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The evolution of the Calabrian Arc: Evidence from paleomagnetic and GPS observations

M. Mattei [a], F. Cifelli [a,*], N. D'Agostino [b]

[a] Dipartimento di Scienze Geologiche, Università di Roma Tre, Largo S. Leonardo Murialdo, I-00146 Rome, Italy
[b] Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata, 605, I-00143 Rome, Italy

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Abstract

The present-day arcuate shape of the Calabrian Arc has been accomplished during Neogene and Early Pleistocene by large and opposite vertical axis rotations along the two arms of the Arc. Clockwise (CW) rotations have been systematically registered in Sicily and Calabria, whereas counterclockwise (CCW) rotations were measured in Southern Apennines. Such opposite vertical axis rotations ceased in the uppermost part of the Lower Pleistocene (about 1 Ma ago) along almost the entire Calabrian Arc and are not observed in the present-day GPS velocity field. The end of the Calabrian Arc bending during the Quaternary marks a decrease in the efficiency of the tectonic processes related to the long-lived subduction of the Ionian slab, which caused the halting of the back-arc opening in the Southern Tyrrhenian Sea.

Keywords: Calabrian Arc; subduction; paleomagnetism; GPS

1. Introduction

The presence of curved orogenic systems and related back-arc basins on top of narrow subducting slabs is a common feature of the Mediterranean Basin (Faccenna et al., 2004; Guegen et al., 1998; Lonergan and White, 1997; Rosenbaum and Lister, 2004). Since Malinverno and Ryan (1986) first presented their interpretation on the formation of the Calabrian Arc as a consequence of the trench retreat because of the narrow Ionian oceanic lithosphere, most later geodynamic models proposed that the Mediterranean arcs formed as a consequence of the progressive retreat of the subducting zone and can be, therefore, considered secondary features achieved through huge and opposite rotations along the edges, shaping the arcs (among others, Faccenna et al., 1997; Guegen et al., 1998; Lonergan and White, 1997; Rosenbaum and Lister, 2004; Royden, 1993; Wortel and Spakman, 2000).

Despite slab rupture and backward migration is a common mechanism governing arc formation, the Mediterranean subduction zone is now segmented in narrow tongues from an original single, wider subduction zone, each characterized by a different evolutionary stage of the subduction process (e.g., Faccenna et al., 2004). The Gibraltar Arc, the westernmost subduction zone segment, mainly formed during the early-middle Miocene. Geologic and geophysical data indicate that the subduction process has now terminated (Faccenna et al., 2004; Lonergan and White, 1997; Royden, 1993; Wortel and Spakman, 2000), although some authors believe that subduction is still active below the Gibraltar Arc

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* Corresponding author.
E-mail address: cifelli@uniroma3.it (F. Cifelli).

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(Gutscher et al., 2002). At the easternmost side of the Mediterranean subduction zone, subduction beneath the Aegean region (Greece) started in the Cretaceous (Dercourt et al., 1986) and it is still active, as proved by the associated active deformation and by frequent earthquakes affecting the area (e.g., McKenzie, 1978). In the Central Mediterranean, the tight and narrow Calabrian Arc attained its shape mostly between the late Miocene and the Pleistocene, during the opening of the Tyrrhenian Sea. The Calabrian Arc is located on top of a very narrow, sub-vertical and NW dipping oceanic slab, the Ionian slab, clearly defined by seismicity and seismic tomography (Wortel and Spakman, 2000) (Fig. 1). In this subduction system, trench retreat was particularly fast over the Neogene and early Quaternary (Patacca et al., 1990) as indicated by high extension rates (50-70 mm/yr) recorded in the new-formed Vavilov (Neogene) and Marsili (Early-Middle Pleistocene) oceanic seamounts (Marani and Trua, 2002; Mattei et al., 2002; Nicolosi et al., 2006), rapid migration of the trench, indicated by the progressive shifting of foredeep basins, and the huge vertical axis rotations which occurred during Miocene to Quaternary, responsible of the arcuate shape of the Calabrian Arc. After this time, a transition toward a different tectonic scenario occurred and presently, despite active seismicity in the slab, there is no clear evidence of significant back-arc extension, foredeep migration and vertical axis rotation in the Calabrian Arc, leaving the question whether the trench retreat process is active or not still open.

The Calabrian Arc subduction system may be considered at an intermediate evolutionary stage between the still active Aegean region subduction system and the mature Gibraltar Arc subduction system. For these reasons, it represents a unique opportunity for studying the transient final stage of the subduction process and the transition toward a new tectonic regime.

In this paper, we use combined geologic, paleomagnetic and GPS data in order to investigate the tectonic evolution of the Calabrian Arc from Neogene to Present-day and to explain the change in the tectonic regime of the Calabrian Arc during the Pleistocene. We interpret this change as a consequence of a variation in the Ionian slab size and geometry, which cause a substantial cessation of the subduction process.

2. Tectonic setting

The Calabrian Arc is constituted by two sectors, the Calabria–Peloritane Domain (CPD) and the Southern Apennines and Sicilian Maghrebides fold-and-thrust belt, which show different tectonic evolutions, structural architectures, and deep lithospheric structures (Bigi et al., 1992; Bonardi et al., 2001; Wortel and Spakman, 2000) (Fig. 1). The Southern Apennine and Sicilian Maghrebide chain ranges from a northwest-southeast orientation in the Southern Apennines to an east-west orientation in Sicily, forming the two limbs of the Calabrian Arc. It is mainly composed of Mesozoic to Tertiary shallow-platform and deep basin sedimentary units of the African and Adriatic continental margins, which form the Apennine fold-and-thrust system together with sediments from Neogene–Quaternary foredeep and thrust-top basins.

The main compressional phases in Southern Apennines and Sicily started in the late Miocene and were almost finished during the early Pleistocene, as testified by the presence of Sicilian (uppermost lower Pleistocene) sediments, which clearly cap the outer fronts of the chain (Argnani et al., 1987; Butler and Grasso, 1993; Patacca and Scandone, 2001, 2004). The emplacement of the thrust nappe in Southern Apennines was followed by extensional tectonics, which progressively disrupted the fold-and-thrust belt. In the Southern Apennines, extensional processes started during late Pliocene–early Pleistocene (Ascione and Romano, 1999) along the Tyrrhenian coast and migrated during the Quaternary to reach the axial part of the chain. Here, active deformation is mostly accomplished by NW-SE oriented normal faults, which are responsible of the largest historical earthquakes recorded in this part of the Italian territory (Montone et al., 2004; Valensise and Pantosti, 2001).

The core of the Calabrian Arc is formed by the CPD domain, which during early Miocene time was located adjacent to Corsica–Sardinia. Since middle-late Miocene the CPD has drifted away from Sardinia to be finally juxtaposed with the Southern Apennine–Maghrebide orogenic system (Alvarez et al., 1974; Bonardi et al., 2001; Faccenna et al., 1997; Malinverno and Ryan, 1986; Mattei et al., 2002). The CPD mostly consist of a Hercynian basement, Alpine polymetamorphic rock successions related to the deformation of the Southern Tethyan margin, and Mesozoic sedimentary units. These units are unconformably overlain by Tertiary sedimentary sequences, deposited in different tectonic provinces of the Calabrian Arc. In particular, upper Tertiary-to-Quaternary forearc basin sedimentary sequences developed along the Ionian side of the CPD (Bonardi et al., 2001; Cavazza et al., 1997) at the rear of an accretionary wedge located offshore in the Ionian Sea (Cernobori et al., 1996). Conversely, Miocene-to-Quaternary deposits cropping out along the Tyrrhenian side are interpreted as extensional back-arc basins, associated with opening and expansion of the Southern Tyrrhenian Sea (Cifelli et al., 2007a; Mattei et al., 2002; Sartori, 1990).

