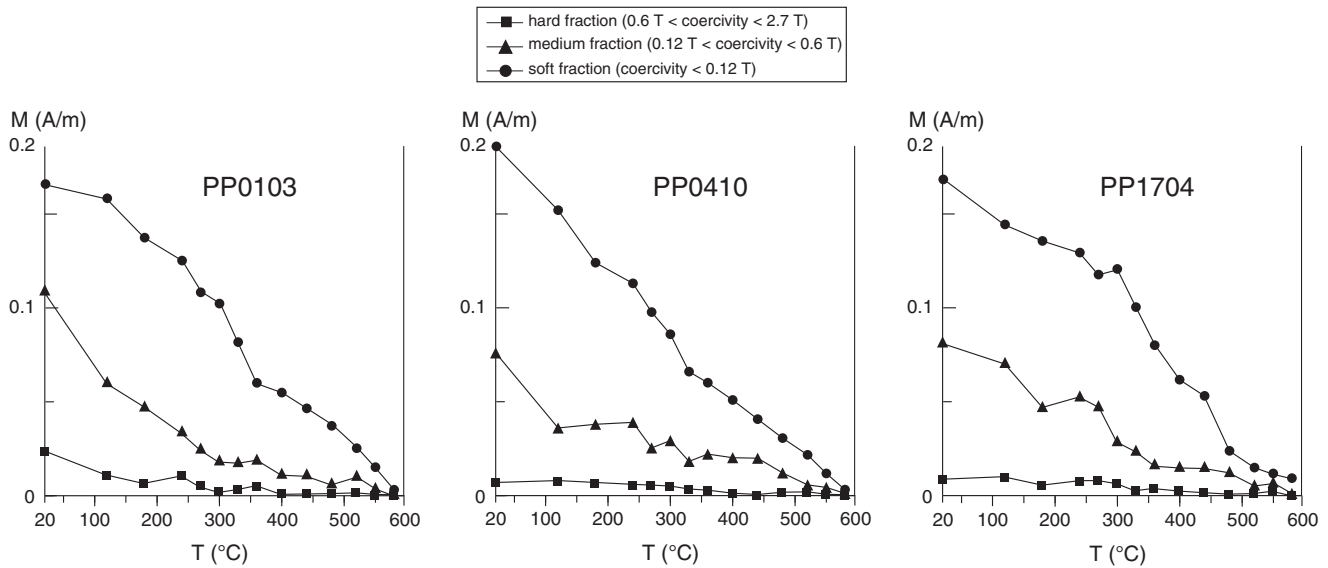


Fig. 6. Thermal demagnetization of a three-component IRM according to the method of Lowrie (1990) for three representative samples.

The deviation from 100% significance might be related to uncertainties in bedding measurement.

A CCW mean rotation (R) of $125^\circ \pm 7.5^\circ$ for the study area resulted by the comparison between the above mean direction for the Gorgoglione Fm. and the expected direction of the 10 Ma African paleopole from Torsvik et al. (2012). Flattening ($F = I_{\text{paleopole}} - I_{\text{measured}}$) is positive and equal to $14.2^\circ \pm 5.5^\circ$. Positive flattening here should not be interpreted as the result of a northward latitudinal drift of the studied crustal block but rather as the effect of compaction of the clayey matrix during diagenesis, which tends to “shallow” the original inclination of the remanence (e.g., Arason and Levi, 1990; Deamer and Kodama, 1990). Analogous results have been obtained from similar lithologies from the Italian Alps and Northern Apennines (Maffione et al., 2008; Speranza et al., 1997).

4.2. Biostratigraphy

Studied samples generally yielded common and moderately preserved calcareous nannofossils, as well as diffused reworking (see supplementary material). The base of MNN5c subzone could be identified between sites PP07 and PP15 where *Helicosphaera walbersdorfensis*

(which is a minor component of the helicoliths group) becomes more common and continuous, thus indicating its First Common Occurrence (FCO, Fig. 10). The top of the MNN5c subzone, marked by the Last Common Occurrence (LCO) of *S. heteromorphus*, was recognized just above site PP24 where this specie is absent or less abundant (<10%). The uppermost part of the sampled sequence was tentatively attributed to the MNN6a subzone on the basis of the absence of *S. heteromorphus* and the occurrence of *Calcidiscus premacintyreii*. Accordingly, the investigated portion of the Gorgoglione Fm. falls between the MNN5b and the MNN6a subzones, spanning the Langhian/Serravallian boundary (Fig. 10), fairly in agreement with Giannandrea et al. (2009) and Lentini et al. (2002).

