Paleomagnetic evidence for a post–1.2 Ma disruption of the Calabria terrane: Consequences of slab breakoff on orogenic wedge tectonics

Fabio Speranza¹, Patrizia Macrì¹, Domenico Rio², Eliana Fornaciari², and Chiara Consolaro²

¹Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Rome, Italy
²Dipartimento di Geologia, Paleontologia e Geofisica, Università di Padova, Via Giotto 1, 35137 Padua, Italy

ABSTRACT

In the past few years, a wealth of paleomagnetic data gathered from Neogene sediments consistently showed that since ca. 10 Ma the Calabria terrane coherently drifted ∼500 km ESE-ward from the Sardinian margin, and rotated 15°–20° clockwise (CW) as a rigid microplate between 2 and 1 Ma. Here we report on a high-resolution paleomagnetic investigation of the Crotone forearc basin of northern Calabria. The integrated calcareous plankton biostratigraphy indicates early Pliocene (Zanclean) to late early Pleistocene (Calabrian) ages for 29 successful paleomagnetic sites and/or sections. Unexpectedly, four domains undergoing distinct rotations are documented. Two blocks have undergone a CW rotation statistically indistinguishable, for both timing and magnitude, from the rigid Calabria rotation documented in the past. Two additional ∼10-km-wide blocks yielded a 30.8° ± 22.5° and 32.0° ± 9.2° post–1.2 Ma counter-clockwise rotation, likely due to left-lateral shear along two NW-SE fault zones. We infer that since advanced early Pleistocene times, after the end of the uniform CW rotation, left-lateral strike-slip tectonics disrupted the Calabria terrane, overwhelming a widespread extensional regime accompanying the Calabria drift since late Miocene times. Seismological evidence reveals that only the southern part of the Ionian slab subducting below Calabria is continuous, while beneath northern Calabria a slab window between 100 and 200 km depth is apparent. We suggest that the partial breakoff of the Ionian slab after 1 Ma induced the fragmentation of the Calabria wedge, and that strike-slip faults from the Crotone basin decoupled “inactive” northern Calabria from southern Calabria, still drifting towards the trench.

INTRODUCTION

In the past few years, several attempts have been made to relate mountain belt evolution to deep mantle dynamics. It is well acknowledged that orogens form above a lithospheric subduction zone, yet the tectonic evidence from a mountain belt has been linked to several different features of the subduction system. Mantle processes related so far to geologic evidence include lithospheric delamination both in terms of detachment and sinking in the mantle of orogenic roots (Hoke and Garzione, 2008), and decoupling between crust and mantle in a passive subduction zone (Cavintino and De Celles, 1999), lateral tears occurring in the subduction system (Govers and Wortel, 2005; Rosenbaum et al., 2008), and slab breakoff due to impingement of continental lithosphere entering into a subduction zone (van der Meulen et al., 1999). Obviously, both the geometry of the subducting slab and the tectonics of the overlying orogen should be tightly constrained before speculating on the depth-to-surface geologic links.

The Apennines turn out to be one of the best regions in the world to gather the required high-resolution geological and geophysical evidence from an orogenic system and underlying mantle. Here deep crust and mantle geometry has been reconstructed with a resolution never attained elsewhere, taking advantage of the huge amount of seismic data provided by permanent and temporary seismic networks deployed during the past thirty years to mitigate seismic hazards of Italy (Lucente et al., 1999; Chiarabba et al., 2009; Di Stefano et al., 2009). At the same time, the paleomagnetic investigation of the thick, continuous, and well-exposed sedimentary sequences developed both above the Adria-Africa passive margin and in the Apennine foreland basins has represented a fundamental proxy to unravel orogenic processes.

Paleomagnetism has clearly demonstrated that the peculiar tectonics of the Mediterranean domain, involving microplate dispersal and rollback of isolated slab fragments, has been accompanied by large-magnitude (sometimes exceeding 100°) rotations about vertical axes of microplates, terranes, and orogenic bends (Channell et al., 1990; Gattacceca and Speranza, 2002; Cifelli et al., 2007a; Fig. 1). Therefore paleomagnetism has proven to be one of the most powerful tools to constrain both paleogeography and the timing of microplate (or terrane) drift and orogenic bending.