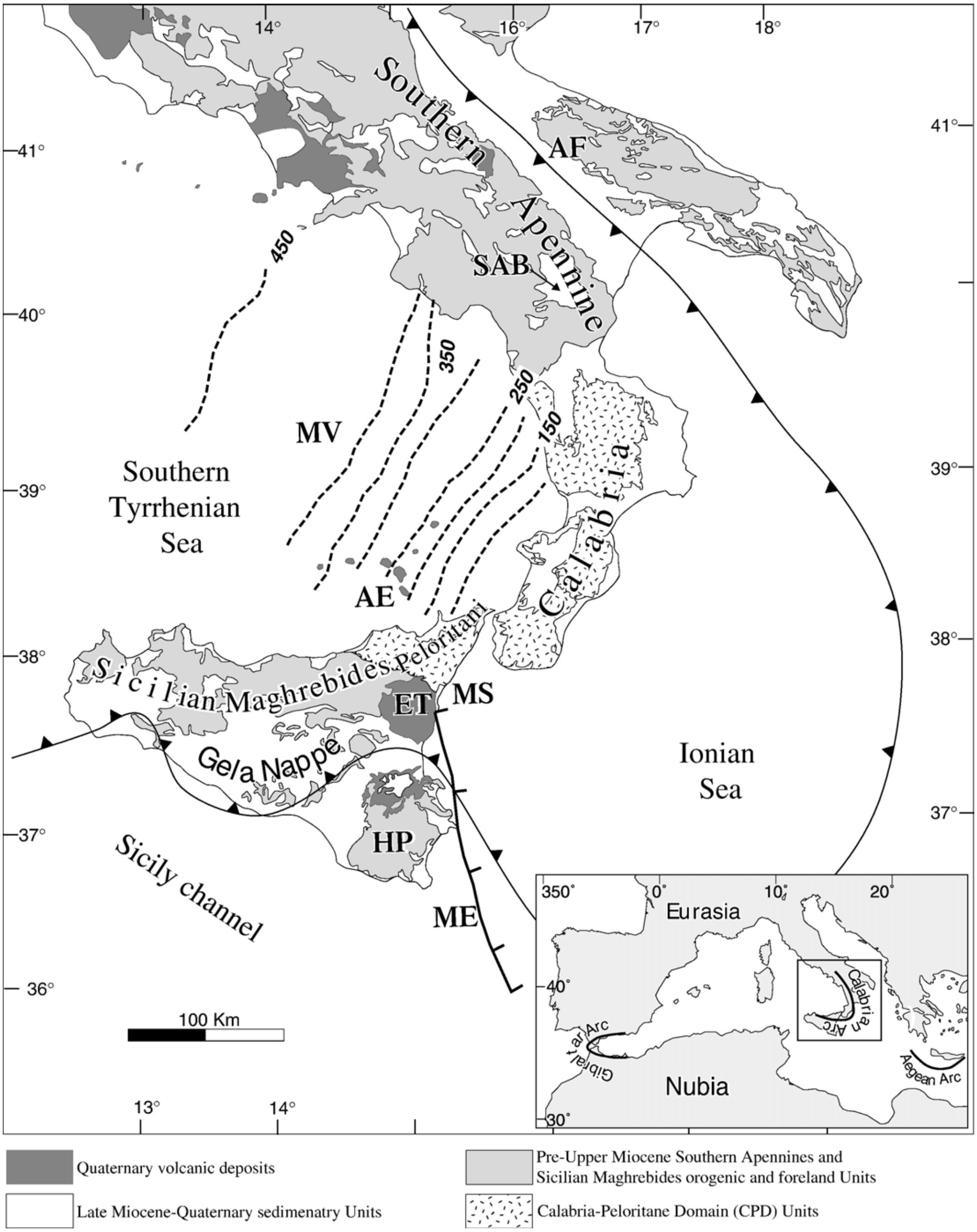

Fig. 1. Schematic geologic map of southern Italy. The black line shows the trace of the outer front of the Apennine chain (black triangles). Deep and intermediate seismicity in the Wadati–Benioff zone beneath the Tyrrhenian Sea are shown as contours of the subducted slab labeled in kilometers (modified from Frepoli et al., 1996). Abbreviations are as follows: AE, Aeolian Islands; AF, Apulian Foreland; ET, Mount Etna; HP, Hyblean Plateau; ME, Malta escarpment; MS, Messina Strait; MV, Marsili Volcano; SAB, Sant'Arcangelo Basin.

Such different tectonic evolution and structural architecture between the CPD, from one side, and Sicilian Maghrebides and Southern Apennines, on the other side, is also reflected in the upper mantle structure. Earthquake distribution and seismic tomography indicate that the CPD is presently located on top of a narrow (roughly 200 km) and steeply dipping (70°) slab for a total length of about 700 km (e.g., Anderson and Jackson, 1987; Lucente et al., 1999; Piromallo and Morelli, 2003; Selvaggi and Chiarabba, 1995; Spakman et al., 1993;

Wortel and Spakman, 2000). The across-strike width of the slab corresponds to the Ionian realm, a Mesozoic oceanic lithosphere, intervening between the Apulia and Africa continental margins. Its northeastern and southwestern boundaries match, at the surface, the boundary between CPD and Southern Apennines and western Sicily, respectively, which conversely, do not show any evidence of deep seismicity (Fig. 1). The relationship between seismicity in the slab beneath the Tyrrhenian Sea and the activity of the subduction zone is not clear. Although the deep earthquakes and the seismic tomography provide clear evidence of the slab (Lucente et al., 1999), the distribution of seismicity does not show any proof of shortening in the accretionary wedge or plate interface deformation beneath the Calabrian wedge (Chiarabba et al., 2005). Furthermore, seismic profiles show no evidence of tectonic deformation in the Quaternary, being the front of the wedge being affected only by large gravity slides (Chamot-Rooke et al., 2005). This evidence prompted the idea of a detached slab that is not kinematically connected with the Ionian Sea lithosphere (Westaway, 1993; Wortel and Spakman, 2000).

3. Paleomagnetic data from the Calabrian Arc

In the last decades, a large amount of paleomagnetic data has been collected in Southern Apennines, Calabria, and Sicily (among others, Aifa et al., 1988; Besse et al., 1984; Butler et al., 1999; Channell et al., 1980, 1990; Cifelli, 2004; Cifelli et al., 2007b; Duermejier et al., 1998; Gattacceca and Speranza, 2002; Mattei et al., 2002, 2004; Sagnotti, 1992; Scheepers and Langereis, 1993, 1994; Scheepers et al., 1993, 1994; Speranza et al., 2003, 1999, 2000). The whole paleomagnetic data set is displayed in Fig. 2, where paleomagnetic rotations have been differentiated according to the age of the sampled sites. Counterclockwise (CCW) and clockwise (CW) rotations have been systematically measured in Southern Apennines, and in Calabria and Sicily, respectively, showing that the progressive reorientation of the orogenic structures, leading to a northwest–southeast trend in Southern Apennines and to an east–west trend in Sicily, is related to opposite vertical axis rotations along the two limbs of the arc. These rotations have been observed only in the orogenic wedge and do not extend to the undeformed Apulian and Nubian foreland basins, which remained almost unrotated during the Neogene and Quaternary (Fig. 2).

Paleomagnetic data from Mesozoic to Lower Miocene sedimentary units come from the internal part of the Apenninic chain in Sicily and Southern Apennines (Fig. 2a). Results are consistent in the different parts of the arc and show large paleomagnetic rotations (up to 145° CW and 80° CCW in Sicily and Southern Apennines, respectively), which indicate that the internal part of the Apennine wedge underwent huge opposite vertical axis rotations since Miocene (e.g., Gattacceca and Speranza, 2002; Speranza et al., 2003).

A large number of paleomagnetic data from late Miocene to Pliocene sedimentary units is available, both in the Southern Apennines-Sicilian Maghrebides and in Calabria (Fig. 2b). In the Southern Apennines and Sicily, paleomagnetic results from late Miocene–Pliocene sediments show opposite sense of rotations (CCW in Southern Apennines and CW in Sicily), but the amount of rotation is significantly lower than that registered in the Mesozoic-Middle Miocene units. In Calabria, paleomagnetic rotations are also CW, with a magnitude comparable to that measured in Sicily, without a significant difference between the extensional basins from the Tyrrhenian margin and the forearc basins in the Ionian side.