5. Discussion

5.1. Nature and age of the magnetic remanence

Observed blocking temperatures as low as $\sim 325^\circ\text{C}$ are suggestive of the presence of high-Ti titanomagnetite ($x \approx 0.5$), whereas higher blocking temperatures (i.e., $420^\circ\text{--}540^\circ$) pointed out to the occurrence of low-Ti titanomagnetite ($x \approx 0.2$) (see Fig. 3.11 in Dunlop and

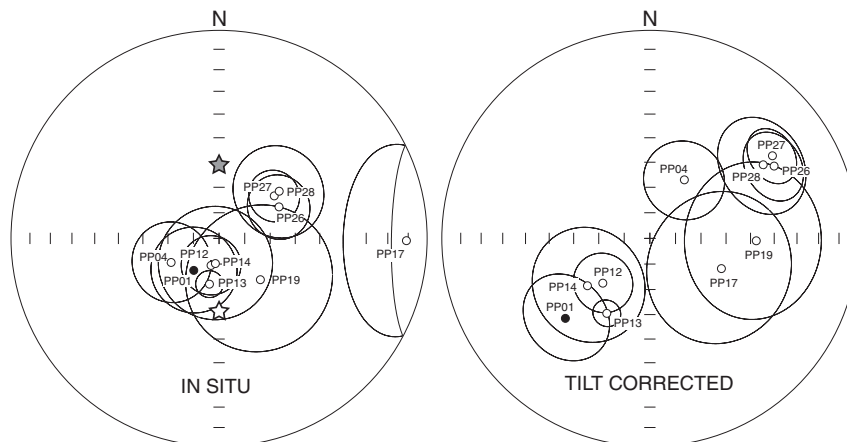


Fig. 7. Equal-area projections of the site-mean in situ and tilt corrected directions with associate projection of the α_{95} cones of confidence around the mean values. Open (solid) symbols represent projection onto the upper (lower) hemisphere. Solid (open) star is the normal (reverse) polarity present-day geocentric axial dipole (GAD) field direction for the study area.

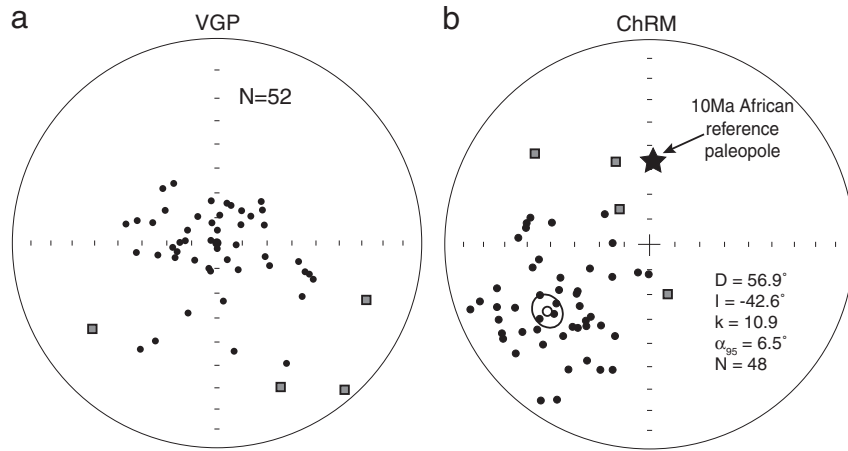


Fig. 8. (a) Stereographic plot showing the distribution of 52 virtual geomagnetic poles (VGPs) correspondent to the paleomagnetic directions carrying pre-tilting magnetization. Black dots are VGPs representative of a paleosecular variation (PSV)-induced scatter for the given number of data ($N=48$) according to Deenen et al. (2011). The dispersion of these 48 VGPs, represented by the A95 value is within the maximum and minimum ranges of dispersion (i.e., $A95_{max}-A95_{min}$) expected for the given number of data, according to Deenen et al. (2011). Gray squares are VGPs that are not representative of a PSV-induced scatter, showing $A95 > A95_{max}$ (see text for a more detailed explanation). (b) Stereographic plot showing the distribution of the 52 characteristic remanent magnetizations (ChRMs) in normal polarity state, the mean values (open dot) and associated α_{95} cone of confidence (ellipsis) for the 48 directions representative of PSV-induced scatter (black dots), and the position of the African reference paleopole (black star). Gray squares are as in (a).

Özdemir (1997)). The presence of a medium-high coercivity fraction (>70 mT) hardly removed by AF demagnetization treatment can be explained by partial oxidation of titanomagnetite into titanomaghemite (see Fig. 3.17 in Dunlop and Özdemir (1997)). This result is partially

supported by IRM experiments that show the presence of very low-Ti titanomagnetite or pure magnetite.

The primary nature of the remanence is supported by three lines of evidence: (i) positive fold test indicating a pre-tilting magnetization;

