TECTONICS, VOL. 23, TC1013, doi:10.1029/2003TC001518, 2004

Neogene and Quaternary rollback evolution of the Tyrrhenian Sea, the Apennines, and the Sicilian Maghrebides

Gideon Rosenbaum and Gordon S. Lister[1]

Australian Crustal Research Centre, School of Geosciences, Monash University, Melbourne, Victoria, Australia

Received 7 March 2003; revised 14 October 2003; accepted 11 November 2003; published 3 February 2004.

[1] Reconstruction of the evolution of the Tyrrhenian Sea shows that the major stage of rifting associated with the opening of this basin began at ~10 Ma. It involved two episodes of back arc extension, which were induced by the rollback of a west dipping subducting slab. The first period of extension (10–6 Ma) was prominent in the northern Tyrrhenian Sea and in the western part of the southern Tyrrhenian Sea. The second period of extension, mainly affected the southern Tyrrhenian Sea, began in the latest Messinian (6–5 Ma) and has been accompanied by subduction rollback at rates of 60–100 km Myr^{-1}. Slab reconstruction, combined with paleomagnetic and paleogeographic constraints, indicates that in the central Apennines, the latest Messinian (6–5 Ma) arrival of a carbonate platform at the subduction zone impeded subduction and initiated a slab tear and major strike-slip faults. These processes resulted in the formation of a narrow subducting slab beneath the Ionian Sea that has undergone faster subduction rollback and induced extreme rates of back arc extension. *INDEX TERMS:* 3640 Mineralogy and Petrology: Igneous petrology; 8109 Tectonophysics: Continental tectonics—extensional (0905); 8010 Structural Geology: Fractures and faults; 9604 Information Related to Geologic Time: Cenozoic; *KEYWORDS:* Tyrrhenian Sea, Apennines, Sicilian Maghrebides, subduction rollback, reconstruction. **Citation:** Rosenbaum, G., and G. S. Lister (2004), Neogene and Quaternary rollback evolution of the Tyrrhenian Sea, the Apennines, and the Sicilian Maghrebides, *Tectonics*, *23*, TC1013, doi:10.1029/2003TC001518.

1. Introduction

[2] The Tyrrhenian Sea is a young (<10 Ma) extensional basin that formed within a complex convergent boundary between Africa and Europe (Figure 1a). It is surrounded by an arcuate orogenic belt consisting of the Apennines in the Italian peninsula, the Calabrian Arc in southern Italy and the Maghrebides in Sicily. This arcuate belt has been subjected to processes associated with subduction of a west dipping lithospheric slab, and simultaneously with back arc extension in the Tyrrhenian Sea [e.g., *Malinverno and Ryan*, 1986]. Both crustal and lithospheric processes are well documented by geological and geophysical data, making the Tyrrhenian-Apennine region an ideal natural laboratory for studying geodynamic interactions linking subduction processes, collisional tectonics and back arc extension [e.g., *Faccenna et al.*, 1996, 2001a, 2001b; *Gvirtzman and Nur*, 2001].

[3] The Tyrrhenian Sea is a back arc basin associated with eastward "rollback" of a west dipping subduction zone [e.g., *Malinverno and Ryan*, 1986; *Kastens et al.*, 1988; *Patacca and Scandone*, 1989; *Gvirtzman and Nur*, 1999, 2001; *Faccenna et al.*, 2001a, 2001b]. The driving mechanism for slab rollback is the negative buoyancy of the slab in comparison with the surrounding asthenosphere [e.g., *Elsasser*, 1971; *Molnar and Atwater*, 1978; *Dewey*, 1980; *Garfunkel et al.*, 1986], implying partial coupling of the descending slab to the forearc. The gravitational instability may result in a gradual steepening of the dip of the subducting slab and in an oceanward retreat (i.e., rollback) of the subducting hinge. If the rate of hinge rollback exceeds the rate of convergence, then extension will start on the edge of the overriding plate leading to the opening of a back arc basin [*Dewey*, 1980; *Nur et al.*, 1993; *Royden*, 1993].

