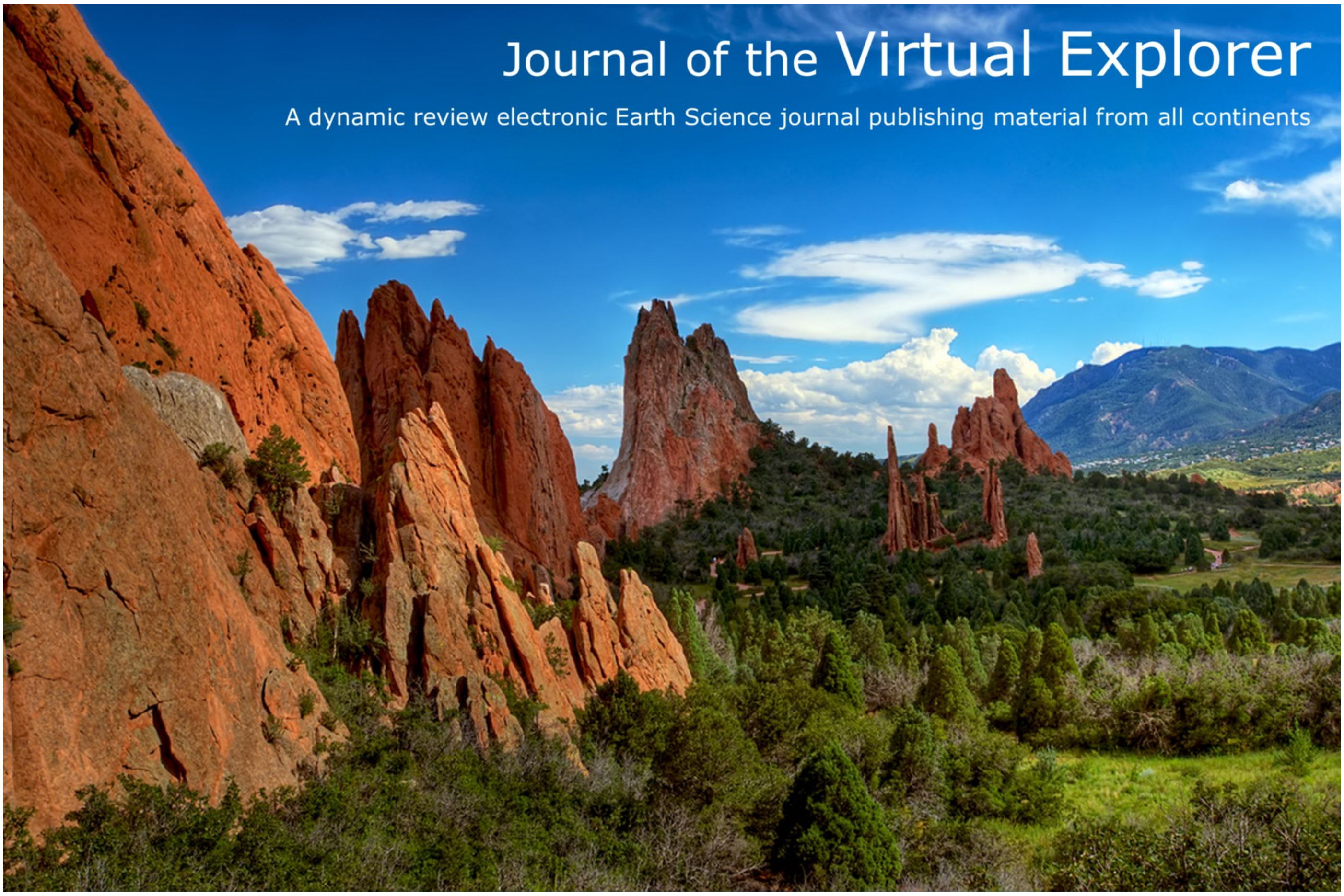

Curved orogenic systems in the Italian Peninsula: a paleomagnetic review

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Journal of the Virtual Explorer, Electronic Edition, ISSN 1441-8142, volume **36**, paper 17
In: (Eds.) Marco Beltrando, Angelo Peccerillo, Massimo Mattei, Sandro Conticelli, and Carlo Doglioni, The Geology of Italy: tectonics and life along plate margins, 2010.

Curved orogenic systems in the Italian Peninsula: a paleomagnetic review

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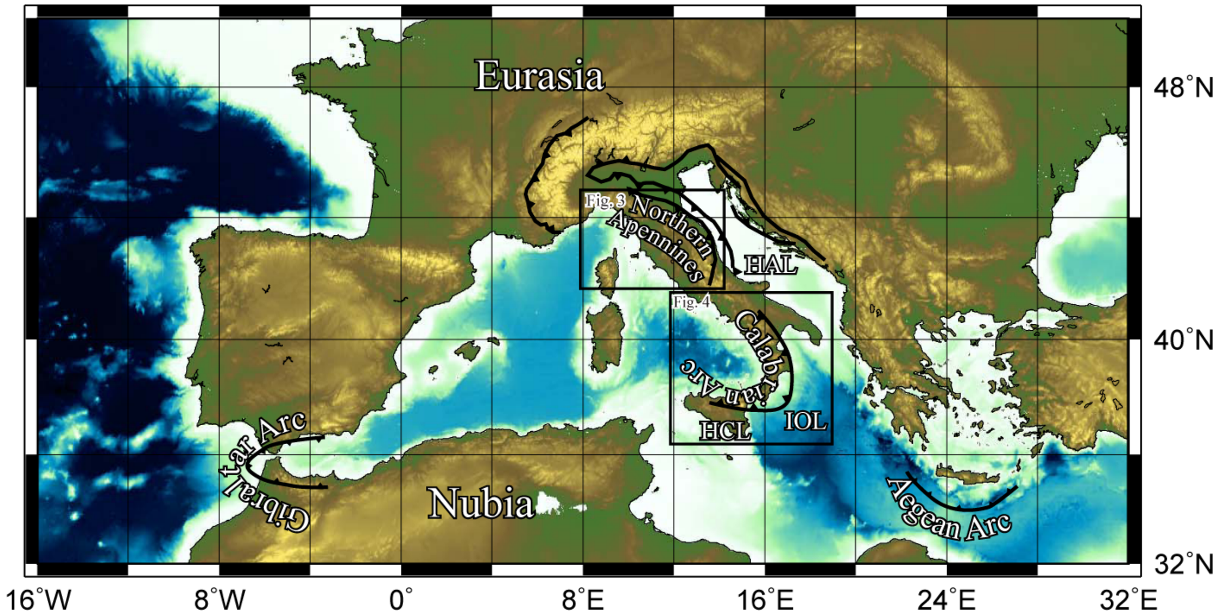
Abstract: During the past few decades, paleomagnetism has been used as a fundamental tool to assess kinematic models of curved orogenic systems around the world because of its great potential in quantifying vertical axis rotations. The Mediterranean area shows a large number of narrow arcs, defining an irregular and rather diffuse plate boundary. In Italy, two curved mountain belts are well documented: the Northern Apennines and the Calabrian Arc, which show distinct evolution and mode of arc formation. The Northern Apennines consists in thrust sheets with a regional structural trend that range from NW-SE in the northern part to N-S in the southern part. The origin of its curvature has been debated since a long time, as paleomagnetic results gave rise to contrasting interpretations. The accurate revision of the existing paleomagnetic data suggest that it is a progressive arc mainly formed during the Neogene. The Calabrian Arc represents one of the tightest arcs in the Mediterranean region. Paleomagnetic rotations highlight the peculiarity of the formation of the Calabrian Arc curvature and imply that either an oroclinal bending model or a progressive arc model cannot be simply applied to its formation. For the Calabrian Arc, the progressive curvature is framed within the space-time evolution of the Ionian subduction system.

Citation: 2010. Curved orogenic systems in the Italian Peninsula: a paleomagnetic review. In: (Eds.) Marco Beltrando, Angelo Peccerillo, Massimo Mattei, Sandro Conticelli, and Carlo Doglioni, *Journal of the Virtual Explorer*, volume **36**, paper 17, doi: 10.3809/jvirtex.2010.00239

Introduction

The origin of curvature in mountain belts is an important topic in tectonic and geodynamic research and represents, for the Northern Apennines and in the Calabrian Arc, a long debated paleomagnetic subject (Fig. 1). The kinematics of an arc and the timing of its curvature are crucial factors for understanding the geodynamic process governing arc formation. In active convergent margins, slab roll back process is considered the most likely candidate for the formation of arcs (e.g. Schellart and Lister 2004). In this geodynamic context, the geometry and nature of both the overriding plate and the subducting slab, their width and space-time evolution, are elements that must be taken into account to fully understand the formation and evolution of related arc-shaped belts (Faccenna *et al.* 2004; Schellart and Lister 2004; Morra *et al.* 2006).