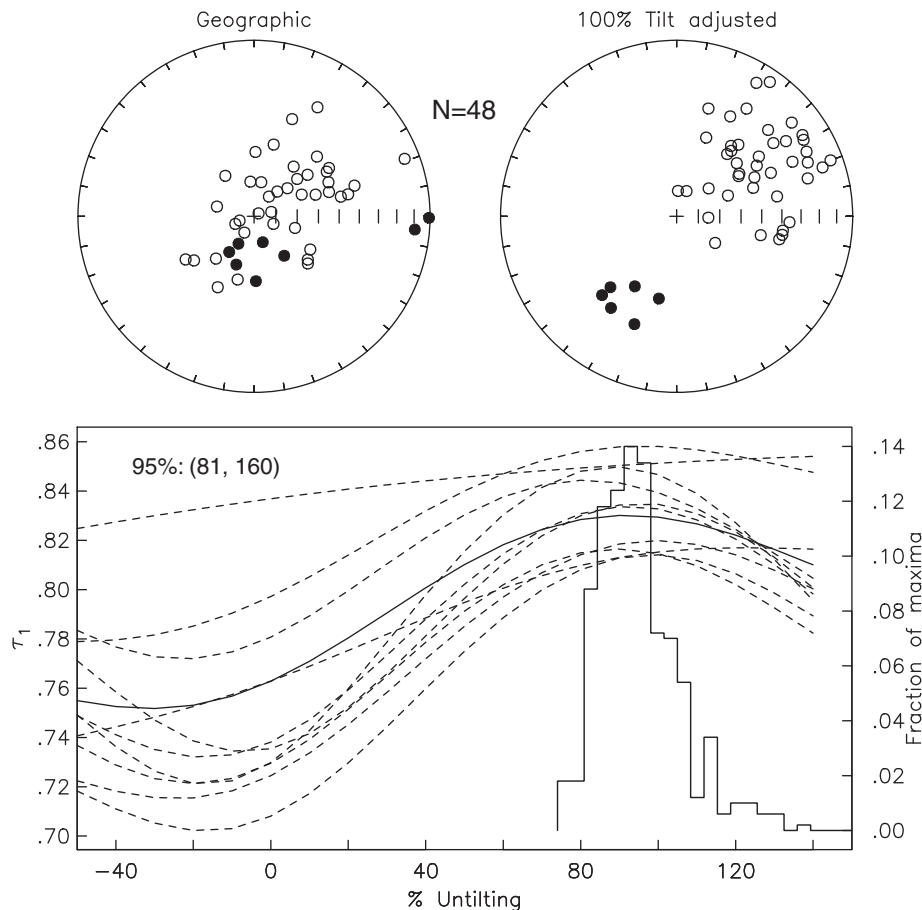


Fig. 9. (Above) stereographic plots of the 48 NE-directed ChRMs in situ (left) and tilt corrected (right) coordinates. Open (full) dots indicate reverse (normal) magnetic polarity. (Below) results of the non-parametric fold test (Tauxe and Watson, 1994) showing the 500 bootstrapped examples of the first eigenvalues (τ_1) upon progressive untilting. Closest grouping (maximum τ_1) occurs at 81%–160% unfolding, with a peak close to 100% unfolding, thus suggesting a positive fold test.