[4] The purpose of this paper is to evaluate spatial and temporal constraints that help to link the geometry of the subducting slab with the history of subduction rollback and back arc extension in the Tyrrhenian-Apennine region. We show that consideration of these constraints provides an insight into the tectonic evolution of the region and better understanding of the tectonic responses caused by tearing of a retreating slab.

2. Tectonic Setting

[5] The Tyrrhenian Sea can be divided into a northern domain and a southern domain. The northern Tyrrhenian Sea is a wedge shaped basin, bounded to the south by a major strike-slip fault zone, the 41 parallel line (41PL), and floored by thin continental crust (Figures 1a and 1b). Heat flow values and the spatial distribution of crustal thickness (Figures 1b and 1c) indicate that the lithospheric discontinuity of the 41PL may continue farther southeast along the Tyrrhenian margin of Italy and into the sinistral strike-slip fault zone, the Sangineto line, in northern Calabria (Figure 1).

[1]Now at Research School of Earth Sciences, Australian National University, Canberra, Australia.

0278-7407/04/2003TC001518

[6] The southern Tyrrhenian Sea is separated from Sicily by another major strike-slip fault, the North Sicily Fault (NSF), which continues into northeast Sicily as the dextral strike-slip Taormina line (Figure 1). In the southern Tyrrhenian Sea, there are stretched fragments of continental crust and deep basins (Vavilov and Marsili Basins) that contain Pliocene to Recent (<5 Ma) mid-ocean ridge basalt (MORB)-type basalts [*Kastens et al.*, 1988]. These basins are considered to represent seafloor spreading in a back arc position with respect to a northwest dipping subduction zone, presently located beneath Calabria (Figure 1a). Further evidence of lithospheric stretching in a back arc environment is based on high values of heat flow (>150 mW m^{-2}) measured in the Tyrrhenian Sea [*Della Vedova et al.*, 1984] (Figure 1c).

[7] The Tyrrhenian-Apennine system has been subjected to simultaneous extension in the Tyrrhenian Sea and shortening in the Apennine-Maghrebide orogen since the late Miocene (~10 Ma) [e.g., *Malinverno and Ryan*, 1986; *Lavecchia*, 1988] (Figure 2). Deformation in the Tyrrhenian-Apennine system followed an earlier deformational event during the late Oligocene-early Miocene that involved the opening of the Ligurian-Provençal Basin (Figure 1a) as a result of the rollback of an older northwest dipping subduction zone [e.g., *Faccenna et al.*, 1997; *Rollet et al.*, 2002; *Rosenbaum et al.*, 2002a]. Rift basin sediments related to the earlier extensional event outcrop in eastern Corsica because they are located on the footwall of the younger fault. The opening of the Ligurian-Provençal Basin was accompanied by a counterclockwise rotation (with respect to Europe) of the Corsica-Sardinia microplate, which led to progressive collision of Corsica-Sardinia with the former western margin of Adria (Apulia), and gave rise to the formation of the Apennines [*Patacca et al.*, 1990]. Paleomagnetic results indicate that Corsica and Sardinia stopped rotating at ~16 Ma [*Speranza et al.*, 2002, and references therein], at the same time that back arc extension terminated in the Ligurian-Provençal Basin.

[8] Opening of the Tyrrhenian Sea is recognized in rifted margins of Corsica and Sardinia, which expose Tortonian synrift sediments [*Mauffret and Contrucci*, 1999; *Sartori et al.*, 2001]. The locus of extensional tectonism, as well as the front of shortening, moved eastward through time, leading to the ongoing destruction of internal parts of the orogen by extensional processes. The same process is reflected by the present-day tectonic activity in the Apennines, which is characterized by thrust tectonics in external parts of the