Paleomagnetic analyses have been predominately used so far to constrain first-order features of the Mediterranean puzzle and to understand the regional rotational behavior of different sectors of the Alpine–Apennine belt. In this paper, we try to paleomagnetically unravel orogenic wedge tectonics at a smaller scale than that investigated so far, by investigating at high-resolution the expanded Plio–Pleistocene marine successions exposed in the Crotone basin (Fig. 1, Calabria forearc of the southern Tyrrhenian subduction zone). We find evidence for post–1.2 Ma block rotation and disruption of the Calabria terrane that we relate to the geometry of the Tyrrhenian subduction system evidenced by recent high-resolution seismic tomography data.

TECTONICS, PALEOMAGNETISM, AND GEODYNAMICS OF THE SOUTHERN TYRRHENIAN SUBDUCTION ZONE

Deep sea drillings of the Tyrrhenian floor (Kastens et al., 1988), and the paleomagnetism of the southern Apennines–Calabro Peloritan (or Calabria) block–Sicilian Maghrebides range salient (e.g., Cifelli et al., 2007a), have shown that the southern Tyrrhenian Sea spread since 8–10 Ma ago behind the Calabria terrane, which underwent a ∼500 km yet virtually nonrotational ESE-ward drift. Calabria pushed apart in a saloon-door-like manner the southern Apennine and Sicilian Maghrebide belt segments, which, conversely, underwent large-magnitude orogenic rotations (Channell et al., 1990; Gattacceca and Speranza, 2002; Speranza et al., 2003; Fig. 1).
At the salient apex, the subduction of the oceanic Ionian lithosphere beneath Calabria has been documented since the 1970s by subcrustal foci deepening down to ~500 km depth below the southern Tyrrhenian Sea (Chiarabba et al., 2008, and references therein). The high-quality geological and geophysical evidence gathered so far has led to an overall consensus on the geodynamics of the Tyrrhenian-Calabria system. In fact, the ESE-ward drift of the Calabria orogenic terrane and backarc spreading of the Tyrrhenian Sea are considered rather independent from the kinematics of major Africa and Eurasia plates but the result of the passive subduction and retreat of a Ionian slab fragment since 8–10 Ma ago (Malinverno and Ryan, 1986; Patacca et al., 1990; Cello et al., 1996; Jolivet and Faccenna, 2000; Faccenna et al., 2001; Rosenbaum and Lister, 2004).

Paradoxically, much less consensus exists on the internal structure and recent tectonics of the Calabria block itself. Basically, two end-member models have been put forward in the past years: (1) the ESE-ward drifting Calabria terrane is fragmented into several blocks, undergoing differential displacements towards the trench, and separated by NW-trending (on average) strike-slip faults (Knott and Turco, 1991; Van Dijk, 1994; Guarnieri, 2006; Tansi et al., 2007; Del Ben et al., 2008); and (2) the 8–10 Ma drift of a rigid Calabria block has been solely accompanied by extensional faulting (at least inland Calabria), as synsedimentary extensional features are documented in the whole middle-upper Miocene to Pleistocene sedimentary succession covering the Calabria backbone affected by older Alpine deformation and metamorphism (Mattei et al., 1999, 2002; Monaco and Tortonici, 2000; Cifelli et al., 2007a, 2007b).

Paleomagnetism would be critical to discriminate between these two tectonic models, because it should highlight both shear zones yielding local rotations and blocks undergoing individual rotations (if existent). So far, several paleomagnetic investigations have almost systematically shown clockwise (CW) rotations in late Miocene to early Pleistocene sediments, suggesting that Calabria has behaved as a rigid microplate, rotating as a whole 15°–20° CW between 1 and 2 Ma (Scheepers, 1994; Scheepers et al., 1994; Mattei et al., 2002; Cifelli et al., 2007a). Yet, our new data from the Crotone basin reveal a paleomagnetic rotational pattern definitely more complex than that documented so far.

GEOLOGICAL SETTING OF THE CROTONE BASIN, PALEOMAGNETIC SAMPLING, AND METHODS

The spectacular Plio-Pleistocene expanded sedimentary succession cropping out in the Crotone basin has served in the past as reference...
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for the global chronostratigraphic scale (e.g., Cita et al., 2008), for central Mediterranean climatic and paleoceanographic reconstruction (e.g., Combourieu-Nebout, 1995), and to understand the interplay of tectonics, climate, and eustasy in shaping the stratigraphic architecture of a sedimentary basin (e.g., Massari et al., 2002). The Plio-Pleistocene marine succession overlies Messinian evaporites and Serravalian-Tortonian clastic sediments, which in turn rest upon the metamorphic rocks of Alpine Calabria (Consiglio Nazionale delle Ricerche, 1991). In general, the basin appears to be little deformed, even if it cannot be excluded that most tectonic structures are not visible because of the predominant clayey substratum and the mild relief. The most evident tectonic features of the basin are N-S to SW-NE normal faults, which separate several horst and grabens (predominantly made by Pliocene sandstones) in the San Mauro Marchesato–Zinga area (Fig. 2; Roda, 1964).