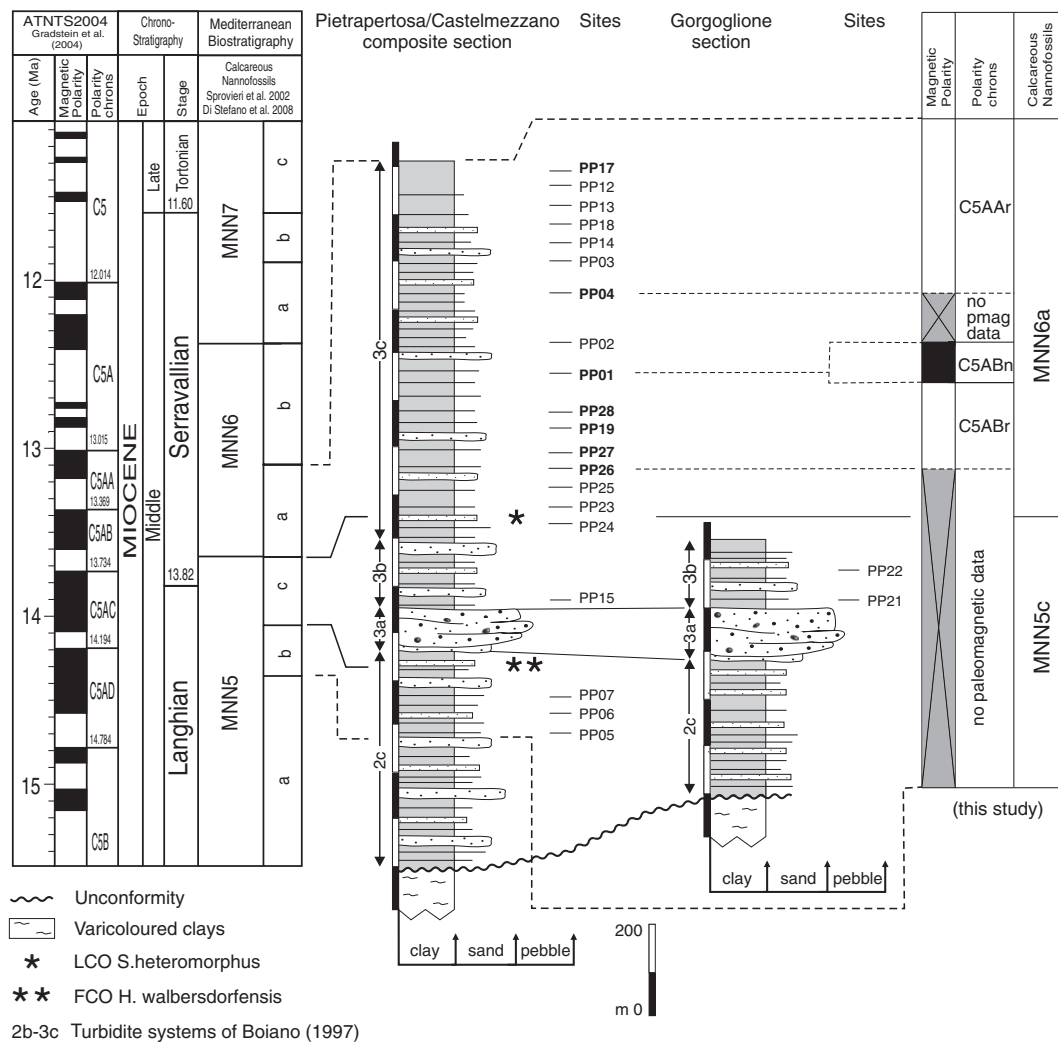


Fig. 10. Composite stratigraphic column of the sampled interval of the Gorgoglione Formation, showing the position of the sampled sites and their correlation to the magnetostratigraphic scale. Sites carrying a primary magnetization are shown in bold.

(ii) in-situ paleomagnetic directions not consistent with a present normal-polarity GAD field magnetic overprint; (iii) scatter of paleomagnetic directions (both at site and regional extent) consistent with a PSV-induced dispersion ($A95_{min} < A95 < A95_{max}$) for the given number of data, contrarily to remagnetized rocks where PSV scatter is underrepresented (i.e., $A95 < A95_{min}$) (see Deenen et al., 2011). Although both normal and reverse magnetic polarities are present in our dataset, the limited number of normal-polarity sites (site PP01 only) did not allow a meaningful reversal test and this evidence could not be used as a proof for the primary origin of magnetization. More importantly, a recent study has demonstrated that also remagnetized rocks can be characterized by both normal and reverse magnetic polarities (e.g., Meijers et al., 2011).

Age analysis for the studied sequence represented a major issue due to diffuse reworking of microfossils. In fact, the frequent occurrence of reworked specimens in the microfossil assemblages of Southern Apennines turbidites, induced in the past some authors (Amore et al., 1988, 2005, 2010; Sgroso, 1998) to rely only on the recognition of the First Occurrence (FO) of marker species, and to reject the use of the Last Occurrence (LO) and the quantitative analysis of the assemblages for their biostratigraphic studies. Other authors (Casella et al., 2012; Gallicchio and Maiorano, 1999; Lentini et al., 2002; Lirer et al., 2007; Maiorano, 1998) overcame this issue carrying out a quantitative analysis based on the abundance fluctuation of

marker taxa (First Common Occurrences, Last Common Occurrence, Paracme intervals, etc.). Our biostratigraphic analysis was based on the second approach and clearly revealed the presence of consistent Langhian to Serravallian assemblages comparable with those reported from different Miocene deep-sea sedimentary settings of the Mediterranean basin (Di Stefano et al., 2008; Foresi et al., 2002; Hilgen et al., 2000, 2003).

Samples carrying a primary magnetization occur within the MNN6a subzone, hence the magnetization was acquired in the early Serravallian (~13.5 Ma) (Fig. 10). Magnetic polarities of these samples were used to correlate the biostratigraphic age we calculated for the Gorgoglione Fm. to the geomagnetic polarity timescale (Gradstein et al., 2004), and eventually precisely constrain the age of the studied formation. We associated the reverse polarity sites PP19, PP26, PP27 and PP28 to subchron C5ABr (13.7–13.6 Ma), the normal polarity site PP01 to subchron C5ABn (13.6–13.4 Ma), and the remaining two reverse polarity sites PP04 and PP17 to subchron C5AAr (13.4–13.2 Ma) (Fig. 10, Table 1). The proximity of LCO of *S. heteromorphus* to the upper part of the C5ABr subchron (Fig. 10), documented from several Mediterranean sequences (e.g., Di Stefano et al., 2008), is strictly consistent with our magnetostratigraphic interpretation and provide a solid constraint for the age of the Gorgoglione Fm.

Relying on the proposed magnetostratigraphy we estimated a maximum sedimentation rate of 96 cm/ka. This value is comparable

to typical sedimentation rates of marginal basins (de Leeuw et al., 2013) and provides a further proof for both the accuracy of our magnetostratigraphic interpretation and the primary origin of the remanence.