Paleomagnetic data from lowermost lower Pleistocene sites were collected in the Southern Apennines, Calabria, Sicily, and in the Apulian and Hyblean foreland (Fig. 2c). In the Southern Apennines and Sicily, paleomagnetic results are from foredeep and thrust-top basin sediments, which record the latest stages of compressive deformation, related to the emplacement of the outer front of the Apenninic chain. In Calabria, results are from the above-mentioned extensional and fore-arc basin sediments. Opposite vertical axis rotations have been measured along the entire arc (CCW in Southern Apennines and CW in western Sicily and Calabria) in lowermost lower Pleistocene sites, suggesting that a significant amount of vertical axis rotation also occurred during the Quaternary.

Finally, paleomagnetic data from uppermost lower to middle Pleistocene sediments in Sicily, Calabria, and the Southern Apennines are reported in Fig. 2d. Paleomagnetic declinations show a significant CW rotation only in one site from Southern Calabria, whereas in the Southern Apennines, northern Calabria, and Sicily paleomagnetic results point out that no significant vertical axis rotations occurred in sediments of that age. It is worth noting that whereas vertical axis rotations have been measured in lower Pleistocene units (Fig. 2c), no rotations have been generally measured in uppermost lower Pleistocene-middle Pleistocene units (Fig. 2d), suggesting that in a large part of the Calabrian Arc, vertical axis rotations occurred during the early Pleistocene and were almost finished by the middle Pleistocene.

In the general picture of the recent geodynamic evolution of the Calabrian Arc, the lack of vertical axis rotation observed in uppermost lower Pleistocene–middle Pleistocene deposits is a fundamental feature. The

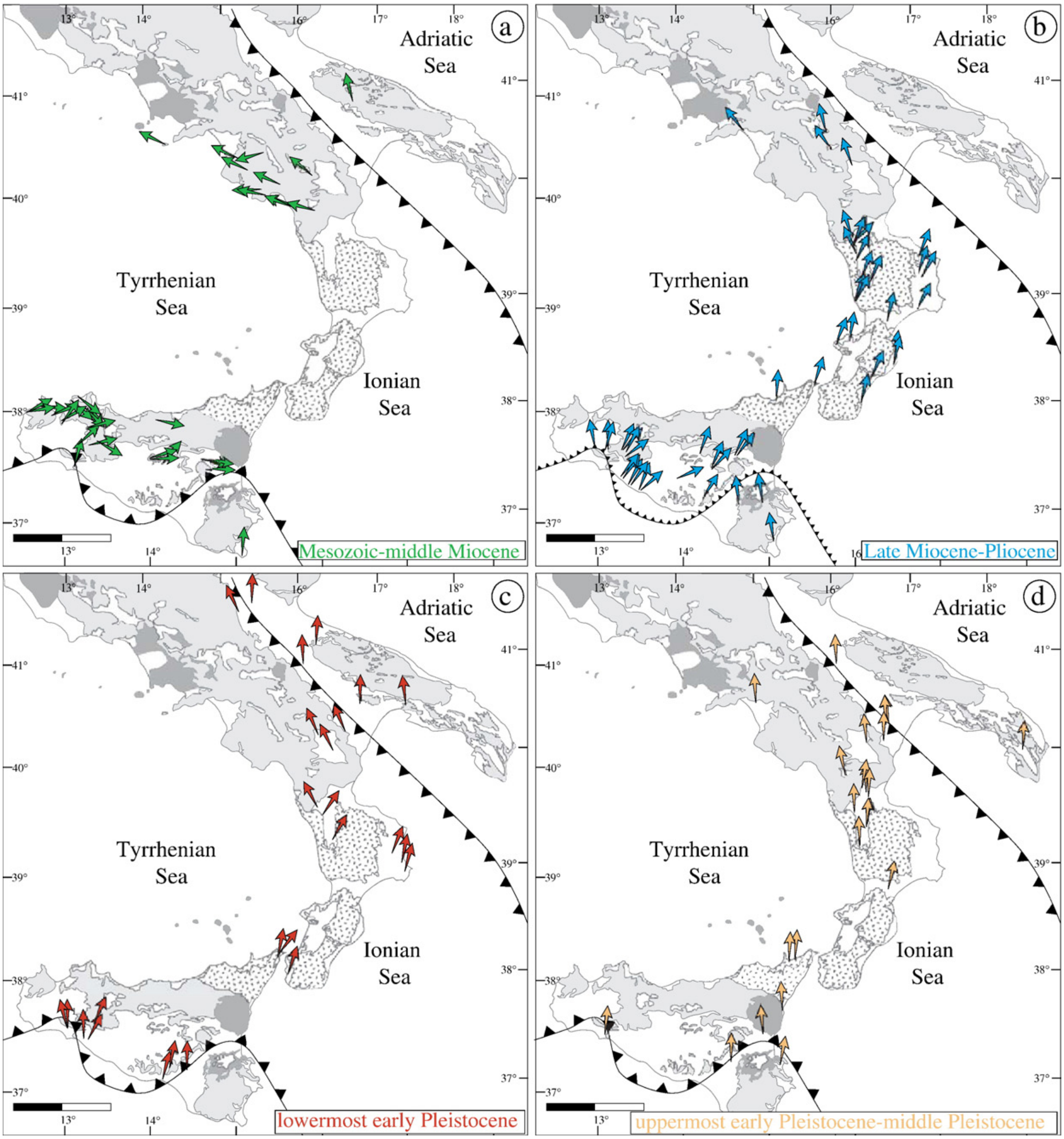

Fig. 2. Synthesis of the paleomagnetic data collected in the Southern Apennines, Calabria and Sicily. Each arrow represents rotation computed from one site or group of sites. Mesozoic–Paleogene and Neogene–Quaternary paleomagnetic rotations are calculated by comparing paleomagnetic declinations to coeval expected African directions (Besse and Courtillot, 2002) and to the geocentric axial dipole (GAD) field direction, respectively. Arrows indicate paleomagnetic rotations in Mesozoic to middle Miocene units (a), upper Miocene–Pliocene units (b), lower Pleistocene units (c), and uppermost lower Pleistocene–Middle Pleistocene units (d). Paleomagnetic data are from: Aifa et al., 1988; Barberi et al., 1974; Besse et al., 1984; Butler et al., 1999; Catalano et al., 1976; Channell et al., 1980, 1990, 1992; Cifelli et al., 2004, 2007b; Duermejier et al., 1998; Gattacceca and Speranza, 2002; Gregor et al., 1975; Jackson, 1990; Manzoni, 1975; Marton and Nardi, 1994; Mattei et al., 2002, 2004; Nairn et al., 1985; Sagnotti, 1992; Scheepers, 1992, 1994; Scheepers and Langereis, 1993, 1994; Scheepers et al., 1993, 1994; Schult, 1976; Speranza, et al., 1999, 2000, 2003; Tauxe et al., 1983.

main question arising from this evidence is whether such lack of rotation is due to inherent uncertainties in paleomagnetic measurements, or whether it reflects the beginning of a new tectonic process associated with a geodynamic regime different from that characterizing the past few million years. In the following section we discuss geologic, paleomagnetic and geodetic evidence that supports the idea that the absence of recent paleomagnetic rotations is indicative of a cessation of the Ionian slab subduction during the Pleistocene.