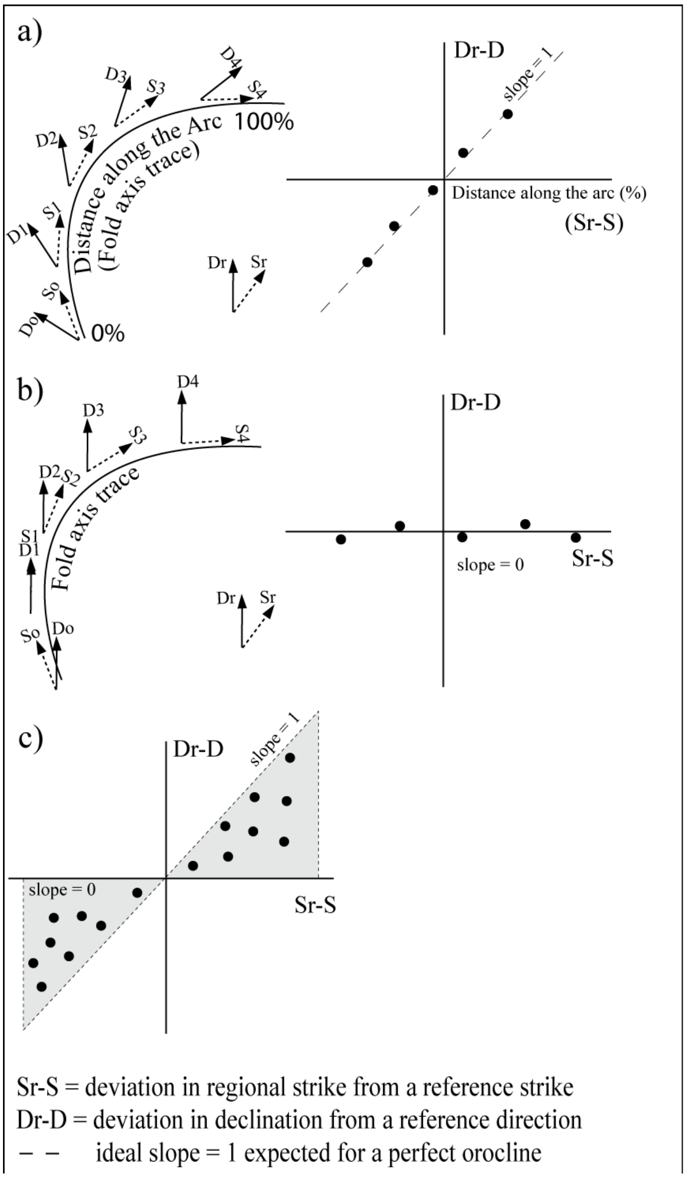
Figure 1. Schematic map of the Mediterranean area.



Schematic map of the Mediterranean area with the main curved orogenic systems traced. Location of Fig. 2 and Fig. 3 is also reported.

Depending on the relationship between the timing of thrusting and vertical-axis rotations, arcs can be classified in: (i) primary curves, where no vertical-axis rotations are required; secondary curves, where vertical-axis rotations post-date thrusting and (iii) progressive curves, where rotation and thrusting occur simultaneously (among others, Carey 1955; Elliott 1976; Sanderson 1982; Marshak 1988; Wirkerson 1992; Hindle and Burkhard 1999; Sussman *et al.* 2004; Weil and Sussman 2004). This classification of curved belts provides two end-members, which can be distinguished by comparing paleomagnetic declinations with structural data (Fig. 2). In primary arcs, paleomagnetic declinations remain parallel along the arc and do not correlate with changes in thrust and fold-axis trend (Fig. 2a). In secondary arcs, paleomagnetic declinations change direction along the arc and follow changes in thrust and fold-axis trend with a one-to-one correlation (Fig. 2b). In the last few decades, increasing evidence has been found that these two end members cannot describe the kinematic evolutions of most curved orogens. In fact, detailed paleomagnetic investigations from well-dated syntectonic sediments show that in several orogens, vertical axis rotations occurred neither before nor after, but during thrust activity (Fig. 2c) (among others, Allerton *et al.* 1993; Mattei *et al.* 1995; Gray and Stamatakos 1997; Pueyo *et al.* 2002; Sussman *et al.* 2004; Barke *et al.* 2007). Furthermore, information from thrust tectonics and stratigraphy of syntectonic sediments shows that fold-thrust belts evolve over a long time span, with complexities in the evolution of deformation (e.g., Elliot, 1976).

Figure 2. Classification of arcs.



Schematic illustrations of the distribution of paleomagnetic declinations as a function of the structural trend or distance along the length of the arc: in (a) an orocline, (b) a primary arc, (c) progressive arcs (modified from Cifelli *et al.* 2008).

Since the first formulation of tectonic models in the 1970's for the Mediterranean area, paleomagnetic data have been collected in Italy as key information for constraining kinematic and geodynamic reconstructions. First paleomagnetic studies were focused on Mesozoic-lower Tertiary sequences and interpreted Italy as a single block rotated counterclockwise since late Cretaceous (Channell and Tarling 1975; Klootwijk and Van den Berg 1975; Lowrie and Alvarez 1975; Vandenberg *et al.* 1978). In the following years, this early tectonic interpretation was drastically modified by the increasing distribution of paleomagnetic data. Channell *et al.* (1978) firstly suggested that the different amount of paleomagnetic rotations observed both in Umbria and western Sicily were related to thrust emplacement and should be considered as related to the kinematics of allochtonous units which were deformed during the Neogene. This tectonic interpretation has been confirmed in the recent years by a large amount of data, which has been collected in the Neogene and Quaternary units. The analysis of sequences coeval with the main geodynamic events suggested for Italy a more complex rotational history than a single rigid rotation, and allowed to constrain the kinematics and timing of curvature of the Northern Apennines and Calabrian arcs (Sagnotti 1992; Scheepers *et al.* 1994; Mattei *et al.* 1995; Speranza *et al.* 1999; Speranza *et al.* 2000; Cifelli *et al.* 2007a, among many others). Paleomagnetic studies detected a different sense and amount of vertical-axis rotations over distinct geodynamical provinces of the Italian Peninsula, with tectonic rotations occurring at different geological times, sometimes as pulses with surprisingly fast rates in short geological time intervals (e.g., Scheepers *et al.* 1993; Mattei *et al.* 2004).

This paper is intended to be an updated review on the contribution of paleomagnetism to the reconstruction of the Neogene geodynamic evolution of the Apennines. In this study we reanalyze the available paleomagnetic database for the Northern Apennines and the Calabrian Arc. This quantitative analysis represents a unique opportunity to constrain the tectonic and kinematic evolution of the arcs during the Neogene, in the general framework of the geodynamic evolution of the central Mediterranean area. In particular, the curved shape of the Northern Apennines and the Calabrian Arc will be quantitatively analysed and compared in order to define whether the shape of these two arcs can be referred to a simple oroclinal model or a more complex evolution has to be invoked.

Geodynamic setting

According to the 'most popular' models, the evolution of the Mediterranean geodynamic system during the Neogene was controlled by the dynamics of subduction in a region of complex convergence between the African and Eurasian plates (Malinverno and Ryan 1986; Faccenna *et al.* 1997; Guegen *et al.* 1998; Faccenna *et al.* 2004). In the central Mediterranean, the Africa and the Eurasia plates underwent several hundred kilometers of convergence since the early Tertiary. Such a convergence has been mainly achieved by north-westward dipping subduction of the Ionian-Adriatic lithosphere underneath the Eurasia plate. The Central Mediterranean subduction system was characterized by trench retreat and progressive fragmentation of the Adriatic-Ionian slab (Patacca *et al.* 1990; Faccenna *et al.* 1997; Faccenna *et al.* 2001; Cifelli *et al.* 2007a and references therein). Presently, evidences of active narrow slabs are given by subcrustal earthquakes occurring down to 90 km depth below the Northern Apennines (Selvaggi and Amato 1992; Chiarabba *et al.* 2009; Di Stefano *et al.* 2009), whereas a well defined Benioff zone down to about 670 km, reveals a direct trace of a still active process of lithospheric subduction from the Ionian foreland below the Calabrian Arc and Tyrrhenian Sea (e.g., Anderson and Jackson 1987; Selvaggi and Chiarabba 1995). Slab roll-back and the decreasing of the width of the active trench through time, resulted in the formation of curved orogenic belts, sometimes characterized by a very tight curvature (Fig. 1), together with extensional back-arc basins (Ligure-Provençal and Tyrrhenian basins) (Alvarez *et al.* 1974; Boccaletti and Guazzone 1974), which have been characterized by the emplacement of medium to large plutonic bodies and by a long-standing volcanic activity which continues up today (Barberi *et al.* 1973; Civetta *et al.* 1978; Serri *et al.* 1993).