5.2. Interpretation of the Gorgoglione Fm. rotation pattern

A mean direction for the Gorgoglione Fm. was calculated on the basis of 48 directions from the seven sites carrying a primary magnetization. The procedure of averaging out individual directions from different sites (rather than site mean values) is reasonable as they come from a relatively small region where no relative tectonic rotations are expected. Also, the age of the sampled rocks encompass a relatively short time span (i.e., 500 ka). The comparison between the observed and expected paleomagnetic directions revealed a post-Serravallian $\sim 125^\circ$ CCW rotation with respect to stable Africa. Two lines of evidence prove that this large rotation is not the result of local deformation: (i) direction of fold axes and thrust faults within the study area is consistent with the regional trend of the Southern Apennines (i.e., NNW–SSE); (ii) sinistral strike-slip faults, which might yield additional, local CCW rotations (Maffione et al., 2009; Sonder et al., 1986) are lacking within the sampling area. Hence, taking into account these evidences and considering the Gorgoglione Fm. as part of the underneath allochthonous unit, we can infer a mean $\sim 125^\circ$ CCW rotation for the entire nappe formed by the allochthonous Sicilide Unit.

Published paleomagnetic data from the Southern Apennines revealed an overall CCW rotation of $\sim 80^\circ$ (with uncertainties smaller than 10°) resulting from a progressive post-Langhian $\sim 60^\circ$ CCW rotation (Gattacceca and Speranza, 2002) and a Plio-Pleistocene $\sim 20^\circ$ CCW rotation (Sagnotti, 1992; Scheepers, 1994; Scheepers and Langereis, 1994; Scheepers et al., 1993). The $\sim 125^\circ$ CCW rotation of the Sicilide Unit exceeds the mean rotation of the Southern Apennines by $\sim 45^\circ$, and remain still significantly larger than the maximum rotations documented by Gattacceca and Speranza (2002) from post-late Cretaceous limestones of the Apenninic platform (i.e., 106° CCW rotation). Accordingly, excluding the effect of local deformations, an explanation for the extra $\sim 45^\circ$ CCW rotation of the Sicilide nappe must be provided.

The rotational pattern of the central Mediterranean have been interpreted so far in the framework of the Tyrrhenian Sea evolution and coeval bending of the Calabrian Arc (Cifelli et al., 2007, 2008; Mattei et al., 2002, 2004, 2007). In particular, both the magnitude and (temporal/geographic) distribution of the rotations in the overriding plate (i.e., the orogenic wedge) appear to be controlled by the Ionian slab dynamics. The along-strike variation of the rotation magnitude throughout the Calabrian Arc described by Cifelli et al. (2008) exhibits a jump (rather than a continuous progression) at the junction between the Southern Apennines and the CPB. This boundary represents a regional sinistral shear zone whereby the CPB migrated \sim ESE-ward during Ionian slab retreat and opening of the Tyrrhenian Sea, with only minor CW rotations ($\sim 20^\circ$ according to Cifelli et al. (2007)). Adjacent to this shear zone, extremely fast and/or variable rotations have been interpreted as the superficial effect of the lateral break-off and/or mantle toroidal flows associated to the underneath Ionian slab (Cifelli et al., 2008; Mattei et al., 2004). Yet, the Gorgoglione basin is located more than 70 km away from this region, and local small-block rotations can be ruled out.

Our new paleomagnetic data obtained from the Gorgoglione Fm. are representative of a small region (Fig. 4) and their regional implications can easily be underestimated. More data from similar rocks from a broader region would be required in order to provide a solid constraint for the evolution of the Southern Apennines. Nonetheless, the Gorgoglione basin represents a key area for the understanding of the tectonic phases affecting the most internal domains of the Southern Apennines. Its uniqueness is in the fact that the Gorgoglione Fm. is the only syn-tectonic piggy-back deposit unconformably

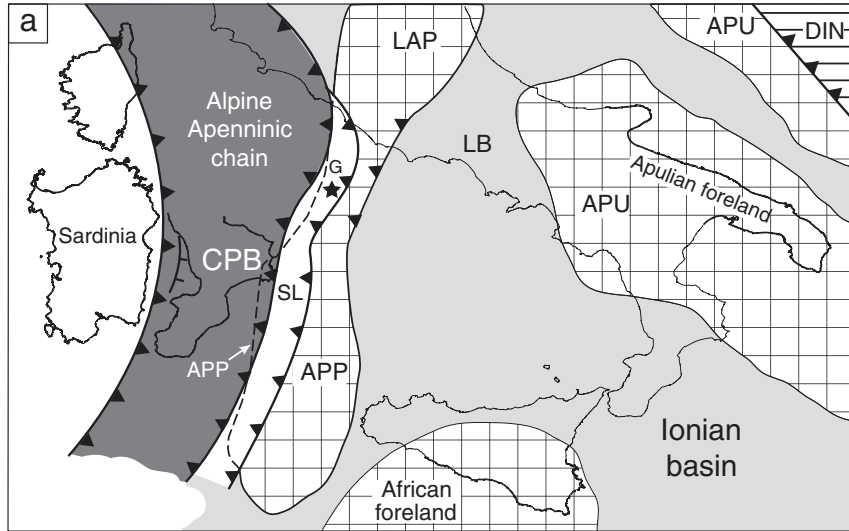
resting on top of (and thus forming a single tectono-stratigraphic unit with) the Sicilide Unit. There is no evidence for similar rocks occurring above (in stratigraphic contact) the Sicilide Unit elsewhere in the Southern Apennines. Accordingly, we tried to interpret our results from the Gorgoglione Fm. within a reliable tectonic scenario.