Clear examples of compressive deformation are visible at only two localities: (1) at San Nicola, where Tortonian (and older?) and Messinian sediments are juxtaposed along an ~5-km-long NW-SE fault, and the Tortonian clastics are cut by meter-scale, NW-SE left-lateral, strike-slip faults; and (2) at NE of Botricello, where Messinian sands and conglomerates are stacked above lower Pliocene clays along an ~1-km-long N200°-verging thrust fault (Fig. 2). These two outcrops are located along two NW-SE left-lateral strike-slip fault zones, which are inferred to bound the Crotone basin according to Van Dijk (1994). Following his suggestions, some authors have argued in the past that sediment

Figure 2. Paleomagnetic declinations from the Crotone basin. Numbers correspond to section and/or site numbers in Table 1. Declinations from previous authors (small arrows and corresponding letters) are detailed in Table 2.
deposition in the Crotone basin has been partly controlled by strike-slip tectonics (Zecchin et al., 2004).

During several campaigns in 2005–2008 we sampled for paleomagnetic analysis 41 sites and/or sections, 38 of which are located in the Crotone basin, while three are from the nearby area of Catanzaro (Fig. 2). A site refers to two to three (at least) outcrops that are a few meters thick, while a section refers to a succession of sediments continuously outcropping, more than 10 meters thick. All sites and/or sections, except for three sites, have been framed in the well-established Pliocene–Pleistocene orbitally tuned time scale for the Mediterranean region (Lourens et al., 2004; GSA Data Repository Fig. DR11; see Table DR1 [footnote 1]) by integrating planktonic foraminifera and calcareous nanofossils biostratigraphies with magnetic polarity results. The obtained chronologies (for the only paleomagnetic successful sites and/or sections) are summarized in Table DR1 (see footnote 1).

At each site and/or section, we drilled 8–40 (18 on average) cores by a petrol-powered portable drill, and oriented them in situ by a magnetic compass, corrected to account for a local ~2° magnetic declination according to Istituto Nazionale di Geofisica e Vulcanologia (2007). The natural remanent magnetization of all specimens was measured in a magnetically shielded room with a DC-SQUID cryogenic magnetometer (2G Enterprises, USA), and its stability was checked by thermal cleaning up to a maximum temperature of 600 °C. The paleomagnetic analyses were carried out in the laboratory of the Istituto Nazionale di Geofisica e Vulcanologia (Rome).

Thermal demagnetization data were plotted on both orthogonal demagnetization diagrams (Zijderveld, 1967) and on equal-area projections, and the magnetization components were isolated by principal component analysis (Kirschvink, 1980). Site-mean paleomagnetic directions were computed using Fisher’s (1953) statistics.

RESULTS

Only 29 sites and/or sections yielded reliable paleomagnetic results, while 12 were found to be nonmagnetized. After the removal of a viscous component at 100–200 °C, a characteristic component of magnetization was isolated in the 100–460 °C temperature interval (Fig. 3). About 80% and 20% of the samples were completely demagnetized at 250–400 °C and 400–460 °C, respectively, indicating that the magnetic mineralogy is dominated by iron sulfides (likely greigite, as documented in several Neogene clay deposits from Italy by Sagnotti and Winkler, 1999), while Fe-rich titanomagnetite is present only in a few sites. Site-mean directions are well constrained, the $\alpha_{95}$ values being comprised between 2.8° and 13.4° (7.4° on average, Fig. 4 and Table 1). Paleodeclinations, showing a

![Figure 3. Orthogonal vector diagrams of typical demagnetization data, tilt-corrected coordinates. Solid and open dots represent projection on the horizontal and vertical planes, respectively. Demagnetization step values are in °C. NRM—Natural remanent magnetization.](image)
considerable spread, can be equated to rotations with respect to nearby plates, because neither Europe nor Africa have undergone significant rotations in Plio-Pleistocene times (Besse and Courtillot, 2002).