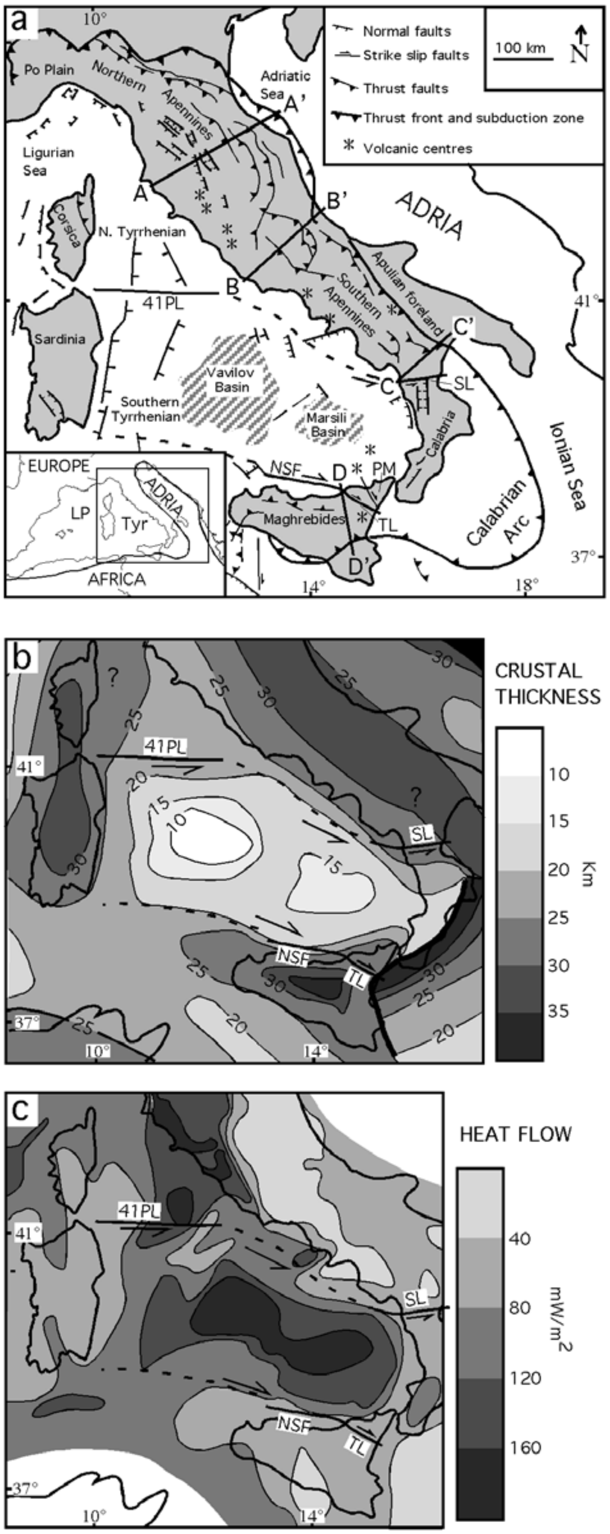

Figure 1. Tectonic setting of the Tyrrhenian Sea. (a) Map showing main structural features (modified after *Patacca et al.* [1993]) and locations of cross sections (Figure 3). The boundary between the northern domain and southern domain is marked by a major fault zone (41PL) that may be linked to the sinistral strike-slip fault in northern Calabria (SL). The southern margin of the Tyrrhenian Sea is marked by a dextral strike-slip fault (NSF), which continues into Sicily as the Taormina line (TL). Abbreviations are 41PL, 41 parallel strike-slip fault zone; LP, Ligurian-Provençal Basin; PM, Peloritan Mountains; SL, Sangineto line, Tyr, Tyrrhenian Sea. (b) Crustal thickness [after *Gvirtzman and Nur*, 2001]. (c) Heat flow [after *Della Vedova et al.*, 1991].