Previous paleomagnetic data from the Northern Apennines (Speranza et al., 1997) and Sicilian Maghrebidides (Channell et al., 1980, 1990; Speranza et al., 1999, 2003) showed that the rotation magnitude of pre-orogenic units decreases from the internal (top unit of the tectonic pile) towards the external (bottom unit of the tectonic pile) paleogeographic domains. In fact, the overall rotation of an internal unit of a fold-and-thrust belt is commonly the sum of progressive rotations yielded by the deformation of more external domains, while the compression migrates toward the foreland. Accordingly, a larger rotation of the Sicilide Unit ($\sim 125^\circ$) with respect to the Apenninic platform ($\sim 80^\circ$) can only be compatible with an internal paleogeographic position of the first unit, in agreement with several authors (Cinque et al., 1993; Critelli, 1999; Lentini et al., 2002; Monaco and Tortorici, 1995; Patacca and Scandone, 2007). We therefore propose that the extra $\sim 45^\circ$ CCW rotation of the Sicilide Unit with respect to the Apenninic platform is the result of a regional deformation affecting the most internal domains of the Southern Apennines during the earliest phases of tectonic rotation.

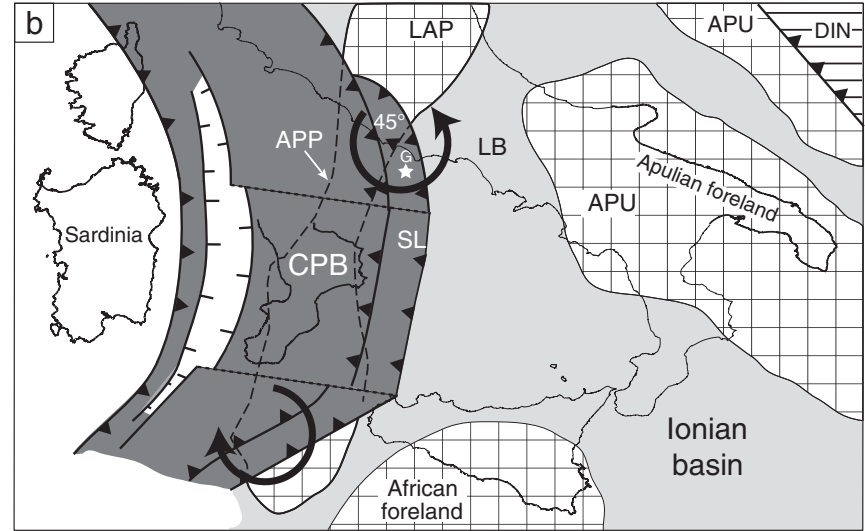
Combining our hypothesis with previous paleomagnetic and geologic evidences from the Southern Apennines we envisaged the following evolutionary scenario. According to Patacca and Scandone (2007) at the Burdigalian–Langhian boundary (~ 16 Ma) the internal basinal units (i.e., the Sicilide Unit and the Gorgoglione Fm. passively carried on top), the Apenninic platform and the Lagonegro Unit were already arranged from top to bottom, respectively, into a pile of partially superimposed, unrotated tectonic nappes (Fig. 11a). In the early Serravallian a portion of the Paleogene Alpine–Apenninic chain next to Sardinia underwent a localized \sim WNW–ESE extension (Mattei et al., 2002) that isolated a small crustal block currently represented by the Calabro-Peloritane block (CPB). Since the early Tortonian (~ 11 Ma), the CPB drifted away from Sardinia following the backward retreating of the Ionian slab and initial opening of the Tyrrhenian Sea (Duermeijer et al., 1998; Faccenna et al., 1997, 2001; Kastens et al., 1988; Malinverno and Ryan, 1986; Patacca et al., 1990, 1993). According to Patacca and Scandone (2007) this process was accompanied by an out-of-sequence thrusting event affecting the internal Sicilide Unit which completely overthrust the Apenninic platform and part of the Lagonegro basin. We propose that the onset of the rotational phase in the Southern Apennines (and possibly in the Sicilian Maghrebidides) was synchronous to this event. The \sim ESE-ward drifting of the CPB might have deformed the most adjacent domains (i.e., the Sicilide Unit) first, yielding fault reactivation and an overall $\sim 45^\circ$ CCW rotation (Fig. 11b). According to this hypothesis, the post-Serravallian rotation we documented from the Gorgoglione Fm. has to be attributed to an early Tortonian age. Nonetheless, our data provide a maximum age limit (early Serravallian) for the tectonic rotations in the Southern Apennines.