**EVIDENCE FOR POST–1.2 Ma BLOCK ROTATION IN THE CALABRIA TERRANE**

Paleomagnetic data from the Crotone basin document four domains undergoing rotations of opposite sign (Fig. 2). Apart from the Catanzaro domain, each rotational block is defined by at least six sites and/or sections yielding a rotation of the same sign. The Catanzaro and Marcedusa-Zinga domains are rotated CW by 7.6° ± 7.0° and 27.0° ± 18.9°, respectively, while the Botricello and Strongoli-Neto domains yield a counterclockwise (CCW) rotation of 30.8° ± 22.5° and 32.0° ± 9.2°, respectively (one site and/or section showing a very different rotation was discarded from each of these three latter domains). All domains include almost coeval lower-middle Pliocene sediments, thus paleodeclination variability reflects rotations of individual blocks, instead of a rotational evolution along time.

The great majority of both normal- (11 out of 29) and reverse-polarity paleomagnetic directions are located at least 10°–20° apart from the (normal and reverse) geocentric axial dipole (GAD) field direction expected at the Crotone area (Fig. 4), thus making the possibility of a recent magnetic overprint unlikely. Given the considerable declination spread, we performed an inclination-only fold test (according to Enkin and Watson, 1996). Maximum clustering occurs at 70% of unfolding (k = 34.77), and it decreases until 0% of unfolding (k = 21.05). The 70% unfolding increase of data clustering is barely significant at the 95% level of significance (k2/k1 = 1.65, with critical value of F95% = 1.57 for N = 29 directions).