The Northern Apennines

GEOLOGICAL SETTING

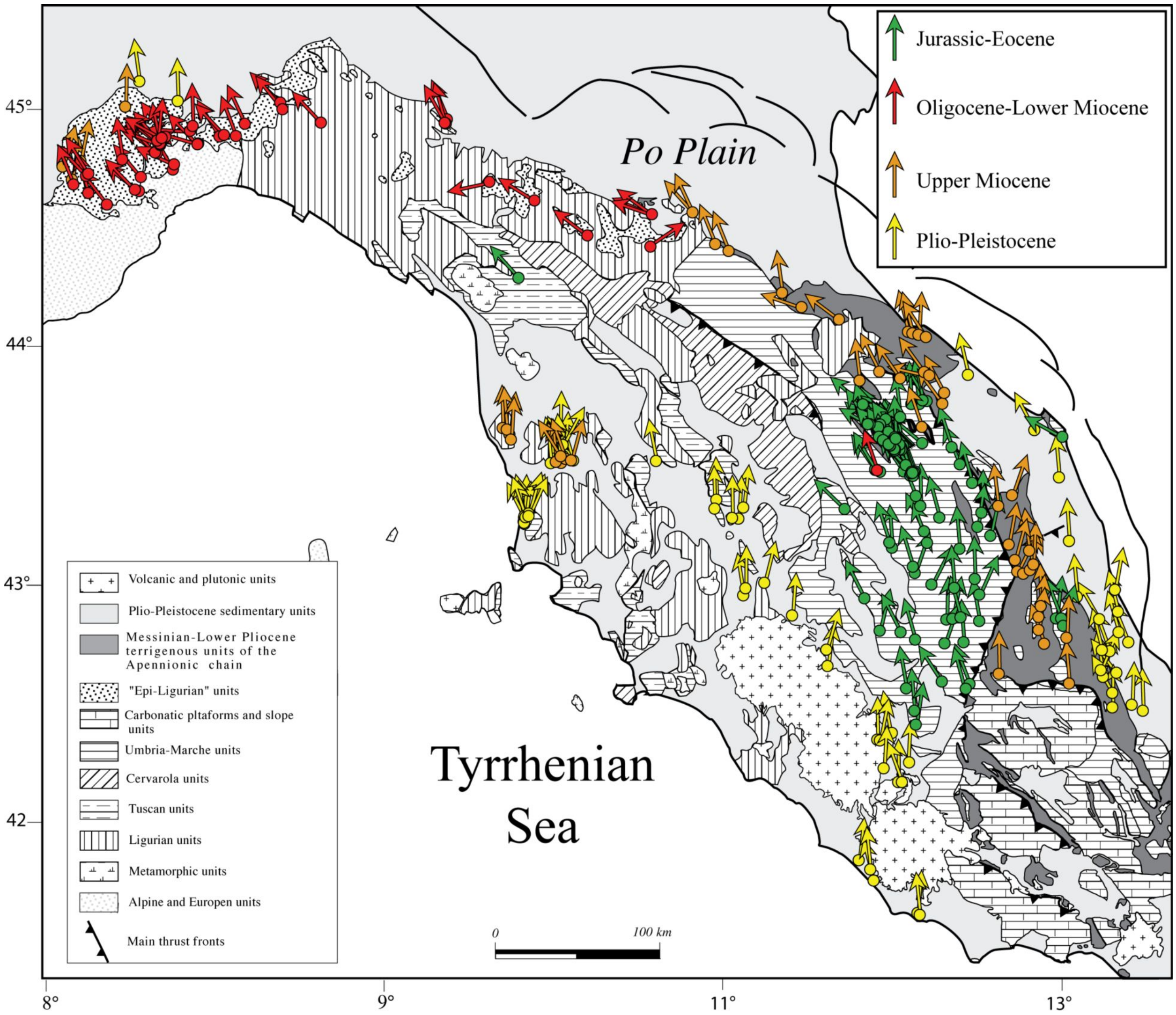
The Northern Apennines consists of different Mesozoic Tethyan paleogeographic domains, organized in folds and thrust sheets forming a broad curved structure with an eastward (Adriatic) vergence (Fig. 3). The curvature of the arc follows the Adriatic margin of the belt, with the main structures ranging from NW-SE/WNW-ESE in the north to almost N-S in the south. Several second-order arcs developed besides the principal arc, in response to multiple compressional phases that induced both out-of-sequence nappe stacking and in-sequence external frontal accretion of the belt toward the Adriatic foreland.

The Ligurian domain constitutes the uppermost nappe of the Northern Apennines. It is represented by oceanic (Ligurides) and transitional (sub-Ligurides) domain units, characterized by the occurence of Jurassic ophiolites and their Jurassic-early Cretaceous sedimentary cover, overlain by Cretaceous-Oligocene flysch sequences. The Ligurian domain units overthrusted eastward the Tuscan domain units starting from the late Oligocene (Principi and Treves 1984). Upper Triassic to Miocene marine carbonates and sandstones constitute the Tuscan unmetamorphosed sequence, deformed in an array of thrust sheets (Tuscan nappe). The Umbria-Marche domain consists of sedimentary sequences deposited on a continental margin with basal late Triassic evaporites, platform carbonates (Lias) and pelagic sequences (Jurassic-Eocene) enriched upward in terrigenous deposits (Paleogene) and flysch sequences (Miocene).

The tectonic evolution of the Northern Apennines is characterized by the progressive migration of the orogenic front toward the Adriatic foreland, which is marked by the onset of siliciclastic deposits which get progressively younger toward the Adriatic-Ionian foreland. The onset of siliciclastic deposition occurred in Northern Apennines during late Cretaceous in the oceanic Ligurian domain. The Ligurian oceanic domain was deformed during late Cretaceous to early Eocene time, and formed a double vergent accretionary wedge, now outcropping from Corsica to Italian peninsula (Treves 1984; Carmignani *et al.* 1994). Starting from the Oligocene onwards, foredeep basins migrated eastward and formed on the top of continental sequences, belonging to the passive margin of Apulia. Their incorporation into the Apennines orogenic wedge marked the subduction of Adriatic continental lithosphere underneath Europe. Afterwards, during the Neogene, foredeep basins further migrated toward the Apulia foreland in front of the migrating thrust nappes. In Northern Apennines such process is well documented by stratigraphic and seismic studies, which precisely constrain the Neogene evolution of the foredeep basins in the front of the Apenninic chain (e.g., Patacca *et al.* 1992; Calamita *et al.* 1994; Pieri *et al.* 1994). Foredeep basins formed on the top of progressively easternmost (external) units, up to the Adriatic foreland, where the foredeep Quaternary deposition is no more active. The formation and evolution of foredeep basins were driven by the loading of the adjacent thrust belt and related to subduction processes, such as the flexural retreat of the subducting lithosphere (Royden *et al.* 1987). This process was particularly severe during Plio-Pleistocene times as evidenced by the presence, in the external part of the

Apenninic chain, of a foredeep-basin system which contains up to 8 km of Pliocene-Quaternary sedimentary rocks (Royden *et al.* 1987).

Figure 3. Simplified geological map of Northern Apennines.



Each arrow represents results from one site, group of sites or magnetostratigraphic sections. Tectonic rotations have been calculated comparing the obtained paleodeclinations to the coeval expected African reference directions (Besse and Courtillot, 2002). Data come from: Aiello and Hagstrum, 2001; Alvarez and Lowrie 1978; Alvarez and Lowrie, 1984; Carrapa *et al.*, 2003; Channell and Tarling, 1975; Channell, 1992; Cirilli *et al.*, 1984; Dela Pierre *et al.*, 1992; Hirt and Lowrie, 1988; klootwijk and Van der Berg, 1975; Lanci & Wezel, 1995; Latal *et al.*, 2000; Lowrie & Alvarez, 1975, 1977, 1979; Lowrie *et al.*, 1980, 1982; Maffione *et al.*, 2008; Marton & D'Andrea, 1992; Mattei *et al.*, 1996; Muttoni *et al.*, 1998; Napoleone *et al.*, 1983; Roggenthen and Napoleone, 1977; Sagnotti *et al.*, 1994, 2000; Sarti *et al.*, 1995; Satolli *et al.*, 2007, 2008; Speranza and Parisi, 2007; Speranza *et al.*, 1997; Tarduno *et al.*, 1992; Thio, 1988; Van der Berg *et al.* 1978.

Extension on the Northern Tyrrhenian sector was coeval with thrust emplacement in the external Umbria-Marche-Romagna chain, with both extensional and compressional fronts migrating toward the Adriatic foreland from middle Miocene up to Pleistocene (e.g., Elter *et al.* 1975). Extensional tectonics dissected the already formed Apennines chain and generated new NW-SE trending extensional basins filled by ‘neoautochthonous’ marine and continental sequences (Jolivet *et al.* 1998; Collettini *et al.* 2006 and references therein). Moreover, crustal thinning, high heat flow and upraise of magmatic bodies accompanied extension along the Tyrrhenian margin. Today, active tectonics is represented by NW-SE normal faults, with a well documented historical and recent seismicity, mostly located in the internal sector of the Umbria-Marche-Romagna region, at the edges of intramontane basins (among others, Chiaraluce *et al.* 2004).

PALEOMAGNETIC DATA

The tectonic history of the Northern Apennines has been largely investigated by paleomagnetic studies in the last 30 years (Fig. 3). The Umbria-Marche region is actually one of the most studied areas in the world, being the late Cretaceous-early Tertiary Scaglia Formation the most studied sedimentary sequence in Italy for paleomagnetism and magnetostratigraphy, from where the concept of counterclockwise rotation of the Italian peninsula arose (e.g., Channell and Tarling 1975; Klootwijk and Van den Berg 1975; Lowrie and Alvarez 1975; Vandenberg *et al.* 1978).

Early paleomagnetic studies on the Umbria-Marche sequences were used to interpret this area as autochthonous and to infer a 30°-40° counterclockwise rotation of the Italian Peninsula during Cretaceous, followed by a 25° post-Eocene rotation (Lowrie and Alvarez 1975; Vandenberg *et al.* 1978). Later paleomagnetic studies recognized the allochthonous character of the Umbria-Marche region, measuring different amount of counterclockwise rotation in the northern and southern parts of the Umbria region (e.g., Channell *et al.* 1978; Channell *et al.* 1992; Van der Voo 1993). On the base of these data these Authors suggested that results from the Umbria arc could not be extrapolated to the entire Italian peninsula. In the following years, several Authors have documented widespread vertical-axis rotations associated with thrusting and folding in Northern Apennines and today the timing of the tectonic rotations has been nicely constrained. Besides Mesozoic and early Tertiary pelagic deposits of the Umbria-Marche region, paleomagnetic data were gained from Messinian to Pleistocene sediments of the external front of the chain (e.g., Dela Pierre *et al.* 1992; Lanci and Wezel 1995; Speranza *et al.* 1997). These data indicate that Plio-Pleistocene rotations affected the external part of the arc contributing to the present-day geometry. These rotations occurred with different senses and variable amount along the arc. In particular, the post-Messinian counterclockwise 20° rotation measured in the Marche-Romagna area are of the same amplitude of those calculated for Mesozoic sequences in northern Umbria, suggesting a Plio-Pleistocene age for the rotations measured in older sequences (Speranza *et al.* 1997; Sagnotti *et al.* 2000).