During the Tortonian–Zanclean time interval (~ 11 –5 Ma) the Sicilide Unit and the Apenninic platform thrust over the Lagonegro Unit and then, in turn all these three units were emplaced over the Apulian platform (Patacca and Scandone, 2007). This main deformation phase resulted into an overall $\sim 60^\circ$ CCW rotation (Gattacceca and Speranza, 2002) while accommodating the \sim ESE-ward migration of the CPB (Fig. 11c). The final stage of the rotations in the Southern Apennines occurred mainly during the early Pleistocene (~ 2 Ma) when the westernmost portions of the Apulian platform were involved into deformation (forming the “buried Apulian belt”), providing additional $\sim 20^\circ$ CCW rotation to the entire orogenic wedge (Mattei et al., 2004; Sagnotti, 1992; Scheepers, 1994; Scheepers and Langereis, 1994; Scheepers et al., 1993). As a final result, the Apulian platform, the Apenninic platform/Lagonegro Unit, and the Sicilide Unit experienced $\sim 20^\circ$, $\sim 80^\circ$, and $\sim 125^\circ$ CW rotation, respectively.

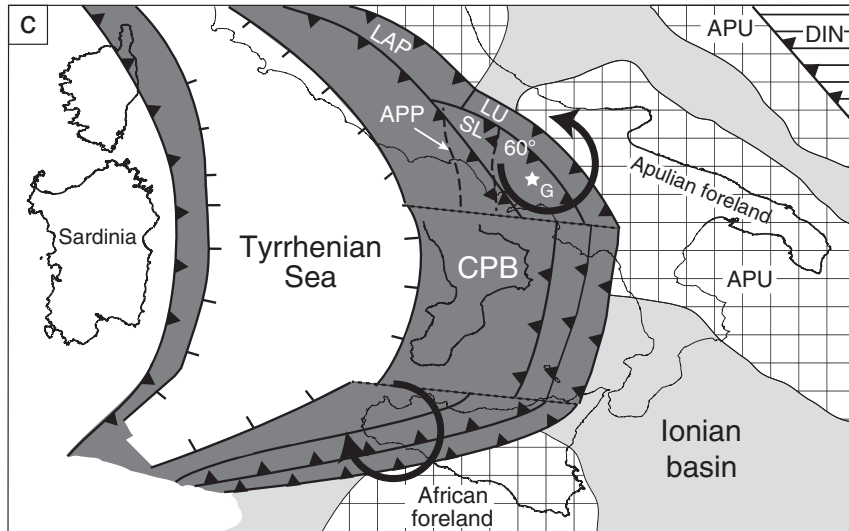
BURDIGALIAN-LANGHIAN BOUNDARY (~16 Ma)



EARLY TORTONIAN (~11 Ma)



EARLY PLIOCENE (~5 Ma)



EARLY PLEISTOCENE (~2 Ma)

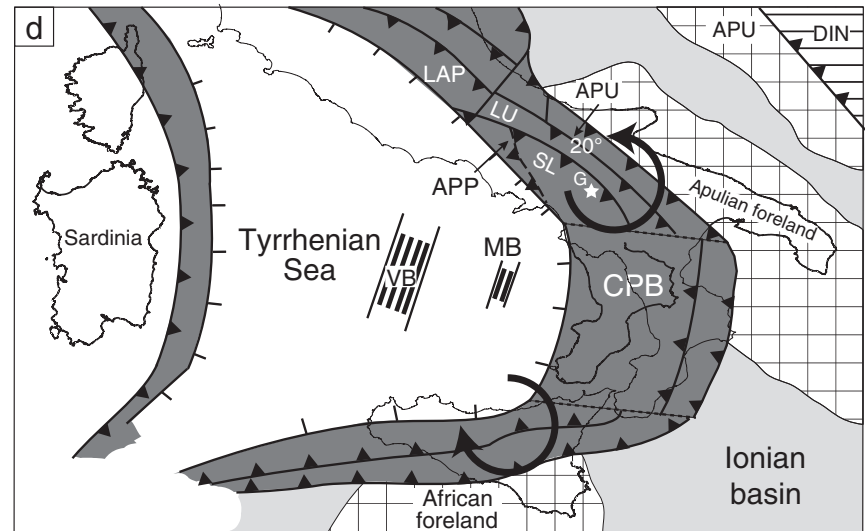


Fig. 11. Evolutionary tectonic model showing the formation of the Calabrian Arc and the opening of the Tyrrhenian Sea at four different stages. The current position of the Italian coast is shown. Tectonic rotations (curve arrows with rotation magnitude) represent the cumulative value recorded between the previous and at indicated age at each stage. (a,c,d) Tectonic setting inferred from previous geological and paleomagnetic evidences. (b) Proposed scenario at the early Tortonian based on our new results from the Gorgoglione Formation. CPB, Calabro-Peloritan block; APP, Apenninic platform; SL, Sicilide-Liguride Units; LB, Lagonegro basin; LAP, Latium-Abruzzi platform; APU, Apulian platform; DIN, Dinarides; G, Gorgoglione basin; VB, Vavilov basin; MB, Marsili basin. Dark gray areas represent regions of active compressional tectonics at the corresponding stage. White areas with squared net are the carbonatic platforms. Thrust and extensional faults are indicated by lines with triangles and ticks, respectively.