However, reverse-polarity paleomagnetic declinations exhibit a considerable scatter, while most of the normal-polarity directions tend to cluster in the vicinity of the GAD field direction, both in in situ and tilt-corrected coordinates. Thus the question arises as to whether some of the normal-polarity directions are biased by a magnetic overprint. The magnetic mineralogy of our sites is dominated by greigite, which has been reported to acquire remanence even some hundreds of thousands of years after sediment deposition (e.g., Sagnotti et al., 2010). To evaluate the occurrence of uncleared secondary magnetization components, we have performed both a reversal (according to McFadden and McElhinny, 1990) and a fold (according to McFadden, 1990) test, separately on each rotational domain. The reversal test is indeterminate for the Catanzaro and Botricello domains and...
<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude (N)</th>
<th>Longitude (E)</th>
<th>D (°)</th>
<th>I (°)</th>
<th>D (°)</th>
<th>I (°)</th>
<th>Age (Ma)</th>
<th>Stage</th>
<th>Bedding</th>
<th>Strata</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zanclean</td>
<td>43.8 °</td>
<td>2.8 °</td>
<td>5.23–4.18</td>
<td>34-4 C3n</td>
<td>6.8</td>
<td>37.3</td>
<td>16°39.53</td>
<td>38°53</td>
<td>Zanclean</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>Simeri †</td>
<td>38°53</td>
<td>16°40.49</td>
<td>4.2–3.6</td>
<td>302-11 C2Ar</td>
<td>195.0</td>
<td>–57.0</td>
<td>212.4</td>
<td>116-13 C3n.1r or C2Ar</td>
<td>195.0</td>
<td>–57.0</td>
<td>212.4</td>
</tr>
<tr>
<td>Monte Basilicata §</td>
<td>38°56°</td>
<td>16°47.09</td>
<td>4.5–4.0</td>
<td>116-13 C3n.1r or C2Ar</td>
<td>195.0</td>
<td>–57.0</td>
<td>212.4</td>
<td>116-13 C3n.1r or C2Ar</td>
<td>195.0</td>
<td>–57.0</td>
<td>212.4</td>
</tr>
<tr>
<td>Botricello Superiore †</td>
<td>38°56°</td>
<td>16°47.09</td>
<td>4.6–4.4</td>
<td>328-4 C3n.2n-C3n.1r</td>
<td>338.9</td>
<td>49.8</td>
<td>339.9</td>
<td>328-4 C3n.2n-C3n.1r</td>
<td>338.9</td>
<td>49.8</td>
<td>339.9</td>
</tr>
<tr>
<td>Vaccarizzo §</td>
<td>38°58</td>
<td>16°47.09</td>
<td>4.6–4.4</td>
<td>328-4 C3n.2n-C3n.1r</td>
<td>338.9</td>
<td>49.8</td>
<td>339.9</td>
<td>328-4 C3n.2n-C3n.1r</td>
<td>338.9</td>
<td>49.8</td>
<td>339.9</td>
</tr>
<tr>
<td>Marcuccio §</td>
<td>39°01</td>
<td>16°50.25</td>
<td>1.24–1.1</td>
<td>285-21 C1r.2r</td>
<td>210.6</td>
<td>–42.8</td>
<td>226.6</td>
<td>285-21 C1r.2r</td>
<td>210.6</td>
<td>–42.8</td>
<td>226.6</td>
</tr>
<tr>
<td>Tufi lica §</td>
<td>39°04</td>
<td>16°53.20</td>
<td>1.24–1.1</td>
<td>285-21 C1r.2r</td>
<td>210.6</td>
<td>–42.8</td>
<td>226.6</td>
<td>285-21 C1r.2r</td>
<td>210.6</td>
<td>–42.8</td>
<td>226.6</td>
</tr>
<tr>
<td>Tera †</td>
<td>39°03</td>
<td>16°52.25</td>
<td>1.24–1.1</td>
<td>285-21 C1r.2r</td>
<td>210.6</td>
<td>–42.8</td>
<td>226.6</td>
<td>285-21 C1r.2r</td>
<td>210.6</td>
<td>–42.8</td>
<td>226.6</td>
</tr>
<tr>
<td>Cavalieri §</td>
<td>39°04</td>
<td>16°53.20</td>
<td>1.24–1.1</td>
<td>285-21 C1r.2r</td>
<td>210.6</td>
<td>–42.8</td>
<td>226.6</td>
<td>285-21 C1r.2r</td>
<td>210.6</td>
<td>–42.8</td>
<td>226.6</td>
</tr>
<tr>
<td>Strongoli ′</td>
<td>39°15</td>
<td>16°53.20</td>
<td>1.24–1.1</td>
<td>285-21 C1r.2r</td>
<td>210.6</td>
<td>–42.8</td>
<td>226.6</td>
<td>285-21 C1r.2r</td>
<td>210.6</td>
<td>–42.8</td>
<td>226.6</td>
</tr>
<tr>
<td>Sette †</td>
<td>39°11</td>
<td>17°00.25</td>
<td>1.24–1.1</td>
<td>285-21 C1r.2r</td>
<td>210.6</td>
<td>–42.8</td>
<td>226.6</td>
<td>285-21 C1r.2r</td>
<td>210.6</td>
<td>–42.8</td>
<td>226.6</td>
</tr>
<tr>
<td>Buca †</td>
<td>39°11</td>
<td>17°00.25</td>
<td>1.24–1.1</td>
<td>285-21 C1r.2r</td>
<td>210.6</td>
<td>–42.8</td>
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<td>285-21 C1r.2r</td>
<td>210.6</td>
<td>–42.8</td>
<td>226.6</td>
</tr>
<tr>
<td>Piano †</td>
<td>39°13</td>
<td>17°00.25</td>
<td>1.24–1.1</td>
<td>285-21 C1r.2r</td>
<td>210.6</td>
<td>–42.8</td>
<td>226.6</td>
<td>285-21 C1r.2r</td>
<td>210.6</td>
<td>–42.8</td>
<td>226.6</td>
</tr>
</tbody>
</table>
| Strongoli-Neto domain is statistically indistinguishable from the 15°–20° CW rotation observed elsewhere in Calabria. The youngest lower Pleistocene section (13, 1.24–1.1 Ma) among those yielding a significant CW rotation would suggest that the regional CW rotation of Calabria was not completed before 1.0 Ma, in agreement with Cifelli et al. (2007a). However, the large-magnitude rotation (66.6° ± 6.2°) from site 18 (1.46–1.23 Ma) strongly suggests a local block-rotation effect (or at least an anomalous paleomagnetic direction arising from several possible sources), which would bias the value of data from the Marcedusa-Zinga domain to address the timing of the regional Calabria rotation.