Moving northwestward along the chain, paleomagnetic data are available for the more internal sector of the chain. Paleomagnetic study of the upper Oligocene–middle Miocene Epiligurian units revealed a 52° counterclockwise rotation with respect to Africa (Muttoni *et al.* 1998). Further data by Muttoni *et al.* (2000) showed that ~24° of this 52° rotation was Oligocene-Miocene in age, and likely related to the drift (and counterclockwise rotation) of the Corsica-Sardinia block (e.g., Montigny *et al.* 1981; Speranza *et al.* 2002; Gattacceca *et al.* 2007). Conversely, the remaining 28° counterclockwise rotation, observed in upper Miocene to Pliocene sediments, was due to Pliocene shortening episodes occurring at the Apennine chain front, which may have (re)activated thrust planes in the Apennines structures below the Ligurian wedge. The latter paleomagnetic data confirmed the above described results from Speranza *et al.* (1997), who found a post Messinian counterclockwise rotation of ~20° in the northern part of the studied area. These data suggest that the deformation of the Apennines continued after the end of the rotational motion of the Corsica–Sardinia block.

Paleomagnetic data at the edge with Western Alps indicate that the sedimentary sequences of the Tertiary Piedmont Basin rotated about 50° CCW during Aquitanian-Serravallian times (Thio 1987; Carrapa *et al.* 2003; Maffione *et al.* 2008), an amount and timing of rotation very similar to those registered for the Sardinia-Corsica block.

During Neogene, thrusting and bending in the external Northern Apennines were accompanied by progressive collapse of the internal sector of the belt, related to the Tyrrhenian basin opening with the formation of several syn-rift basins along the Tyrrhenian margin. The late-orogenic collapse was, however, irrotational (Lowrie and Alvarez 1979; Sagnotti *et al.* 1994; Mattei *et al.* 1996). Paleomagnetic data indicate, in fact, that the Messinian-Pleistocene extensional Tyrrhenian basins did not underwent tectonic rotations, differentiating the Northern Apennines and the Tyrrhenian margin as two different rotational domains (Mattei *et al.* 1996).

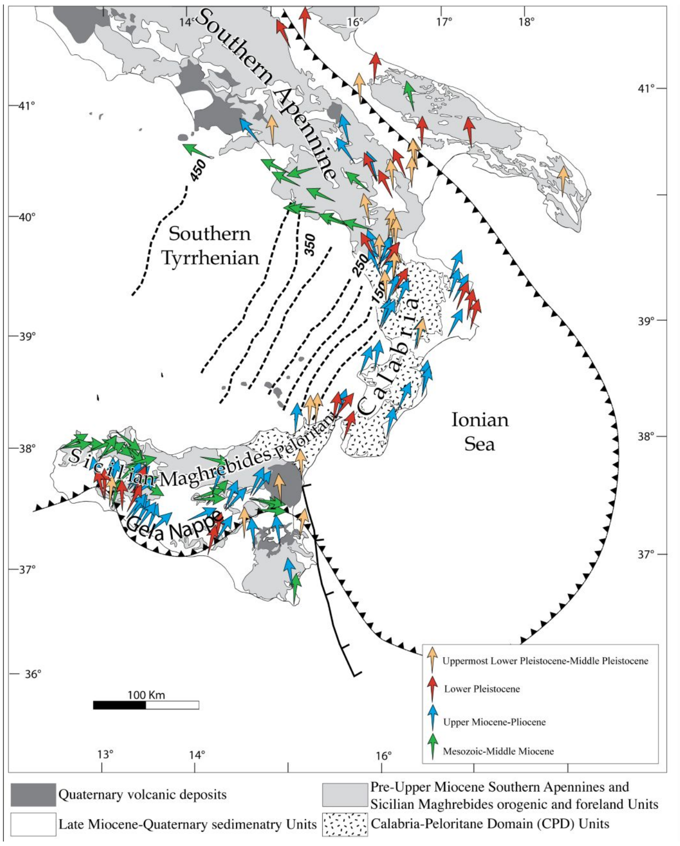
In Northern Apennines a mechanism of oroclinal bending was first confirmed (Channell *et al.* 1978; Eldredge *et al.* 1985) and then rejected (Van der Voo and Channell 1980; Lowrie and Hirt 1986; Hirt and Lowrie 1988) on the base of different data sets from Mesozoic-lower Tertiary sediments in the internal domain of the chain. Channell *et al.* (1978) proposed that the Umbrian Apennines underwent oroclinal bending, suggested by the curvature of the mountain belt and its fold axes from north (fold axes strike = 315°) to south (fold axes strike = 350°) and the change in paleomagnetic direction from north (declination = 316°) to south (declination = 338°). Eldredge *et al.* (1985) applied the method proposed by Schwartz and Van der Voo (1983) to determine a possible relationship between fold axes and declinations, confirming the hypothesis of an orocline for the Umbrian orogen. Hirt and Lowrie (1988) found some weaknesses in the analysis of the Eldredge *et al.* (1985), such as the scarce accuracy in determine fold axis strike and paleomagnetic declinations, and the use of a single reference declination for the whole Scaglia formation where the sites came from, whose age covers a too long time span. From the study of the Maiolica formation (upper Jurassic-lower Cretaceous), Hirt and Lowrie (1988) proposed that the changing of declination values along the arc was not related to the orientation of fold but, in turn, to rotations associated with the deformation of the sedimentary cover. From the study of Messinian sediments of the external domain, Speranza *et al.* (1997) indicated that the present shape of the northern Apennine arc is related to the oroclinal bending of an originally N320° trending straight belt. These Authors suggested that vertical axis rotations accompanied the migration of the main thrust front toward the Adriatic foreland and characterized also the development of second-order arcuate thrust fronts in the Apennines.

The Calabrian Arc

GEOLOGICAL SETTING

The Calabrian Arc defines a mountain belt encircling the Tyrrhenian Sea, from Southern Apennine to Sicilian Maghrebides. It is characterized by two sectors: the Calabria-Peloritane Domain in the central part, and the Southern Apennines and Sicilian Maghrebides thrust and fold belts at the edges of the curved-shape belt, characterised by different tectonic evolution, structural architecture, and deep lithospheric structure (Fig. 4).

Figure 4. Simplified geological map of the Calabrian Arc.



Each arrow represents results from one site, group of sites or magnetostratigraphic sections (modified form Cifelli *et al.*, 2007a).

The Southern Apennines and Sicilian Maghrebides are 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 (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. 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 (Valensise and Pantosti 2001; Montone *et al.* 2004).

Juxtaposed between Southern Apennines and Sicilian Maghrebides, the Calabria-Peloritane Domain is located in the core of the Calabrian Arc. The Calabria-Peloritane Domain 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 Calabria-Peloritane Domain (Cavazza *et al.* 1997; Bonardi *et al.* 2001) 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 (Sartori 1990; Mattei *et al.* 2002; Cifelli *et al.* 2007a).

PALEOMAGNETIC DATA

Starting from the 70's, in Southern Italy more than 500 sites were sampled either for paleomagnetic or magnetostratigraphic investigations. The age of the investigated rocks range from middle Jurassic to Pleistocene (for a recent review, see Cifelli *et al.*, 2007a).

Paleomagnetic data collected in Southern Apennines and Sicily show a different distribution in time and space compared to Calabria-Peloritane Domain. In Southern Apennines and in Sicily paleomagnetic data from Mesozoic and lower Tertiary sedimentary sequences come from different paleogeographic units of the southern Tethyian passive margins, which presently form the fold and thrust belt of the Southern Apennines and Maghrebian chain. Paleomagnetic results indicate that such units record large magnitude, opposite sense, rotations either in Sicily or in Southern Apennines, clockwise and counterclockwise, respectively (Fig. 4). Paleomagnetic data from upper Miocene and Pleistocene deposits come from foredeep and piggyback basins lying in the external part of the Maghrebian and Southern Apennines thrust belts. In Sicily, most of the data show a significant magnitude of clockwise rotation until lower Pleistocene (Butler *et al.* 1992; Scheepers and Langereis 1993; Duermejier *et al.* 1998; Speranza *et al.* 1999; Speranza *et al.* 2003). In Southern Apennines, only one result is available from upper Miocene foredeep siliciclastic sediments outcropping along the Tyrrhenian side of the chain, which show about 40° of counterclockwise rotations, whereas most of the data have been obtained from Pliocene strata collected in claystones from the Potenza, Calvello, and Sant'Arcangelo foredeep and piggyback basins (Sagnotti 1992; Scheepers *et al.* 1993). Data from the Sant'Arcangelo basin and Bradanic foredeep lower Pleistocene sediments indicate a counterclockwise rotation of 25° (Sagnotti 1992; Scheepers *et al.* 1993; Scheepers and Langereis 1994). Finally, both in Sicily and Southern Apennines, uppermost lower Pleistocene and middle Pleistocene sediments are substantially no rotated (Scheepers *et al.* 1994; Cifelli *et al.* 2004; Mattei *et al.* 2004).