5.3. Role of the Ionian slab within the geodynamics of the central Mediterranean

We have interpreted the observed paleomagnetic directions from the Gorgoglione Fm. as the result of progressive rotations recorded by the most internal domains of the Southern Apennines (i.e., Sicilide Unit) since the early Tortonian. According to our hypothesis, the mean $\sim 125^\circ$ CCW rotation of the Sicilide Unit is directly comparable to the largest rotations experienced by the internal domains of the Sicilian Maghrebides (i.e., 134° CW, Speranza et al., 1999, 2003). Consistent (maximum) rotations throughout the Calabrian Arc are indicative of a symmetrical bending and a saloon-door-style opening of the Tyrrhenian Sea. A similar scenario was first pictured by Cifelli et al. (2007) who suggested a quasi-symmetrical bending of the salient. A purely symmetrical bending of the Calabrian Arc, resulting more clearly from our tectonic model, would emphasize even more the primary role of the Ionian slab and exclude any major contribution of the Europe–Africa convergence (which is oriented \sim N–S in present-day coordinates) to the geodynamic evolution of this arcuate system. Nevertheless, as proposed by some authors (Johnston and Mazzoli, 2009) the Europe–Africa convergence might have limited orogen-parallel stretching generated by progressive bending of the wedge.

A further proof for the central role of the Ionian slab is provided by the relationship between the rotation rates from the Southern Apennines and the spreading events occurring in the Tyrrhenian Sea. A rotation rate as high as $\sim 40^\circ/\text{Ma}$ was described by Mattei et al. (2004) for the external domains of the Southern Apennines (Sant’Arcangelo basin) where an ultra-rapid $\sim 20^\circ$ CCW rotation occurred during the early Pleistocene (~ 2 Ma) in a time span shorter than 0.5 Ma. Such event was likely synchronous to an ultra-fast oceanic spreading episode (19 cm/a) that occurred at the Marsili seamount in the southern Tyrrhenian Sea (Fig. 11) inferred from subparallel 1.6–2.1 Ma-old magnetic anomaly stripes (Nicolosi et al., 2006). This ultra-rapid event might have resulted from an episodic pulse of the Ionian slab subduction triggered by heterogeneity of the slab panel and tears forming in the Ionian lithosphere undergoing strong lateral stretching (e.g., Faccenna et al., 1997). The concomitance of these events clearly evidences the intimate geodynamic link between the subduction of the Ionian slab and progressive bending of the Calabrian Arc.

According to our reconstructed evolutionary scenario, about 105° CCW rotation occurred during the Miocene ($\sim 45^\circ$ early Tortonian rotation plus $\sim 60^\circ$ Tortonian–Pliocene rotation) coeval to the main rifting episodes in the Tyrrhenian Sea (Mattei et al., 2002; Patacca et al., 1990). This translates into a minimum rotation rate of $\sim 18^\circ/\text{Ma}$. This value, significantly smaller than the former estimate by Mattei et al. (2004) for the early Pleistocene rotational phase may suggest that the evolution of the Calabrian Arc occurred through short, fast episodes well exceeding the average Miocene rate of $\sim 18^\circ/\text{Ma}$, followed by longer periods of quiescence.

6. Conclusions

Our new paleomagnetic and biostratigraphic study of the Gorgoglione Fm., a piggy-back deposit of the Southern Apennines unconformably resting on top of a paleogeographic unit of internal affinity (i.e., Sicilide Unit), documented a post-early Serravallian $\sim 125^\circ$ CCW rotation. This rotation, associated to the underneath Sicilide Unit, exceeds by $\sim 45^\circ$ the mean CCW rotation of the Southern Apennines documented so far. Geological evidence ruled out the occurrence of local deformations at the study area as a potential source of additional rotations. Such a large-magnitude rotation of the Sicilide Unit is consistent with its internal paleogeographic provenance, and was interpreted as the result of an earlier rotational phase affecting the most internal domains of the Southern Apennines, adjacent to the initial locus of the Tyrrhenian back-arc extension. We propose that the $\sim 45^\circ$ CCW rotation of the

Sicilide Unit was triggered by the \sim ESE-ward drifting of the Calabro-Peloritan block (CPB) and the onset of the Tyrrhenian Sea opening in the early Tortonian.

Relying on our proposed scenario, consistent maximum rotations ($\sim 130^\circ$) throughout the Calabrian Arc would indicate a purely symmetrical bending. This evidence, together with coexisting processes affecting both the orogenic wedge and Tyrrhenian Sea ultimately confirm the primary role of the Ionian slab in the Neogene-to-Recent geodynamic evolution of the Calabrian Arc.

Acknowledgments

This work benefited of INGV and FIRB MIUR C2 (responsible L. Sagnotti) funds. We are grateful to M. Meijers, D. Bilardello, and an anonymous reviewer for thorough review, which helped to substantially improve the original manuscript. MM gratefully acknowledge P. Macrì for the help given in the sampling campaign, and C. Langereis and D.J.J. van Hinsbergen for helpful advices during the manuscript revision.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.tecto.2013.01.005>.

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