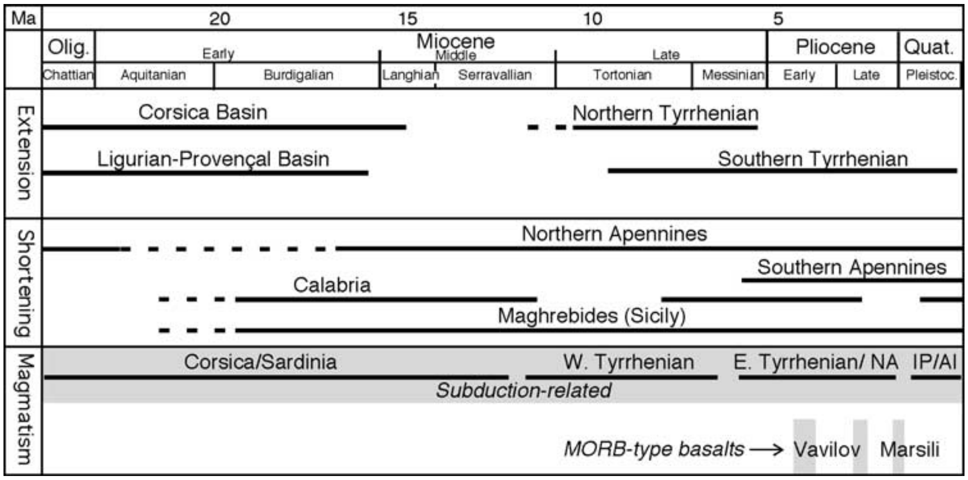

Figure 2. Chronology of synrift sedimentation, shortening and magmatism in the Tyrrhenian Sea and the Apennine-Maghrebide belt. See text for discussion. Timescale is after *Remane et al.* [2000]. Abbreviations are AI, Aeolian Islands; IP, Italian Peninsula; NA, northern Apennines.

orogen and extension in the internal zone [e.g., *Mariucci et al.*, 1999; *Montone et al.*, 1999].

3. Constraints on Crustal Deformation

[9] Observations show that deformation in the Tyrrhenian-Apennine region involved simultaneous shortening and extension. Since the Miocene, shortening has been taking place in the front of the Apennine belt, and is currently occurring in the most external parts of the orogen (Figure 3). In contrast, more internal parts of the orogen have been subjected to extension associated with the formation of the Tyrrhenian Sea (Figures 3 and 4).

3.1. Movement of the Thrust Front

[10] The spatiotemporal distribution of shortening is inferred from the ages of thrusting along Apennine-Maghrebide nappe structures and from depositional ages in foreland basins [e.g., *Boccaletti et al.*, 1990a]. The pattern of shortening in the Tyrrhenian-Apennine system is charac-