In the Calabro-Peloritane Domain, paleomagnetic data have been mainly collected in upper Miocene to Pleistocene sedimentary sequences cropping out both in the post-orogenic basins along the Tyrrhenian coast and in the forearc basins located along the Ionian side of the region. Notwithstanding the large amount of paleomagnetic results, no data are available from Mesozoic and lower Tertiary units, hindering the possibility to reconstruct the older rotational history of the Calabro-Peloritane Domain crustal block. With the exception of the northwestern sector of the Crati basin, where counterclockwise rotations were measured (Cifelli *et al.*, 2008), upper Miocene to Pleistocene paleomagnetic sediments show a general CW rotational pattern along the entire Calabro-Peloritane Domain. Serravallian to upper Tortonian sediments sampled from the Tyrrhenian and Ionian side of Calabria show similar 20° clockwise rotations. This same value has been also obtained from Pliocene to lower Pleistocene strata in Calabria and Peloritani area (Tauxe *et al.* 1983; Aifa *et al.* 1988; Scheepers *et al.* 1994; Speranza *et al.* 2000; Mattei *et al.* 2002; Cifelli *et al.* 2004). Similar to Southern Apennines and Sicily, in the Calabro-Peloritane Domain the uppermost lower Pleistocene–middle Pleistocene sediments generally do not show appreciable rotations. This is well documented in the Crati Basin, where paleomagnetic data from the uppermost lower Pleistocene–middle Pleistocene sedimentary strata are not affected by tectonic rotations (Cifelli *et al.*, 2007b), These data indicate that no significant vertical axis rotations affected sediments of that age, suggesting that the major episodes of the Calabrian Arc bending were almost completed by that time.

The Calabrian Arc has long been considered a classic example of an orocline, which assumes that its curvature was acquired through bending of an originally almost linear orogenic chain (e.g., Eldredge *et al.* 1985). From a structural point of view, the arcuate trend of the Calabrian Arc is defined by the regional variation in the strike of fold axes, striking from NW-SE with a NE vergence in Southern Apennines to E-W with a southern vergence across Sicily. Paleomagnetic data show a correlation between the changes in paleomagnetic declinations and the changes in the trend of the orogen, indicating that the present-day shape of Calabrian Arc is a secondary feature, achieved throughout circa symmetrical opposite rotations along the two limbs of the belt, with counterclockwise rotations in southern Apennines and clockwise rotations in the Calabria-Sicilian Maghrebides (e.g., Channell *et al.* 1980; Channell *et al.* 1990; Speranza *et al.* 1999; Gattacceca and Speranza 2002; Speranza *et al.* 2003). A recent reanalysis of the large paleomagnetic database collected in the last 20 years demonstrates that the orocline model is inappropriate for explaining the spatial distribution and temporal evolution of paleomagnetic rotations along the arc (Cifelli *et al.*, 2008), and that, as we will discuss in this paper, the Calabrian Arc is better described as a progressive arc, following the kinematic classification proposed by Weil and Sussman (2004).

Reconstruction of rotational history in the Apennines arcs

The huge quantity of paleomagnetic data collected in the last few decades in Northern Apennines and the Calabrian Arc enables reconstruction of the rotational history of these two arcs. In particular, the totality of data allows to describe a realistic distribution of tectonic rotations in space and time along the arcs.

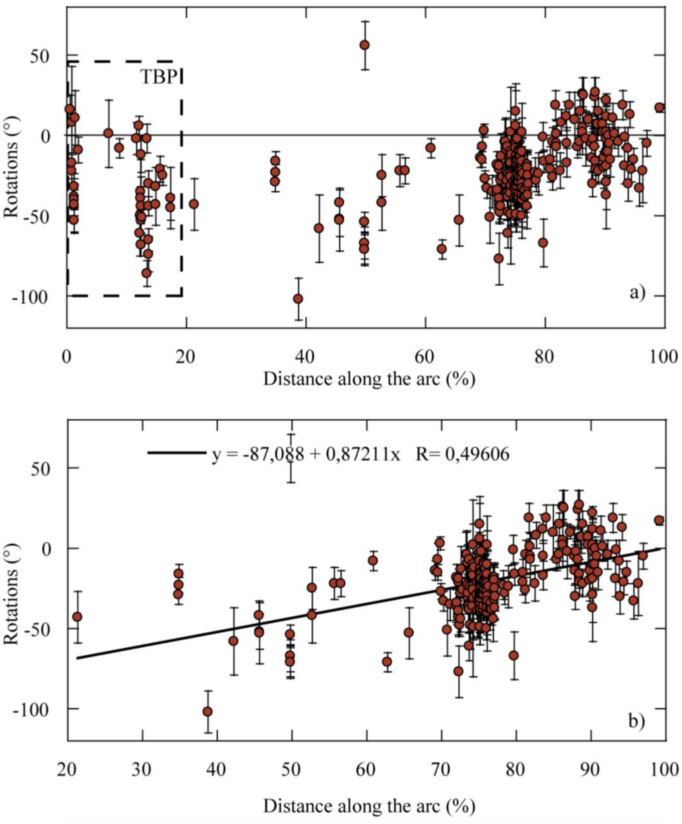
NORTHERN APENNINES

In order to describe the rotational history of the Northern Apennines, we collected published paleomagnetic data available in this region. A total of 375 data have been computed, collected either for tectonic or magnetostratigraphic purposes from Jurassic to Pleistocene strata. In this analysis, paleomagnetic rotations were calculated, according to Demarest (1983), by comparing Northern Apennines paleomagnetic results with coeval expected African paleopoles computed by Besse and Courtillot (2002).

The overall data set is represented in Fig. 3, where paleomagnetic rotations have been differentiated according to the age of the sampled rocks. In this figure the different rotational pattern between the external and the internal sector of the chain is clearly highlighted. While the internal sector of the Tyrrhenian margin is characterised by an irrotational pattern with any tectonic rotations in the last 5 million years, the external sector is characterised by a complex pattern of tectonic rotations, which involves Jurassic to Pleistocene strata. In the following,paleomagnetic data from the Tyrrhenian margin will be excluded whereas paleomagnetic data collected in the orogenic nappes, where the rotations are confined, will be considered in our analysis.

In general, in the external arc, paleomagnetic data show a correlation between the changes in paleomagnetic declination and changes in the orogenic trend, with the exception of the northwestern sector, represented by the Tertiary Piedmont Basin (Fig. 3). In order to analyze the spatial distribution of paleomagnetic rotations in the Northern Apennines, we plotted them as a function of their location along the length of the arc. Starting from the northwestermost sector of Northern Apennines where paleomagnetic data are available, paleomagnetic rotations were analyzed in relation to their relative distance, in percentage, along the arc. A hypothetical axis of the chain was traced across the arc and tectonic rotations were represented as the projection of the sampled sites on this axis (Fig. 5a). A progressive variation of the tectonic rotation is observed moving from SE toward NW, except for the Tertiary Piedmont Basin, where the counterclockwise rotation pattern do not fit with the general trend expected in an orogenic arc. This sector is located in a controversial tectonic setting, at the boundary between the Northern Apennines and the Western Alpine arc, which constitute two orogenic segments characterized by opposite tectonic transport and by a different tectonic history. This distribution of paleomagnetic data indicates that the rotations of the Tertiary Piedmont Basin are not related to the northern Apennine curvature processes. If we exclude this sector, we observe a gradual change (even if with a large scatter) in the magnitude of along-strike paleomagnetic rotations (Fig. 5b), as expected in an orocline.

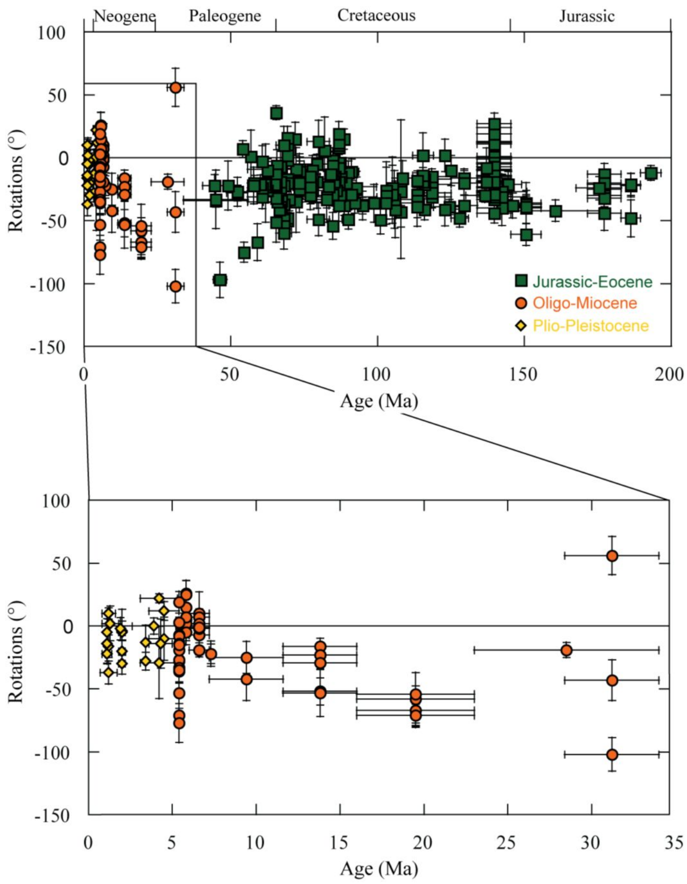
Figure 5. Spatial distribution of paleomagnetic rotations in Northern Apennines.