4. Geologic, paleomagnetic and geodetic evidence supporting the end of the Calabrian Arc bending

4.1. Structural and geologic constraints to the timing of paleomagnetic rotations

Paleomagnetic data reported in Fig. 2 indicate that lower Pleistocene sediments registered significant CCW in Southern Apennines and CW rotations in Calabria and Sicily, whereas uppermost lower Pleistocene and middle Pleistocene sediments in most parts of the arc do not show paleomagnetic rotations. In order to evaluate the close correspondence between the timing of paleomagnetic rotations and the activity of the thrust structures in Southern Italy during the Quaternary, we discuss two different regions located along the two edges of the arc, where sedimentary sequences record in detail the Quaternary tectonic evolution of the outer part of the Southern Apennines and Sicilian Maghrebides chains: the Sant'Arcangelo basin in the southernmost Apennines and the Gela nappe, in central Sicily (Table 1 and Fig. 3). We selected these two regions for the following reasons: i) they have been the object of detailed structural and stratigraphic studies which allow precise description of their Quaternary tectonic evolution (Argnani et al., 1987; Butler et al., 1995, 1992; Grasso et al., 1995; Hippolyte et al., 1991; Patacca and Scandone, 2001, 2004; Pieri et al., 1994); ii) in these areas several paleomagnetic studies have been carried out and the rotational history is, therefore, very well constrained (e.g., Butler et al., 1999; Mattei et al., 2004; Sagnotti, 1992; Scheepers et al., 1993).

4.1.1. The Sant'Arcangelo Basin

The Sant'Arcangelo basin is a north-northwest–trending thrust-top basin located in the external part of the Southern Apennines, filled by 3000 m of Pliocene–lower Pleistocene marine sediments (Patacca and Scandone, 2001; Pieri et al., 1994; Vezzani, 1967) (Fig. 1). The geometry of this basin mainly derives from the Pliocene–Pleistocene eastward propagation of the Apennines thrust over the Apulia foreland. Its eastern boundary is given by the Nocara ridge, a thrust-related anticline which grew up during lower Pleistocene and was responsible of the isolation of the lower Pleistocene Sant'Arcangelo basin from the Bradanic foredeep (Fig. 3a). As a consequence, in the Sant'Arcangelo basin the Santernian–Emilian foredeep marine sediments pass upward to Sicilian–middle Pleistocene brackish, lacustrine, and alluvial continental sediments, whereas in the Bradanic foredeep the upward transition is to marine clays and sandstones. These latter units mark the end of compressional tectonics in this region, as evidenced by the presence of folds, growth strata, and progressive unconformities overlain by almost horizontal, undeformed strata (Fig. 3a). On the other hand, seismic data and deep wells show that the outer thrust front of the southern Apennines deforms lower Pleistocene (Santernian–Sicilian) sediments, whereas it is sealed by lower (Sicilian)–middle Pleistocene sedimentary units of the Bradanic foredeep (Patacca and Scandone, 2001; Pieri et al., 1994). The termination of thrust activity along the outer front of the chain (Patacca and Scandone, 2001) coincides with increasing extensional processes along the axial part of Southern Apennines during the uppermost early Pleistocene, testified by the formation of several fault-bounded intramontane sedimentary basins which unconformably lie on top of the fold and thrust Apennine units (e.g., Cinque et al., 1993). These basins are bounded by NW-SE oriented normal faults, which have been also responsible for the strong and disruptive historical seismicity in the region (Valensise and Pantosti, 2001).

In the Sant'Arcangelo basin and in the adjacent Bradanic foredeep deposits, a large amount of paleomagnetic data is available (Table 1). They indicate a general CCW rotation in upper Pliocene–lower Pleistocene sediments. In particular, CCW have been measured in upper Pliocene marine sediments of the Sant'Arcangelo basin (18°±8°), in the Santernian–Emilian marine clays (1.85-1.25 Ma) of the Sant'Arcangelo basin (24°±6°) and of the Bradanic foredeep (23°±17°) (Sagnotti, 1992; Scheepers et al., 1993). On the other hand, no significant paleomagnetic rotations (−4°±10°) have been measured in the uppermost (Sicilian) lower Pleistocene lacustrine deposits which outcrop in the core of the Sant'Arcangelo syncline, or on the marine clays which outcrop along the Bradanic foredeep basin (−4°±8°) and in this region seal the outer front of the Southern Apennines chain (Mattei et al., 2004; Scheepers et al., 1993) (Fig. 3a). On this basis, paleomagnetic data from Sant'Arcangelo area show that this region underwent substantial CCW paleomagnetic rotations during the early Pleistocene. These rotations occurred during the emplacement of the outer front of the Southern Apenninic chain, and were almost completed at about 1.0 Ma, when the cessation of the thrust activity and the halting of the compressional tectonics in this part of the belt occurred (Mattei et al., 2004; Scheepers et al., 1993) (Figs. 3 and 4).

Table 1
Plio-Pleistocene paleomagnetic rotations in the Apennine thrust belt

		D	I	α_{95}	Rot	Err(±)	Sites	Ref.
Southern Apennines								
Sant'Arcangelo	Upper Pliocene	341.6	50.6	5.2	−18	8	2	1
					−18	**8**	**2**	**a**
Sant'Arcangelo	Lower Pleist.	157.2	−57.2	4.4	−23	8	11	1
Sant'Arcangelo	Lower Pleist.	155.4	−59.1	4.5	−25	9	11	2
					−24	**6**	**22**	**b**
Sant'Arcangelo	uppermost L. Pleist.	356.5	48.5	6.6	−4	10	15	3
					−4	**10**	**15**	**c**
Craco	Lower Pleistocene	337.5	53.7	9.8	−23	17	6	2
					−23	**17**	**6**	**d**
Pisticci	uppermost L. Pleist.	357.5	56.6	6.5	−3	12	7	2
Pomarico	uppermost L. Pleist.	352.4	60.4	2.4	−8	5	3	2
Tursi	uppermost L. Pleist.	179.4	−56.6	6.1	0	11	7	2
					−4	**8**	**17**	**e**
Sicilian Maghrebides								
Punta di Maiata	Lower Pliocene	34.6	46.2	2.7	35	4	5	4
Eraclea Minoa	Lower Pliocene	33.7	46.6	1.7	34	2	5	4
Porto Empedocle	Lower Pliocene	228	−50	7	48	11	1	4
SI09	Lower Pliocene	205	−32.2	19.4	25	23	1	5
SI10	Lower Pliocene	42.6	51.7	6.8	43	11	1	5
SI13	Lower Pliocene	235.8	−56	3.5	56	6	1	5
SI18	Lower Pliocene	39.4	38.8	14.4	39	18	1	5
Grottacalda	Lower-Middle Plioc.	42	39	15	42	19	1	6
Grottacalda	Lower-Middle Plioc.	23	33	7.9	23	9	1	6
Villapriolo	Lower-Middle Plioc.	19	34	10.7	19	13	1	6
SI11	Lower-Middle Plioc.	27.9	46.4	7.3	28	11	1	5
					+34	**9**	**19**	**f**
Punta Secca	Middle Pliocene	21.9	44	3.7	22	5	1*	7
Punta Piccola	Middle-Upper Pliocene	27.1	38.8	4.2	27	5	6	4
San Nicola	Upper Pliocene	32.1	44.2	8.3	32	11	1*	9
					+27	**10**	**8**	**g**
San Nicola	Lower Pleistocene	191.7	−58.2	8.3	12	16	1	8
Montelungo	Lower Pleistocene	194.1	−49.1	3.9	14	6	5	8
SI12	Lower Pleistocene	27.7	30.3	6	28	7	1	5
SI15	Emilian	208	−55.3	5.6	28	10	1	5
					+21	**23**	**8**	**h**
Caltagirone	Lower Pleistocene	179.8	−51.8	6	0	10	5	8
					0	**10**	**5**	**i**
Misterbianco	Middle Pleistocene	354.8	39.4	6.6	−5	8	2	10
CI03	Middle Pliostocene	357.5	62.6	5	−3	11	1	10
					−5	**8**	**3**	**j**

Ref. numbers are: 1) Sagnotti (1992); 2) Scheepers et al. (1993); 3) Mattei et al. (2004); 4) Scheepers and Langereis (1993); 5) Speranza et al. (1999); 6) Speranza et al. (2003); 7) Duermeijer and Langereis (1998); 8) Scheepers (1994); 9) Channell et al. (1992); 10) Cifelli et al. (2004).