The youngest CCW rotated sites (25 and 26) from the Strongoli-Neto domain document a 36.1° ± 10.0° and 114.4° ± 11.2° rotation, respectively, occurring as recently as after 1.46–1.23 Ma. Though the great rotation of site 26 may be related to slip along an adjacent fault, overall these data prove that CCW rotations in the Crotone basin are synchronous and/or younger than the regional CW rotation of the Calabria block.
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DISRUPTION OF THE CALABRIA TERRANE LINKED TO PROGRESSIVE BREAKOFF OF THE IONIAN SLAB

Lacking evidence of widespread thrust tectonics in the Crotone basin, the ~30° CCW rotation observed in two ~10-km-wide domains must uniquely be related to left-lateral shear along two regional-scale strike-slip faults (e.g., Sonder et al., 1994). Effectively, the two CCW-rotated domains lie along or adjacent to both the two NW-SE left-lateral shear zones put forward by Van Dijk (1994), and to the sole two outcrops of the Crotone basin where compressive deformation is apparent (San Nicola and Botricello, Fig. 2).

Field evidence of such shear zones from the Crotone basin itself remains weak at present, but Galli and Scionti (2006) recently documented just west of the Crotone basin a NW-SE fault (virtually coinciding with the southern shear zone of Van Dijk, 1994; Fig. 2) with normal and left-lateral displacement components, yielding two M > 6 earthquakes during the past 2000 years. Moreover, the southern shear zone of the Crotone basin roughly corresponds to the seismogenic box of the 1832 earthquake, characterized by $I_0 = 9.5$ on the Mercalli-Cancani-Sieberg (MCS) scale and a $M_w$ estimated at 6.6 (Galli and Scionti, 2006). The fault scarp produced by this event have been possibly eroded, due to the occurrence of clayey and/or sandy deposits in the Crotone basin.

Our paleomagnetic data show that after 1.2–1.5 Ma ago the Calabria terrane underwent a major internal disruption, and likely ceased to behave as a rigid microplate. Therefore we infer that the onset of strike-slip tectonics and related CCW rotation postdated the rigid CW rotation of Calabria, occurring between 1 and 2 Ma according to Cifelli et al. (2007a). Since widespread extensional tectonics (e.g., Mattei et al., 1999, 2002; Cifelli et al., 2007b) characterized the late Miocene–early Pleistocene drift of the Calabria terrane, following the ESE-ward rollback of the Ionian lithosphere, a geodynamic change must have occurred in late early to mid Pleistocene times. The rigid rotation (and drift) of the Calabria microplate stopped, and extension was accompanied by strike-slip tectonics along at least two shear zones (as paleoseismological evidence from Galli and Scionti [2006] confirms).

Table 2. Previous paleomagnetic directions from the Crotone basin

<table>
<thead>
<tr>
<th>Locality</th>
<th>Age</th>
<th>Dtc (°)</th>
<th>Itc (°)</th>
<th>k</th>
<th>$\alpha_{95}$ (°)</th>
<th>N</th>
<th>References</th>
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<tbody>
<tr>
<td>A—Giudei</td>
<td>Lower Pliocene</td>
<td>26.8</td>
<td>41.8</td>
<td>21</td>
<td>20.5</td>
<td>3</td>
<td>1</td>
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<tr>
<td>B—San Mauro</td>
<td>Lower Pleistocene</td>
<td>21.1</td>
<td>43.3</td>
<td>125</td>
<td>125</td>
<td>7</td>
<td>1</td>
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<tr>
<td>Marchesato</td>
<td>Lower Pleistocene</td>
<td>6.5</td>
<td>53.2</td>
<td>365</td>
<td>–</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>C—Crotone</td>
<td>Lower Pleistocene</td>
<td>10.6</td>
<td>53.8</td>
<td>260</td>
<td>–</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>D—San Leonardo</td>
<td>Lower Pleistocene</td>
<td>10.6</td>
<td>53.8</td>
<td>260</td>
<td>–</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>E—Vrica</td>
<td>Upper Pliocene–lower</td>
<td>15.0</td>
<td>52.0</td>
<td>226</td>
<td>5</td>
<td>1</td>
<td>1, 3</td>
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<td>F—Lese</td>
<td>Pleistocene boundary</td>
<td>349.6</td>
<td>45.3</td>
<td>121</td>
<td>5.6</td>
<td>1</td>
<td>2</td>
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<td>G—Basilicci</td>
<td>Tortonian</td>
<td>347.2</td>
<td>48.0</td>
<td>21.6</td>
<td>5.1</td>
<td>1</td>
<td>2</td>
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<td>H—Belvedere</td>
<td>Lower Pliocene</td>
<td>28.5</td>
<td>50.4</td>
<td>13</td>
<td>35.6</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

Note: Dtc and Itc are site-mean declination and inclination calculated after tectonic correction. k and $\alpha_{95}$ are statistical parameters after Fisher (1953). N is the number of sites. References: 1—Scheepers (1994); 2—Duermeijer et al. (1998); 3—Tauxe et al. (1983).