Distribution of paleomagnetic rotations in Northern Apennines, as a function of the distance along a hypothetical axis of the chain, from NW to SE. (TPB = Tertiary Piedmont Basin)

The totality of data sets allows a valuable time extension, and it is possible to describe the rotational history through time. In Fig. 6, paleomagnetic rotations are plotted as a function of the age, indicating with different colours paleomagnetic rotations detected in Jurassic-Eocene, Oligocene-Miocene and Plio-Pleistocene rocks. In this type of diagrams, the structural influence on paleomagnetic rotations is not detectable and, as a consequence, paleomagnetic sites of the same age may show very different values of paleomagnetic rotations if come from opposite sectors of the curved arc. This is the case of the upper Jurassic-lower Cretaceous Maiolica formation (Hirt and Lowrie, 1988), whose large range of paleomagnetic rotations at 140 My is due to the fact that sites are distributed in a very wide area along the arc. A similar dispersion is noted in the Scaglia formation (around 50 and 90 Ma), sampled by several Authors along different portions of the arc. Late Miocene deposits show a scatter distribution around 6 Ma; these data come from the external flysch deposits and their geographic distribution cover the entire arc length, characterized by different structural trend. In general, data from younger sedimentary sequences show a more regular trend with paleomagnetic rotations decreasing with time.

Figure 6. Temporal distribution of paleomagnetic rotations in Northern Apennines.

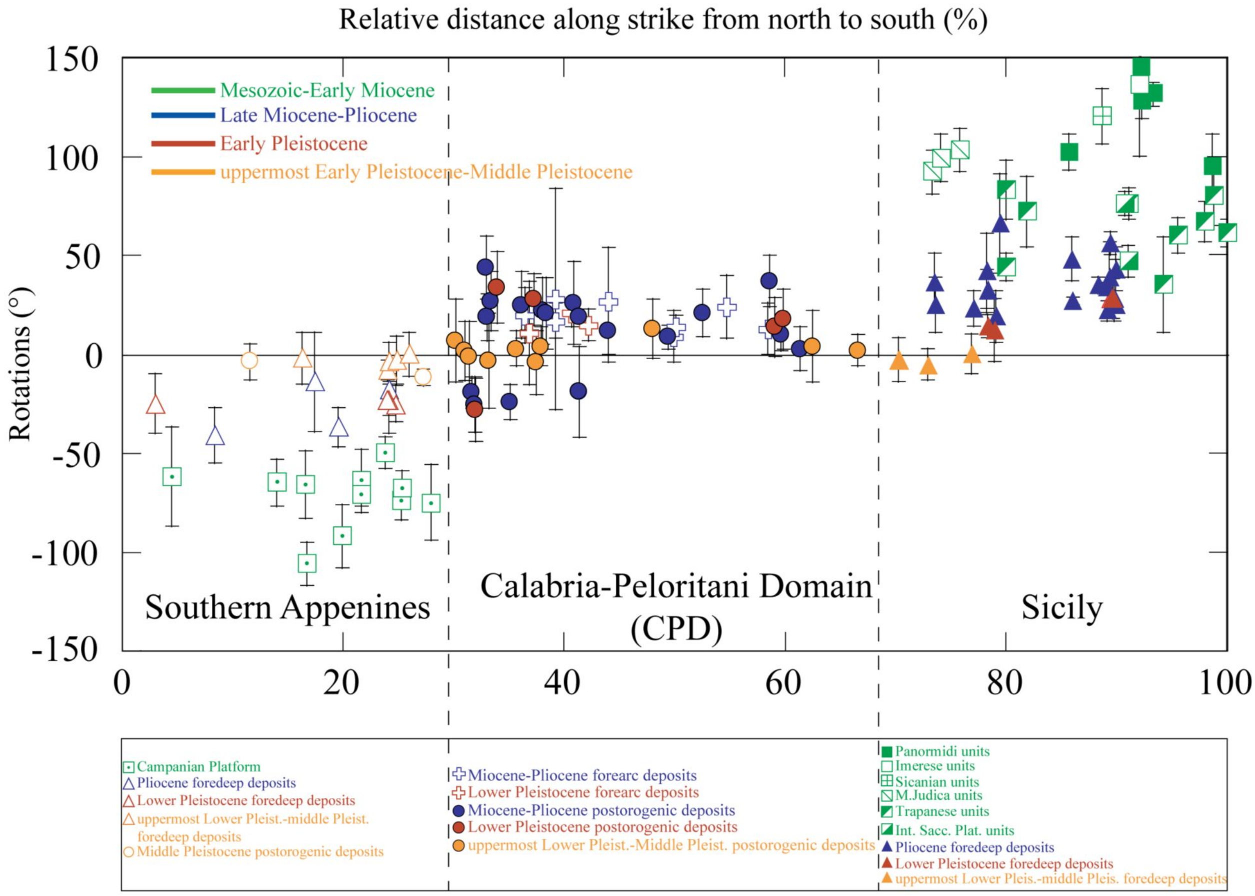


Paleomagnetic rotations (in degrees) versus age in Northern Apennines. Paleomagnetic data shown are those reported in Fig. 3, except the Tertiary Piedmont Basin and the Tyrrhenian margin.

CALABRIAN ARC

Paleomagnetic rotations available for Sicily, Southern Apennines and Calabria-Peloritane Domain can be used to unravel the history of paleomagnetic rotations through space and time of the Calabrian Arc. In Fig. 7, the distribution of paleomagnetic rotations is plotted as a function of distance (from north to south) along the arc. In Southern Apennines and Sicily, sedimentary deposits underwent counterclockwise and clockwise rotations, respectively. The magnitude of paleomagnetic rotations appears to be a function of their position within the thrust belt, being the more internal tectonic units systematically more rotated with respect to the external ones (Oldow *et al.* 1990; Speranza *et al.* 2003). In correspondence of the transition between Southern Apennines and the Calabria-Peloritane Domain, the distribution of paleomagnetic rotations along the arc shows an abrupt change in paleomagnetic rotations, in an area where a complex pattern of paleomagnetic rotations has been detected (Cifelli *et al.* 2007b). This abrupt change is not expected in a typical orocline, where a gradual change of rotations through the arc should occur. Moreover, in the Calabria-Peloritane Domain, measured paleomagnetic rotations are almost uniform along the entire region, and in particular there is no significant difference between paleomagnetic rotations measured in the Ionian fore-arc basins and in the Tyrrhenian postorogenic extensional basins, suggesting that the Calabria-Peloritane Domain behaved as an almost rigid block.

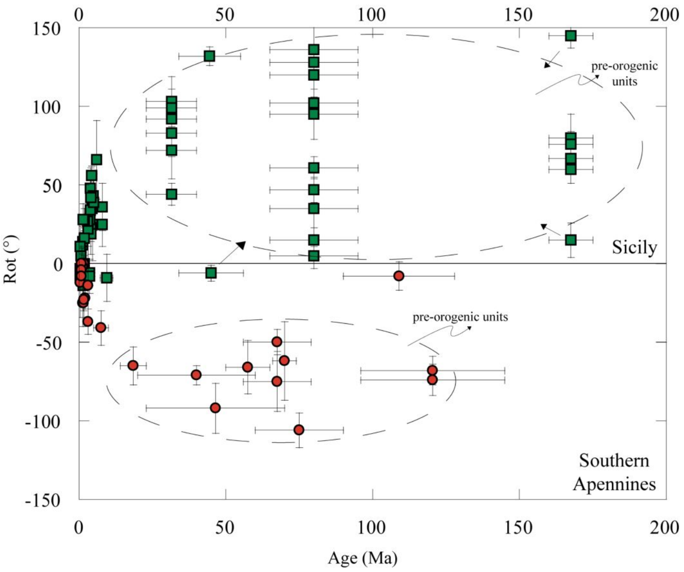
Figure 7. Spatial distribution of paleomagnetic rotations in the Calabrian Arc.



Distribution of paleomagnetic rotations in the Calabrian Arc as a function of distance (from N to S) along a hypothetical axis of the chain (modified from Cifelli *et al.*, 2008).

The distribution of paleomagnetic rotations as a function of the age (Fig. 8) shows as the Southern Apennines and Sicily thrust belts rotational pattern is remarkable different from that observed in the Calabria-Peloritane Domain, reflecting the peculiar tectonic evolution of the Calabrian Arc. In Sicily and Southern Apennines, from Jurassic to middle Miocene time rotations are very high but remain constant during the entire time span (highlighted b y dashes ellipses in Fig. 8). From middle Miocene a progressive decrease in the magnitude occurs (Figs. 7 and 8). The observed trend marks the progressive incorporation of different paleogeographic domains in the Apennines and Maghrebian orogenic wedge and suggest that the observed Miocene paleomagnetic rotations initiated during middle to late Miocene, when internal Apennines and Maghrebian strata started to be included in the orogenic wedge (Cifelli *et al.*, 2008). The significant magnitude of opposite sense rotations measured in lower Pleistocene sediments in Sicily and Southern Apennines indicate that vertical axis rotations played a very important role during the recent history of the Calabrian Arc (e.g., Scheepers and Langereis 1993; Scheepers *et al.* 1993; Speranza *et al.* 1999). The 'rotational' behavior of the Calabria-Peloritane Domain is completely different. In this sector, there is no evidence of a decrease of paleomagnetic rotations with time, because an almost constant value of about 20° of clockwise rotations has been obtained from Serravallian to lower Pleistocene strata (Fig. 8). These data suggest that during the early Pleistocene the Calabria-Peloritane Domain rotated as an almost homogeneous block, which underwent significant 15–20° clockwise rotations, and that no significant rotations occurred during late Miocene–Pleistocene time (Cifelli *et al.*, 2007a).