Da, Ia: Locality (site) declinations and inclinations values after tectonic correction.

α_{95}: statistic parameter after Fisher (1953).

Err (±): error for rotations values calculated as $\mathrm{err}=\alpha_{95}/(\cos I)$.

Values in bold represent mean values for site(s) of the same age (+ and – signs indicate CW and CCW rotations, respectively). Letter references are used in Fig. 3.

4.1.2. The Gela Nappe

In south–central Sicily, upper Miocene–Pleistocene successions were deposited in thrust-top and foredeep basins, above and in front of the deforming structures of the Maghrebian fold and thrust belt. Detailed structural, sedimentological and stratigraphic analyses, together with data from seismic exploration and deep wells show that during the Pliocene and Early Pleistocene the foredeep and thrust top basins migrated progressively south–eastward to form the outer front of the Maghrebian

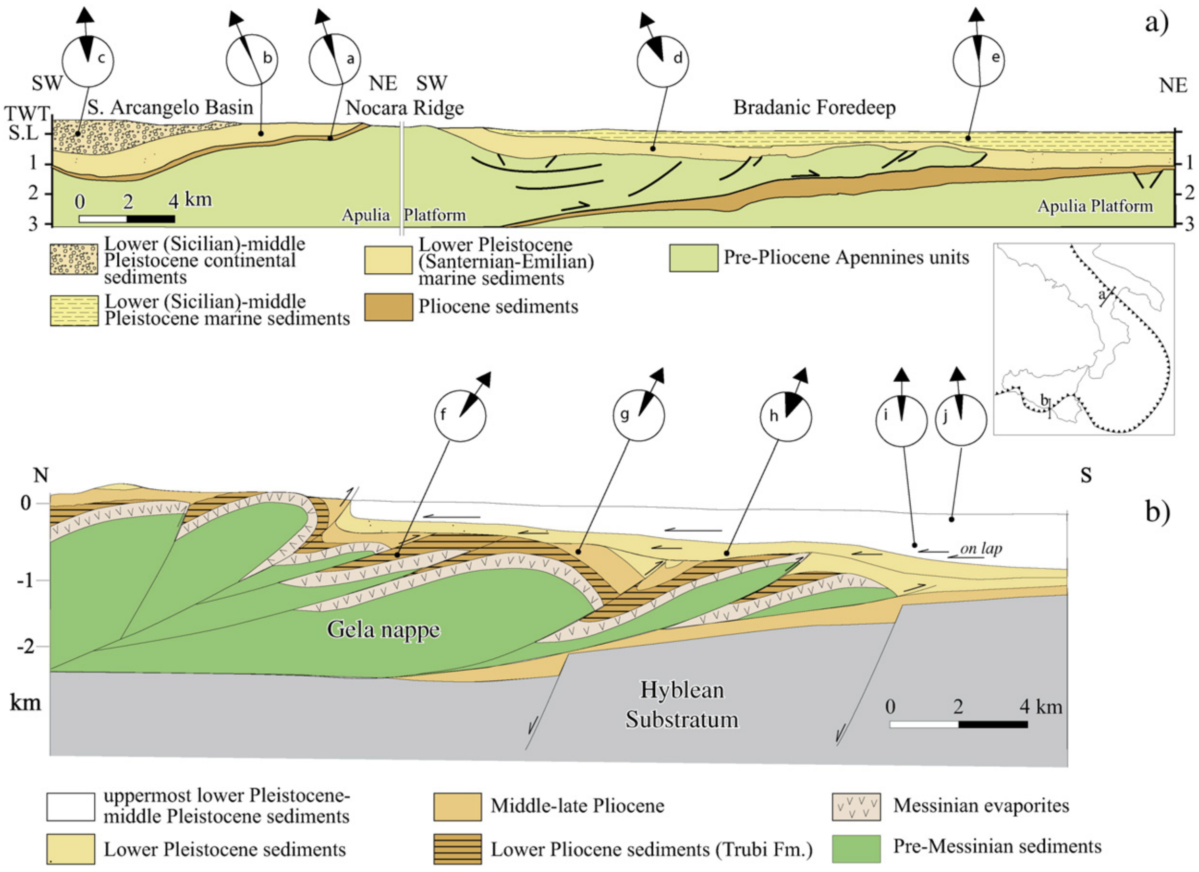

Fig. 3. Schematic geologic sections along the outer front of the Southern Apennines (a) and Sicilian Maghrebides (b). Measured paleomagnetic rotations (and relative confidence limits) have been calculated according to data reported in Table 1 (see reference letters). (Geologic sections have been modified from Butler et al., 1992; Grasso et al., 1995; Patacca and Scandone, 2001).

chain, named the Gela Nappe (among others, Argnani et al., 1987; Butler et al., 1992, 1995; Grasso et al., 1995; Patacca and Scandone, 2004). The precise chronology of the last phases of the Gela nappe emplacement can be well constrained along the outer front of the chain, where Plio-Pleistocene sediments deposited above the thrust belt can be associated to those of the foredeep basin, outcropping along the northwestern margin of the Hyblean and Sicily

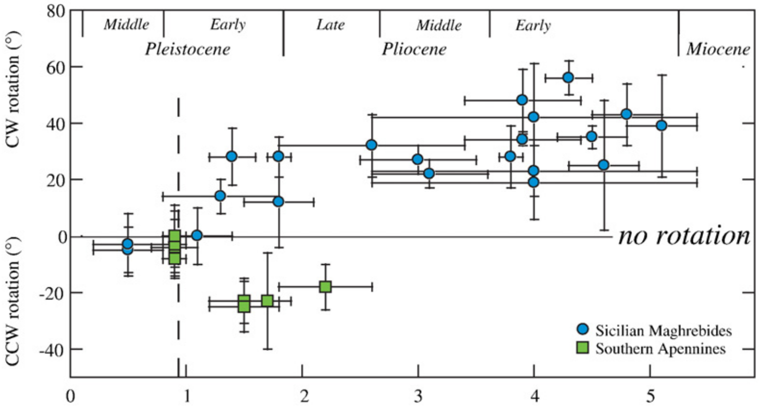

Fig. 4. Age of the Plio-Pleistocene paleomagnetic rotations in the northeastern (Sant'Arcangelo basin) and southwestern (Gela nappe) edges of the Calabrian Arc. The dashed line represents the age of the last thrust activity in the Gela nappe according to Patacca and Scandone (2004). Error bars for rotation are $\alpha_{95}/(\cos I)$ site values (where I is paleomagnetic inclination). Paleomagnetic data illustrated in this figure are the same reported in Table 1.

channel foreland (Argnani et al., 1987; Grasso et al., 1995; Patacca and Scandone, 2004). Grasso et al. (1995) showed that the outer front of the Gela nappe is sealed by clay sediments containing Hyalinea balthica (i.e., younger than 1.5 Ma). However, these sediments are deformed in a footwall syncline at the toe of a more internal thrust, where Messinian sediments are thrust on top of lower Pleistocene (Emilian) clays and sands (Fig. 3b). This timing of deformation in the southern front of the Maghrebian chain is also suggested by other authors, which show that the latest episode of compressional deformation along the outer part of the Gela nappe can be dated as uppermost early Pleistocene, as Santernian–Emilian sediments are still involved in thrust and fold deformation, whereas Sicilian sediments seal the Gela Nappe compressional deformation (Patacca and Scandone, 2004).