Figure 5. Comparison between (A) the geometry of the south Tyrrhenian subduction system according to recent seismological evidence (Chiarabba et al., 2008; Neri et al., 2009) and (B) tectonics and magmatism of the orogenic domain–backarc system during the past 2 Ma. See text for explanation.
The recent fragmentation of Calabria seems to closely mirror deep features of the deep Tyrrhenian subduction zone, as documented by seismological data. The most recent and complete seismological data sets available to date (Chiarabba et al., 2008; Neri et al., 2009) clearly show that the ongoing Ionian subduction is solely restricted to the southern part of the Calabro-Peloritan block (Fig. 5). Below northern Calabria, there is a lack of seismicity between 100 and 200 km depth, accompanied by negative P-wave anomalies. Thus seismological evidence indicates that the Ionian slab beneath northern Calabria has broken, and that ongoing subduction is nowadays restricted to a small (~150-km-wide) lithosphere fragment in correspondence with southern Calabria and NE Sicily.

The strike-slip zones of the Crotone basin lie roughly in correspondence (though obviously more externally) with the boundary between the continuous and broken Ionian slab fragments (Fig. 5). Therefore they may represent the effects of the geodynamics of a subducting slab onto the tectonics of an orogenic wedge, a scenario suggested for several mountain belts by Govers and Wortel (2005). The continuous southern part of the subducting slab still undergoes rollback towards the Ionian Sea, inducing the overlying wedge to drift SE-ward. Conversely, the northern Calabria wedge, overlying a broken slab, may have ceased its migration towards the trench, and be progressively decoupled from the southern Calabria block by left-lateral shear zones. This model is consistent with recent global positioning system (GPS) data (D’Agostino et al., 2008), revealing that only southern Calabria is nowadays drifting SE-ward towards the Ionian Sea.

**MANTLE DYNAMICS AND RECENT EVOLUTION OF THE TYRRHENIAN-CALABRIA SYSTEM SINCE 2 Ma**

The data reported in this work integrated with independent geological and geophysical evidence allow us to chronic mantle geodynamics and tectonic events occurring in the Tyrrhenian Sea–Calabria arc domain since late Pliocene times (ca. 2 Ma). Between 2.1 and 1.6 Ma, the ultrafast (~20 cm/yr) NW-SE spreading of the Marsili oceanic slab (Nicolosi et al., 2006) was likely the consequence of the abrupt rupture of the slab panel, undergoing progressive bending and along-strike stretching. This evolution is suggested by a ~150-km-wide slab window imaged by seismic tomography beneath the northern Apennines between 100 and 300 km depth (Chiarabba et al., 2008). Synchronous with the Marsili basin spreading, Calabria underwent a similarly ultrarapid drift towards the trench, and started colliding to the south with the African continental lithosphere. A faster subduction to the north, in correspondence with the oceanic Ionian lithosphere, may explain the rigid CW rotation of Calabria between 2 and 1 Ma ago.

Finally, in advanced early Pleistocene times (ca. 1 Ma), the slab panel underwent additional disruptions, both below northern Calabria and NE Sicily, where a small low-Vp window is documented at 100 km depth (Chiarabba et al., 2008). The part of the Calabria wedge lying above the narrow Ionian fragment still undergoing subduction was decoupled from the rest of the inactive range salient along some shear zones, the northern ones cutting the Crotone basin. This youngest episode of the Ionian subduction yielded the Aeolian volcanic arc, and in the backarc domain the spreading of the huge Marsili and Palinuro seamounts of the Tyrrhenian Sea, both younger than 0.8 Ma (Consiglio Nazionale delle Ricerche, 1991; Nicolosi et al., 2006). While the Marsili seamount rose parallel to the trench along the backarc spreading axis, the orthogonal Palinuro seamount might have spread along a transversal fault zone. Our data may reveal the effects of a progressively narrowing passive subduction system on the surface tectonics. Subsequent episodes of slab breakoff make the width of the subducting slab progressively smaller, and are reflected by the occurrence of strike-slip faults bounding the actively drifting orogenic wedge.

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