Figure 8. Temporal distribution of paleomagnetic rotations in the Calabrian Arc.



Paleomagnetic rotations (in degrees) versus age for Sicily (green squares) and Southern Apennines (red circles). (Modified from Cifelli *et al.*, 2007a).

The shape of the Northern Apennines and the Calabrian Arc

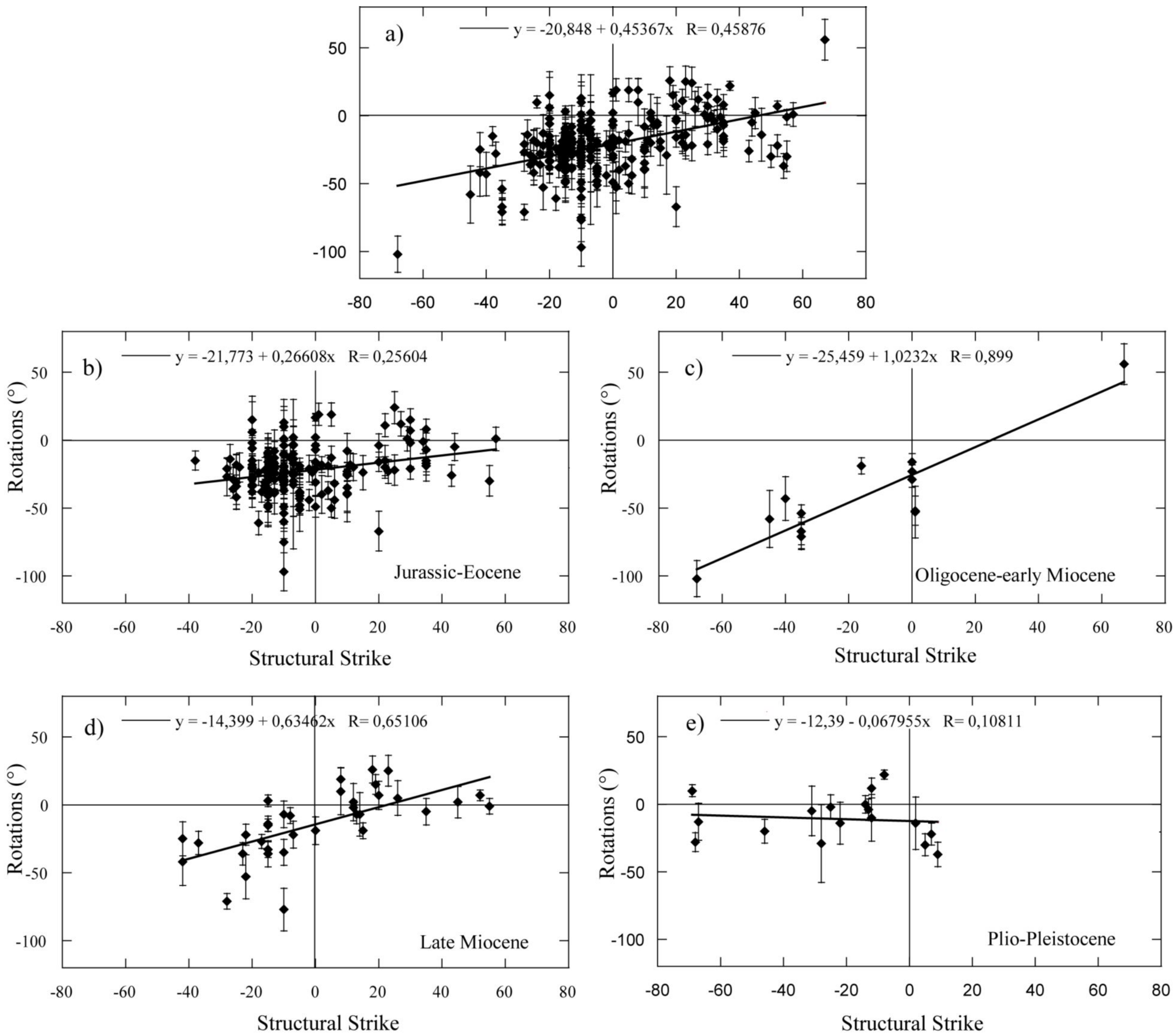
Paleomagnetism is a fundamental tool to assess kinematic models of curved orogenic systems around the world because of its great potential in quantifying vertical axis rotations (e.g., Carey 1955; Eldredge *et al.* 1985; Marshak 1988; Van der Voo *et al.* 1997; Weil and Sussman 2004; Cifelli *et al.* 2008). On the basis of the spatial and temporal relationship between deviations in structural trend and the vertical axis rotation that took place within the belt, curved belts have been interpreted as primary, secondary or composite features. Primary arcs initiate in their present curved shape and their curvature does not increase during subsequent deformation. In this type of arcs, paleomagnetic declinations remain parallel along the arc and do not correlate with changes in thrust and fold-axis trend. Conversely, secondary arcs are originally linear fold-thrust belts that acquire curvature in a second phase of tectonic deformation, accompanied by opposite large-scale vertical axis rotations shaping the arc. In oroclines (e.g., Carey 1955; Marshak 1988) paleomagnetic declinations change direction along the arc and follow changes in thrust and fold-axis trend with a one-to-one correlation. Between these two end-members, progressive arcs represent either orogenic belts that acquire their curvature during progressive deformation or belts that acquire a portion of their curvature during a subsequent deformation phase (Vogt *et al.* 1976; Weil and Sussman 2004). This intermediate category describes the formation of most of ancient and modern curved orogenic systems (Fig, 2).

The origin of the arcuate shape in the Northern Apennines and in the Calabrian Arc represent a long debated paleomagnetic subject in the scientific community. In the following, results from the oroclinal tests for the two sectors of the Italian peninsula are described, in order to define whether the shape of these two arcs can be referred to the same mechanism or to different causes.

OROCLINAL TEST FOR NORTHERN APENNINES

For the oroclinal test, we focused on data coming from the external arc. The relationship between paleomagnetic declinations and structural directions was investigated using the method originally proposed by Schwartz and Van der Voo (1983) for the Appalachians and later applied in different curved orogenic systems, Northern Apennines included (Eldredge *et al.* 1985; Lowrie and Hirt 1986; Speranza *et al.* 1997). Differently from the previous oroclinal tests, in our analysis we directly compared paleomagnetic rotations with relative fold axis deviation. We used 315° as the reference fold axis direction, whereas fold axes at each site were determined either from the original publications or from geological maps of appropriate scale. When available, anisotropy of magnetic susceptibility data were used to estimate fold axis directions, representing the in-situ site mean direction of the principal maximum susceptibility a good indicator of the local fold axis direction (e.g., Kligfield *et al.* 1983; Kissel *et al.* 1986; Cifelli *et al.* 2005). We did not consider those data where the relationship between paleomagnetic rotation and structural elements were poorly constrained or those that could not be located in the map because information from the original papers was missing.

Figure 9. Oroclinal test for the Northern Apennines



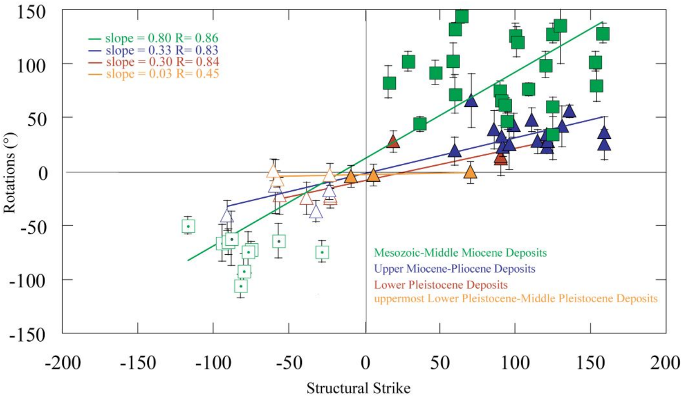
Oroclinal test for the Northern Apennines considering the totality of data (a), Jurassic-Eocene data (b), Oligocene-early Miocene data (c), late Miocene data (d), and Plio-Pleistocene data (e). Rotations are those reported in Fig. 4. Strike is the difference between a reference fold axis direction (315) and the structural direction at the site scale (see text for further details).