A large amount of paleomagnetic data has been collected in the Gela nappe (among others, Butler et al., 1999; Cifelli et al., 2004; Scheepers and Langereis, 1993; Speranza et al., 2003), which show a significant CW paleomagnetic rotations (Table 1). In particular, 20° to 55° of CW rotations have been measured in lower (34°±9° in average) to upper (27°±10° in average) Pliocene sediments (Channell et al., 1992; Duermejier and Langereis, 1998; Scheepers, 1994; Scheepers and Langereis, 1993; Speranza et al., 1999, 2003), whereas lower Pleistocene (Santernian–Emilian) sediments show about 20° to 30° (21°±23°) of CW rotations (Scheepers and Langereis, 1993; Speranza et al., 1999). These sediments have been deposited on top or in front of southward migrating thrust, and are fully involved in the compressional tectonics of the Gela nappe. On the other hand, the uppermost lower Pleistocene sediments outcropping along the external front of the nappe (Scheepers, 1994) and the Middle Pleistocene sediments from Eastern Sicily (Cifelli et al., 2004) show no significant paleomagnetic rotations (0°±10° and −5°±8°, respectively), suggesting that the end of paleomagnetic rotations in this area occurred during the upper part of the lower Pleistocene, coincident with the cessation of compressional tectonics along the external part of the Maghrebian chain (Figs. 2 and 3b).

Fig. 4 summarizes the paleomagnetic declinations from Pliocene-Pleistocene sediments as a function of the age of the sampled sites. This diagram shows that during Pliocene and early Pleistocene opposite paleomagnetic rotations constantly occurred in the Southern Apennines and in the Sicilian Gela nappe, whereas no paleomagnetic rotations have been measured since the end of early Pleistocene. Our hypothesis is that the absence of paleomagnetic rotations after early Pleistocene has regional geodynamic significance, corresponding to the halting of the Calabrian Arc bending.

4.2. Are paleomagnetic results significant in defining the ending of vertical axis rotations?

One of the main problems in detecting recent vertical axis rotations using paleomagnetic data is given by the inherent uncertainties in paleomagnetic measurements, which for recent rocks (approximately around 1 Myr old) makes detecting rotations virtually impossible. In fact, even in the case of very active tectonic regions, the rate of present-day rotations, as measured using GPS data, is typically only a few degrees/Myr (Wallace et al., 2005), which is comparable with the intrinsic degree of confidence of many paleomagnetic results (Butler et al., 1992). Therefore, finding paleomagnetic directions close to the present-day geocentric axial dipole (GAD) magnetic field in recent rocks is not necessarily indicative of a non-rotational tectonic regime, unless rate of rotations are exceptionally fast. Knowledge of the definition of the rotational rate for a given region in order to evaluate whether paleomagnetic results are indicative or not of true vertical axis rotations is therefore crucial. The time evolution of paleomagnetic rotations may help to reconstruct the rotational history of a given region and the significance of the measured rotations.

The rate of paleomagnetic rotations over the different time intervals for Sicily and Southern Apennines has been estimated and reported in Fig. 5. First, data from early Pliocene to early Pleistocene have been separately considered to evaluate the average rate of paleomagnetic rotation in the period between 5–1.5 Myr. The rotation rate is 5.2°/Myr, with the least-square best fit indicating a non-zero value of paleomagnetic rotation at present time. The most likely explanation for this result is an increase in the rotation rate after 1.5 Ma. When we consider paleomagnetic results from Pleistocene units, the rate of paleomagnetic rotations is very high (22.7°/Myr), and the value of 0 rotation lies at about 0.7 Ma, which is approximately the age of the cessation of thrust activity in Southern Apennines and Southern Sicily. These results show that paleomagnetic data are consistent with a simple evolutionary scenario where Pliocene rates of paleomagnetic rotations of about 5°/Myr, have been followed by rapid rotation rates of about 20°/Myr during the early Pleistocene, and termination of paleomagnetic rotations at about 1–0.7 Ma. It is interesting to remark that the very high rate of rotation in late Pliocene–early Pleistocene corresponds with fast back-arc opening of the Marsili basin in the Tyrrhenian Sea from 2.1 to 1.6 Ma (Nicolosi et al., 2006), suggesting a direct link between back-arc extension, arc bending and tectonic rotations. On this basis, the finding of no rotations in uppermost lower Pleistocene sediments really does seem

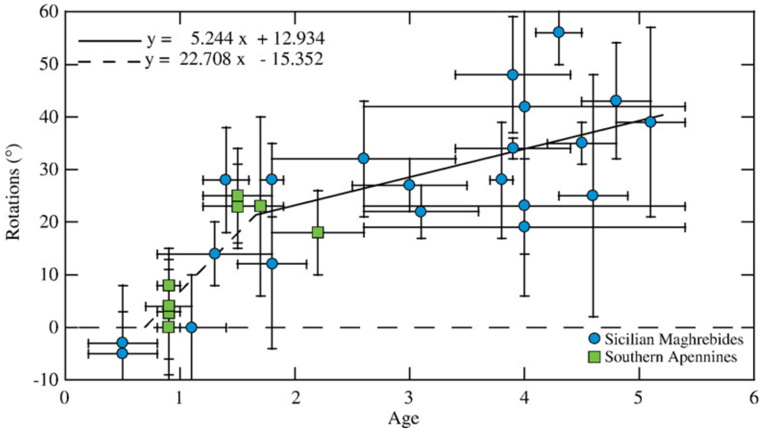

Fig. 5. Plot of paleomagnetic rotations for sites in Sant'Arcangelo and Gela Nappe regions as a function of age. Data are the same of Fig. 4. Counterclockwise (negative) rotations measured in the Sant'Arcangelo basin are reported as clockwise (positive) values (modulus values are plotted).

to indicate the cessation of vertical axis rotation, which suggests a first-order modification in the kinematics and geodynamic setting of the Calabrian Arc in the very last phase of its tectonic evolution.

4.3. Finite rotations and GPS instantaneous velocity field

Paleomagnetic data described in the previous sections suggest rapid, finite, opposite-sense vertical axis rotations, apparently active until the end of the early Pleistocene, on the two arms of the Calabrian Arc. We relate these rapid paleomagnetic rotations to the bending of the Calabrian Arc resulting from the subduction of the Ionian lithosphere. In this context, it is interesting to see whether such rapid rotations are observed in the present-day velocity field obtained from GPS. The comparison between finite paleomagnetic rotations and the rotational component of the instantaneous velocity field is generally difficult for various reasons (Holt and Haines, 1993; Lamb, 1987; McKenzie and Jackson, 1983). The rate of rotation of crustal blocks in a zone of distributed deformation depends, in general, on the shape of the blocks and on their orientation with respect to the shear (Lamb, 1987). Assuming that the instantaneous deformation can be represented by a continuous velocity field, the rotation of a line joining any two points will depend on the initial orientation, potentially resulting in opposite senses of rotation (Holt and Haines, 1993). On the other hand, simple tectonic models describing the crust as composed of equidimensional or elongate blocks provide end-member estimates of rotation rates and analytical relations with the gradients of the velocity field. These estimates range from 0, for blocks aligned to the simple-shear direction to 2Ω, for blocks lying transverse to the shear, where the spin Ω is derived from the component of the velocity field $\Omega = 1/2(\partial V_x/\partial y - \partial V_y/\partial x)$ and where x and y point north and east, respectively. Our approach here is to describe the present-day velocity field and then compare the rates of paleomagnetic rotations, as evaluated from the diagrams in Fig. 5, with the gradients of velocity observed in the instantaneous present-day GPS velocity field.

Geodetic data and seismicity (Fig. 6) show that the present-day kinematics differs significantly from the tectonic pattern that dominated the whole region's evolution during the last 8–10 Myr, suggesting a recent major change in the geodynamic setting (D'Agostino and Selvaggi, 2004; Goes et al., 2004; Hollenstein et al., 2003). The major differences may be summarized in the following points. In Sicily, the present-day velocity field does not show significant on-shore NW–SE shortening, and the Eurasia–Nubia convergence appears to be currently accommodated north of Sicily where seismicity is clustered mainly along a narrow W–E strip (Goes et al., 2004) (Fig. 6). This suggests the lack of significant on-going deformation on the thrust front, even though minor contraction can still be active, as shown by the focal solution of the Belice 1968 earthquake (Fig. 6).