The huge number of data used in this analysis and the wide geographic distribution of sites, make data representative of the Northern Apennines. The totality of data is reported in Fig. 9a. Data are dispersed in the diagram, with the slope of the regression line far from 1, indicating a scarce correlation between changes of paleomagnetic declinations direction and changes in thrust and fold-axis trend. In order to analyze the temporal variations of paleomagnetic rotations paleomagnetic data were grouped into four distinct age intervals, representative of different stages of the Northern Apennines evolution: Jurassic-Eocene, Oligocene-early Miocene, late Miocene, Pliocene-Pleistocene (Fig. 9b-e). Data from the Jurassic-Eocene sediments come from the internal part of the chain, mostly from the Umbrian sequence, which represent the pre-orogenic tectonic history of the Northern Apennines (Fig. 9b). The geographic distribution of data is limited compared to the total extension of the arc (Fig. 3), whereas data span over a large temporal interval. This area is also characterized by a complex faulting and folding, often cut by normal faults. The scatter of paleomagnetic declinations may therefore result from local tectonic effects. Paleomagnetic data from Oligocene- Miocene mainly come from the external part of the chain and have a representative geographic distribution along the arc. Most of these sites have been sampled in the Epiligurian units which record the progressive thrusting of the Ligurian nappes toward the Adriatic foreland. Calculation of the best fit line of the Oligocene-early Miocene data gives a correlation coefficient of 0.899, which describe a close one-to-one correlation with the variation between changes in declination and the structural trend (Fig. 9c). These data suggest that at least this part of the arc is not a primary feature. Data from late Miocene, coming from the external flysch units of the Umbrian domain, show the same trend, with a correlation coefficient of 0.65 and a slope of 0.63 (Fig. 9d). This result is different from result published by Speranza *et al.* (1997), as they excluded sites from the Acquasanta structure, which are instead included in our calculation. Notwithstanding these values indicate quite a good correlation between changes in declination and the orogen trend, ideal oroclinal bending would display a line of unite positive slope. In Fig. 9c, in fact, rotations range between the slope of zero and one, similar to that expected in a progressive arc. In Plio-Pleistocene sediments, which represent the foredeep sediments related to the last stages of the Northern Apennine deformation, the correlation coefficient is very low, indicating that the process of curvature was almost finished (Fig. 9e).

OROCLINAL TEST FOR THE CALABRIAN ARC

The distribution of paleomagnetic rotations along the Calabrian Arc indicates that the limbs of the arc underwent circa-symmetrical opposite rotations, with counterclockwise rotations in the Southern Apennines and clockwise rotations in Sicily (Fig. 4). An oroclinal test allows verifying whether this distribution correlates with changes in the trend of the orogen, supporting the orocline model. Paleomagnetic data described above indicate that the Calabria-Peloritane Domain had a different tectonic history compared to the other portions of the Calabrian Arc (see Cifelli *et al.* 2008 for a full discussion). For this reason, we excluded paleomagnetic data collected in the Calabria-Peloritane Domain from the oroclinal test, focusing only on data from the Southern Apennines and Sicily. We directly compared paleomagnetic rotations with structural strikes determined from the original publications, geological maps or Anisotropy of Magnetic Susceptibility (AMS) data. We did not consider those data where the relation between paleomagnetic rotation and structural elements was poorly constrained (for more details refer to Cifelli *et al.*, 2008).

Figure 10. Oroclinal test for the Southern Apennines and Sicily.



Oroclinal test for the Southern Apennines and Sicily. The different colours describe the temporal distribution of paleomagnetic rotations as a function of the structural trend of the chain. (modified from Cifelli *et al.*, 2008).

In order to quantify the temporal variation in paleomagnetic directions as a function of change in the regional structural trend, we used a linear regression technique (e.g., Eldredge *et al.* 1985; Schwartz and Van der Voo 1983), grouping paleomagnetic data into four distinct age intervals, representative of the different stages of Calabrian Arc evolution: Mesozoic to middle Miocene, late Miocene-Pliocene, early Pleistocene, and uppermost early Pleistocene-middle Pleistocene. The distribution of the data in Fig. 10 indicates that tectonic rotations in the two edges of the Calabrian Arc are well correlated with the structural trend. Calculation of the best-fit line of the data gives a correlation coefficient of 0.73, with a line of slope 0.55 (black solid line in Fig. 10). This value indicates quite a good correlation between changes in declination and the orogen trend, indicating that Calabrian Arc curvature is not a primary feature. However, the distribution of paleomagnetic rotations ranges between the slope of zero and one, similar to that expected in a progressive arc. The distribution of vertical axis rotations through time indicates that paleomagnetic rotations systematically decrease in progressively younger sedimentary deposits in both the Southern Apennines and in Sicily. These data clearly indicate that the curvature of the Calabrian Arc was acquired progressively and that, taking into account only the Southern Apennines and Sicily, the Calabrian Arc could be considered a progressive arc, following the kinematic classification proposed by Weil and Sussman (2004).

Discussion

Paleomagnetic data collected in Italy indicate that vertical axis rotations played a key role in the Neogene and Quaternary geodynamic evolution of this part of the Mediterranean Basin.

The distribution of tectonic rotations indicate that no rotations occurred before the sedimentary units were involved in the orogenic wedge, both in the Northern Apennines and the Calabrian Arc, suggesting that the measured paleomagnetic rotations totally occurred during the deformation of the orogenic belts. It is worth to note that in the Northern Apennines paleomagnetic data have been mostly collected in the more external units (i.e., Umbria-Marche and Miocene-Pleistocene foredeep units) and only few data are available for innermost units (Epiligurian and Tuscan units). This hampers the possibility to investigate a possible extension of thecounterclockwise rotation of the Corsica-Sardinia block to the Apennine orogenic wedge.

Oroclinal tests carried out for the two arcs indicate that they were progressively shaped during the main deformational phases. In the Northern Apennines the curvature of the arc was acquired mostly during early Miocene to lower Pliocene, as the Plio-Pleistocene units show any relationships between structural trend and paleomagnetic rotations. In the Calabrian Arc the curvature of the arc was acquired during the middle Miocene to early Pleistocene, being the uppermost lower Pleistocene-middle Pleistocene deposits completely unrotated.

Concerning with the geodynamic mechanism responsible for the curvature of the Calabrian and Northern Apennines arcs, one common feature observed in both the arcs is that the core of the arc is located on top of subducting slab, evidenced by seismic tomography and subcrustal seismicity (Selvaggi and Amato 1992; Selvaggi and Chiarabba 1995; Chiarabba *et al.* 2009; Di Stefano *et al.* 2009). On the other hand, the different distribution of tectonic rotations in the Northern Apennines and the Calabrian Arc suggest a distinct evolution and mode of arc formation. In particular, the different amount of curvature of the arcs can be related to the nature, length and different evolution of the subducting lithospheres.

In Northern Apennines subducting lithosphere is continental since Oligocene times, and almost homogeneous all along the arc. The correlation between subduction, nappes emplacement and paleomagnetic rotations is demonstrated by the lack of vertical axis rotations along the internal Tyrrhenian margin, during the same time span of the acquisition of the Northern Apennines curvature. In this sector, minor (second order) arcs also concurred to the observed paleomagnetic rotations. These small-scale arcs are mainly related to heterogeneities in the sedimentary successions or to the presence of magmatic bodies which influenced the geometry and development of thrust propagation.

In the Calabrian Arc, the upper mantle structure is more complex and reflects, on surface, the different structural architecture and tectonic evolution between the Calabria-Peloritane Domain, from one side, and Sicilian Maghrebides and Southern Apennines, on the other side. Earthquake distribution and seismic tomography indicate that the Calabria-Peloritane Domain is presently located on top of a narrow and steeply dipping slab (e.g., Anderson and Jackson 1987; Spakman *et al.* 1993; Selvaggi and Chiarabba 1995; Lucente *et al.* 1999; Wortel and Spakman 2000; Piromallo and Morelli 2003). The across-strike width of the slab (about 700 km) corresponds to the Ionian Mesozoic oceanic lithosphere, intervening between the Apulia and Africa continental margins. Its northeastern and southwestern boundaries match, at the surface, the boundary between Calabria-Peloritane Domain and Southern Apennines and western Sicily, respectively, which conversely, do not show any evidence of deep seismicity. According to the current geodynamic models, the evolution of the Calabrian Arc during the Neogene and Quaternary was driven by the southeastward retreat of the Ionian slab (among others, Malinverno and Ryan 1986; Faccenna *et al.* 2001). The fast retreat of the Ionian slab during Neogene was responsible of the southeastward drifting of the Calabria-Peloritane Domain far away from Sardinia-Corsica, to be finally juxtaposed to the Southern Apennine-Maghrebide orogenic system (Alvarez *et al.* 1974; Malinverno and Ryan 1986; Faccenna *et al.* 1997; Bonardi *et al.* 2001; Mattei *et al.* 2002). Differently from Northern Apennines, where only laterally homogeneous continental lithosphere was subducted, in the Calabrian Arc, the peculiar configuration of the subduction system (an oceanic lithosphere locked between two continental lithospheres) initially favored the fast roll-back of the Ionian oceanic lithosphere and enhanced the tight curvature of the Calabrian Arc. Later on, when the reduction of the amount of oceanic lithosphere available for subduction led to shortening of the continental lithosphere, the retreat of the Ionian subducting slab was prevented and the curvature halted, together with back-arc opening in the Southern Tyrrhenian Sea.

The different shape and tectonic evolution of the Northern Apennines and the Calabrian Arc indicate how the internal heterogeneities within the subducting lithosphere may influence the mode and the shape of arc formation, confirming that the nature of both the overriding plate and the subducting slab, their geometry, width and space-time evolution, are elements that must be necessarily taken into account to fully understand the formation and evolution of related arc-shaped belts.

Conclusions

In the last decades, paleomagnetism strongly contributed to understanding the geodynamic evolution of the Apennines system, providing quantitative constraints for the development of geodynamic models. Vertical axis rotations played a primary role in the Neogene and Quaternary geodynamic evolution of the Italian region.

In this paper, the curved shape of the Northern Apennines and the Calabrian Arc have been described in the framework of the space-time evolution of the Ionian-Adriatic subduction system. For both the arcs a mechanism of progressive arc has to be invoked. The main differences in the distribution of paleomagnetic rotations along the two arcs and in the amount of curvature find an explanation in the nature, length and different evolution of the lithospheres involved in the subduction process.

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