At the present time, sites located in the northern Sicily and Calabria are moving north or northeast, in an Eurasia reference field, with respect to sites located in Sardinia and Corsica (D'Agostino and Selvaggi, 2004). This is not expected for an actively extending Tyrrhenian back-arc basin, which should result in the elongation of the baselines between the Sardinia–Corsica block and the sites in the Calabrian Arc. These data suggest that rollback of the Calabrian trench, which was very fast during Neogene and early Pleistocene times, is no longer an active process. Finally GPS data show that Calabria,

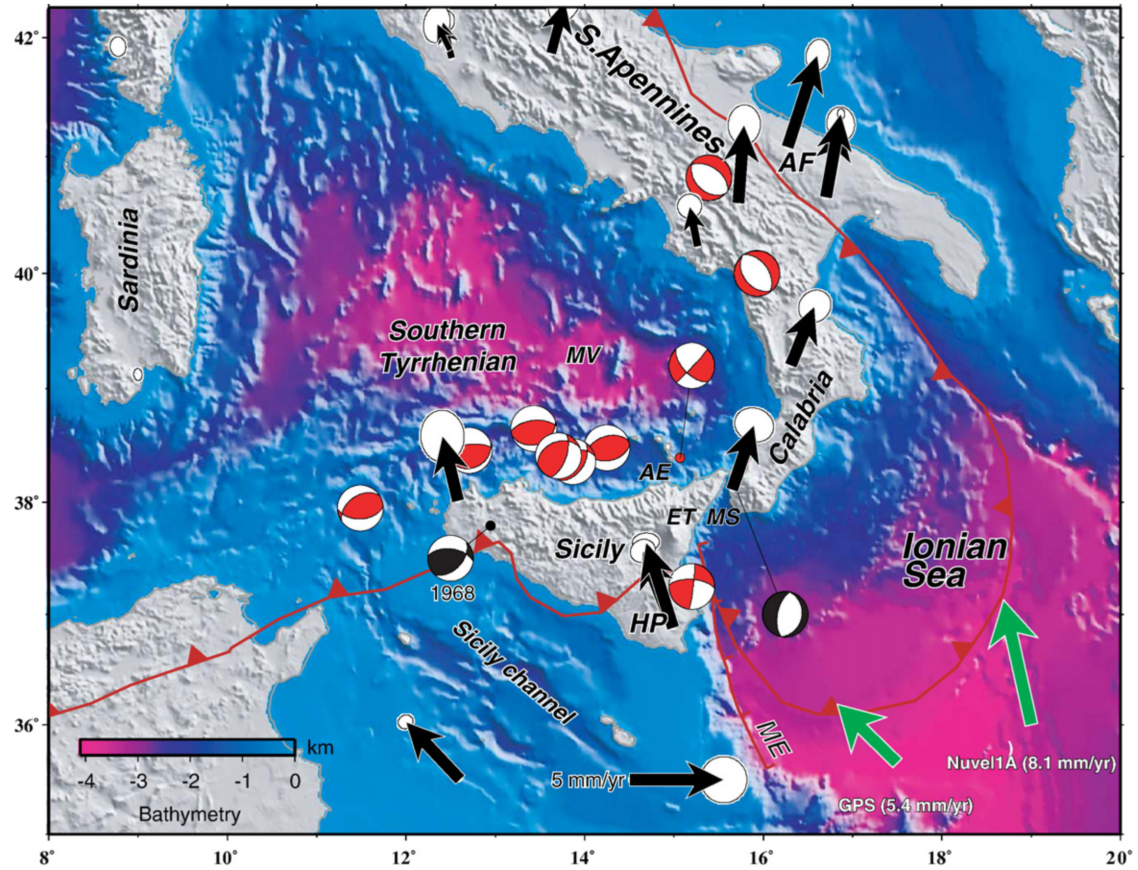

Fig. 6. Regional map of southern Italy including present-day Eurasia-fixed velocity field and seismicity of the Calabrian Arc (modified from D'Agostino and Selvaggi, 2004). Crustal focal mechanisms are selected from the CMT Catalog (Mw>5, in red) and from Anderson and Jackson (1987) in black. Green arrows show the predicted convergence between Nubia and Eurasia according to the Nuvel-1A model and the GPS-derived pole of rotation. Deep bathymetry marks the oceanic-floored Tyrrhenian (Neogene–Quaternary) and Ionian (Mesozoic) basins. Abbreviations are reported as in Fig. 1.

together with Southern Apennines and Apulia, has an independent motion with respect to both Nubia (5 mm/yr to ESE) and Eurasia (3 mm/yr to NNE), as well as a clear motion with respect to Sicily, with a tectonic boundary between Sicily and Calabria presently located in the Messina Straits area (D'Agostino and Selvaggi, 2004). GPS data also show that the Southern Apennines, Apulia, and Calabria regions are now altogether translating to NNE with respect to Eurasia, with an increase in NNE velocity observed toward the Apulian region. This differential motion causes active extension of about 3 mm/yr across the Southern Apennines, which is mainly achieved by active NW–SE oriented normal faults (D'Agostino and Selvaggi, 2004).

Although the sparse GPS measurements do not allow the calculation of a reliable strain field over the area of interest, a preliminary analysis suggest that the large velocity gradients required by the Early Pleistocene rapid rotations are not observed today. Rotation rates of 20°/Myr require velocity gradients on the order of 300–400 nanostrain/yr which are not currently observed where large paleomagnetic rotations have been measured (Sant'Arcangelo Basin and Gela Nappe). Large velocity gradients are concentrated in only three areas. In the Messina Straits strain rates in the order of 100 nanostrain/yr (D'Agostino and Selvaggi, 2004) seem to accommodate the relative motion between Sicily and Calabria. North of Sicily north–south velocity gradients (Hollenstein et al., 2003) correspond with the belt of active shortening observed in the seismicity. Active extension in the southern Apennines is observed in the GPS velocity field (D'Agostino and Selvaggi, 2004) and by remeasurements of the triangulation network (Hunstad et al., 2003), resulting in rates of strain accumulation of about 100 nanostrain/yr.

At the regional scale the analysis of the GPS velocity field (D'Agostino et al., 2006) suggests that crustal motion in the Central Mediterranean portion of the Africa-

Eurasia plate boundary can be described by the independent rotations of two microplates: the Adriatic region and a microplate which includes the Apulian and the Ionian regions. Plate convergence and the distribution of crustal strength heterogeneities, appear to be the main factors controlling the velocity field and the distribution of active deformation in the Central Mediterranean. D'Agostino et al. (2006) suggest that the present-day microplate configuration follows a recent fragmentation of the Adriatic promontory which during the Neogene rigidly transferred the Africa motion to the orogenic belts that now surrounds the Adriatic region.

On the basis of all this geodetic evidence, it appears clear that the tectonic evolution outlined by paleomagnetic and geologic data during Neogene and Quaternary, is not reflected in the present-day velocity field, suggesting a changing in the geodynamics of the Calabrian Arc during recent times.

5. Discussion

Paleomagnetic data available from the Calabrian Arc define the magnitude and timing of rotations in the different branches of the arc and constrain its tectonic history and kinematics. These data show that vertical axis rotations represented an important process during the Calabrian Arc formation. In particular, paleomagnetic data indicate that the different sectors of the Calabrian Arc underwent opposite vertical axis rotations, which occurred during the main phases of compressional deformation together with the emplacement of the Apennine nappes and with the progressive migration of the orogenic front and foredeep basins, related to slab roll-back processes.

Paleomagnetic, geologic and geodetic data document that the recent tectonic evolution of the Southern Tyrrhenian system is now governed by a different mechanism from the deformational pattern that drove the main phases of the Calabrian Arc formation and evolution. The change in the geodynamic regime is suggested by the following evidence: i) paleomagnetic data show that opposite vertical axis rotations, which occurred during the Neogene to early Pleistocene along the entire Calabrian Arc, are no longer active, showing that Calabrian Arc bending was almost completed at the end of Early Pleistocene; ii) the outer fronts of the Southern Apennine and Maghrebide chain are sealed by uppermost early Pleistocene sediments, suggesting that shortening is no longer active along those structures since that time. In particular, in the Southern Apennines thrusting ceased in the uppermost early Pleistocene in the outer front of the chain, and extension became the main tectonic process, as showed by the occurrence of uppermost early Pleistocene NW-trending extensional sedimentary basins along the axial part of the chain and by earthquake activity concentrated along NW–SE-trending normal faults (Cinque et al., 1993; Valensise and Pantosti, 2001). In western Sicily, the southward nappe translation of the outer front of the chain halted at the same time and compression was transferred towards the north, where active deformation is revealed by present-day seismicity (Fig. 1); iii) GPS data and seismicity indicate that back-arc opening has effectively ceased in the Southern Tyrrhenian Sea, and that Calabria and the Southern Apennines now form an independent crustal domain moving NE with respect to Eurasia. Furthermore, GPS data show that the present-day strain rates values in the Calabrian Arc reach maximum values in the order of 100 nanostrain/yr only in the Messina Strait region. These values are not consistent with the very high (10°–20°/Myr) rotation rates measured by paleomagnetic data during the late Pliocene–early Pleistocene.

The change in the paleomagnetic pattern that occurred at the end of early Pleistocene finds an explanation in the geodynamic regime governing the Central Mediterranean evolution during the Quaternary and, in particular, in the space-time evolution of the Calabrian Arc subduction system, schematically represented in Fig. 7, and based on paleomagnetic and paleogeographic reconstructions available in literature (Bonardi et al., 2001; Faccenna et al., 2004; Guegen et al., 1998; Patacca et al., 1990). During the Neogene, the peculiar configuration of the subducting system favored the fast roll-back of the Ionian oceanic lithosphere, and enhanced the curvature of the Calabrian Arc (Fig. 7a-c). This process was active until the reduction in the amount of oceanic lithosphere available for subduction led to shortening of the continental lithosphere, which prevented the Ionian subducting slab from continuing to retreat. In this hypothesis the deep seismicity would photograph an inactive slab passively sinking underneath the Calabrian Arc, presently detached from the Ionian plate (Chiarabba et al., 2005; Wortel and Spakman, 2000). By reduction (or cessation) of subduction activity, the tectonics of central Mediterranean became dominated by the convergence between the Nubia and Eurasia plates, rather than by the formation of the Tyrrhenian Sea, leading to different active tectonic regimes in western Sicily, and in the Calabria-Southern Apennines. In particular, the differential motion between Sicily, Calabria, and Southern Apennine, together with the CCW rotation of the Adria microplate (Anderson and Jackson, 1987; D'Agostino et al., 2006; D'Agostino and Selvaggi 2004) produced, during the Quaternary,

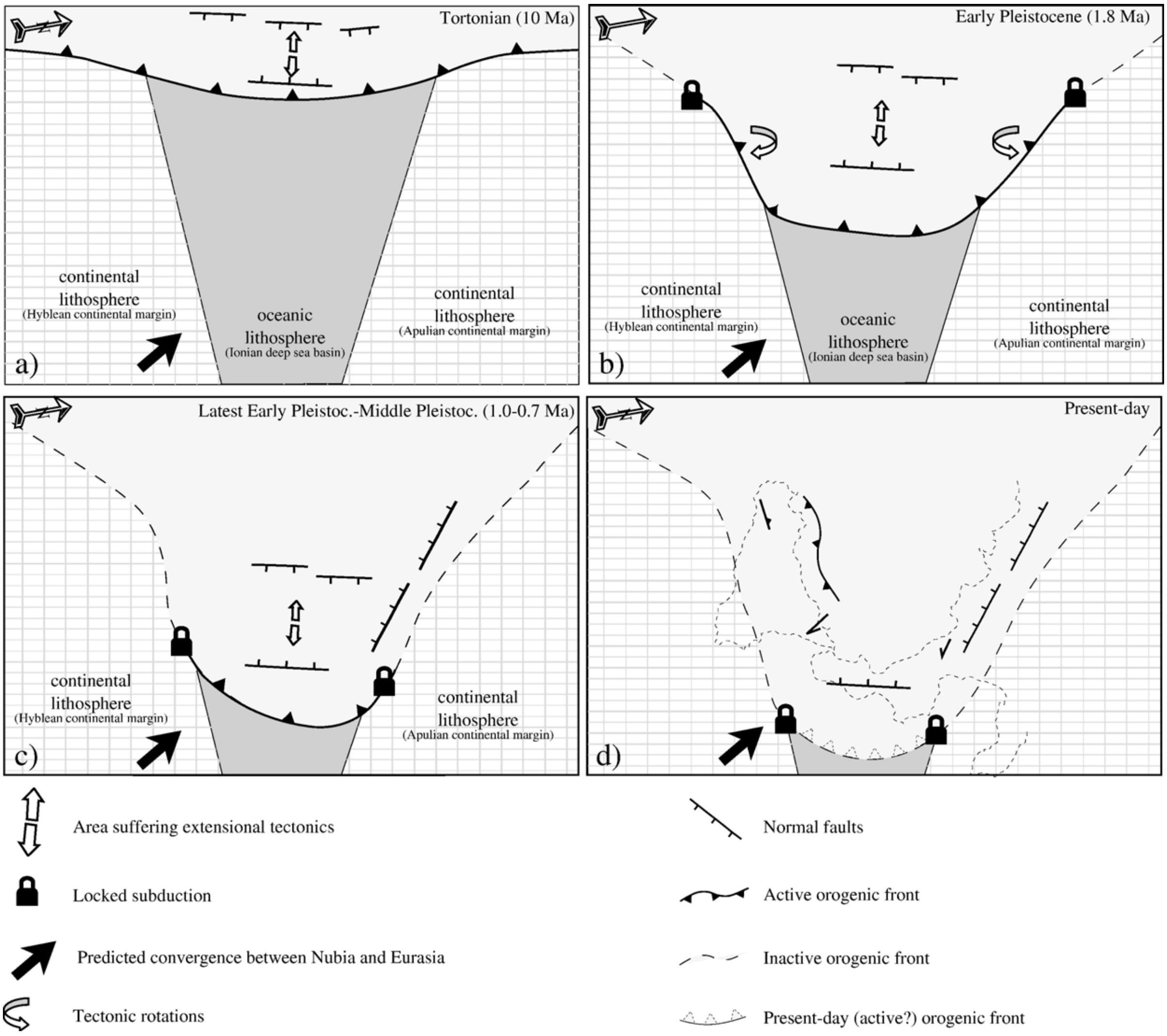

Fig. 7. Top view schematic cartoon of the Calabrian Arc evolution, illustrating tectonic changes occurred from Late Miocene to Recent.

an extensional regime along the Southern Italy and eastern Sicily.

6. Conclusions

In this paper, geologic, paleomagnetic and GPS data have been combined to document the tectonic evolution of the Calabrian Arc from Neogene to its present-day kinematics. The precise definition of the time and amount of paleomagnetic rotations demonstrates that the deformation of the Southern Apennines and Sicily orogenic wedges has been accompanied by large and opposite-sense paleomagnetic rotations. Paleomagnetic data also indicate that vertical axis rotations in the Calabrian Arc were almost finished about 1 Ma, in correspondence with the cessation of thrust activity along the outer front of the Southern Apennines and Sicilian Maghrebides thrust belts. This evidence is supported by GPS results, which show that the present-day crustal kinematics is different from that responsible of the formation of the whole Calabrian Arc, and that back-arc extension in the Southern Tyrrhenian Sea is no longer an active process.

We interpret this change in the Central Mediterranean kinematics as a consequence of a changing in the Ionian slab size and geometry, which led to an effective cessation of the subduction process. The tectonic evolution of Calabrian Arc indicates that in regions characterized by strong laterally heterogeneities of the subducting plate, such as the Mediterranean region (Faccenna et al., 2004), subduction processes are subjected to strong variation of their style, in time and space. Comparison of geodetic and paleomagnetic data can provide first-order constraints for reconstructing the temporal evolution of geodynamic process in rapidly evolving subduction systems.

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