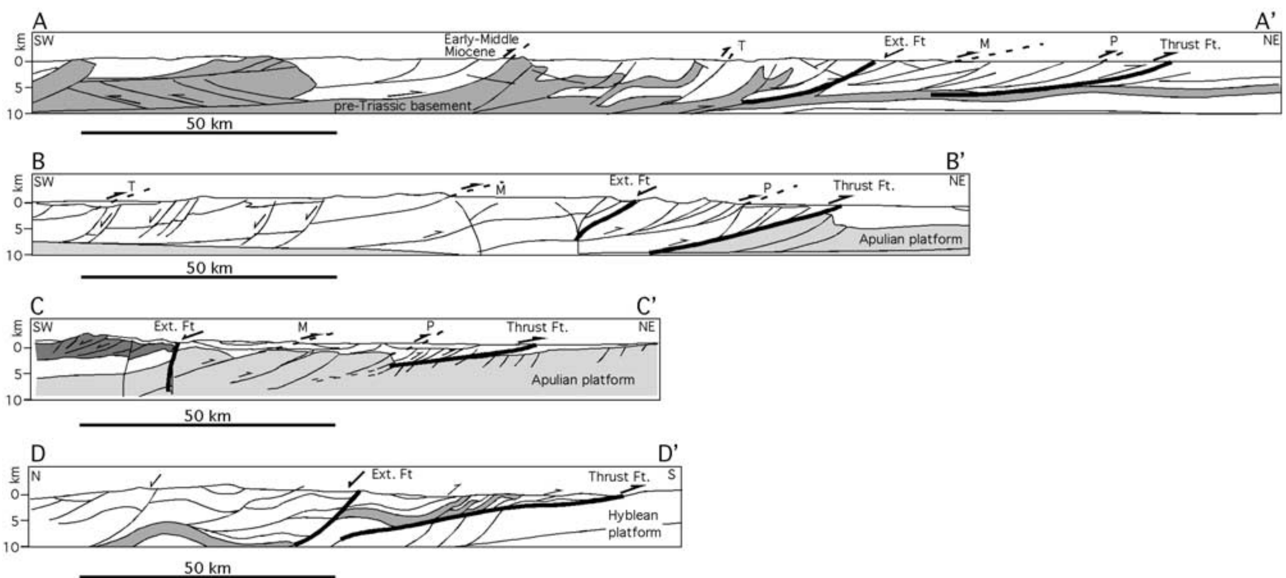

Figure 3. Schematic cross sections (a) AA′, (b) BB′, (c) CC′, and (d) DD′ across the Apennines-Maghrebides (see location map in Figure 1a) showing the approximate location of the thrust front through time and the present-day location of the thrust front and the extensional front (thick lines). Cross sections are modified after *Finetti et al.* [2001], *Mariucci et al.* [1999], *Cipollari et al.* [1999], *Cello and Mazzoli* [1999], and *Roure et al.* [1990]. Abbreviations are M, Messinian (7.5–5.3 Ma); P, Pliocene-Pleistocene (<5.3 Ma); T, Tortonian (11–7.3 Ma).

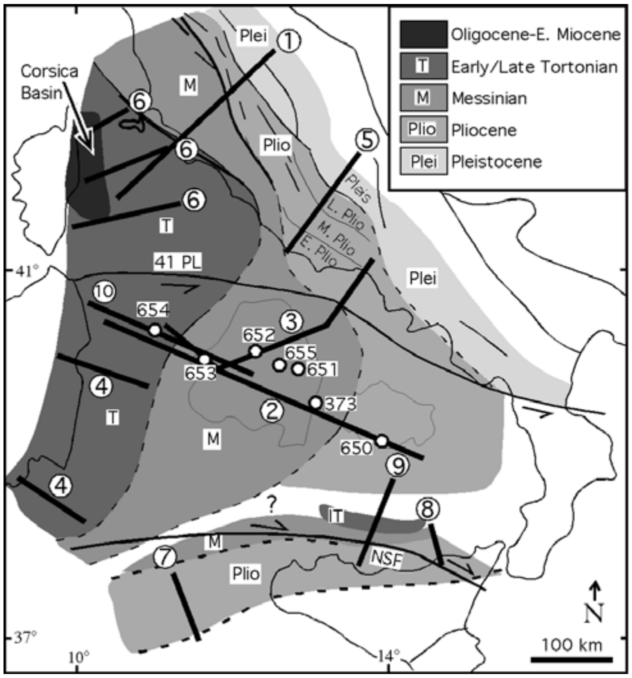

Figure 4. Map showing spatial distribution and ages of the earliest synrift sediments in the Tyrrhenian Sea. The map is based on published seismic lines, well data, and field observations. Thick lines indicate locations of sections from which data have been obtained. Uncertain boundaries are indicated by dashed lines. Synrift sediments from the Calabrian block and its margins are not shown because they were deposited farther west. References are (1) *Bartole* [1995], (2) *Kastens et al.* [1988], (3) *Cipollari et al.* [1999], (4) *Sartori et al.* [2001], (5) *Cavinato and De Celles* [1999], (6) *Mauffret and Contrucci* [1999], (7) *Gamberi and Arganani* [1995], (8) *Nigro and Sulli* [1995], (9) *Pepe et al.* [2000], and (10) *Spadini et al.* [1995]. Locations of Ocean Drilling Program (ODP) sites (650–655) and an DSDP site (373) are also shown. Abbreviations are 41PL, 41 parallel strike-slip fault zone; CB, Corsica Basin, NSF, North Sicily Fault.

terized by movement of thrust faults toward external parts of the orogen (Figure 3). In addition, deformation in the southern Tyrrhenian-Apennine system is relatively young compared with the timing of deformation in the north.

[11] Structural evidence from the northern Apennines points to a northeastward movement of shortening [*Jolivet et al.*, 1998] (Figure 3). Shortening structures are associated with northeastward verging folds and thrusts and with deposits in foreland basins that become progressively younger toward external (i.e., northeasterly) parts of the orogen [*Lavecchia*, 1988; *Boccaletti et al.*, 1990a]. The timing of deformation also becomes younger in the central and southern Apennines. In the southern Apennines, shortening occurred predominantly during the Pliocene and the Pleistocene and was characterized by eastward and southeastward movement of the thrust front [*Roure et al.*, 1991].

[12] The pattern of deformation in Calabria is more complex, showing evidence for a prolonged tectonometamorphic history that involved several Alpine deformational episodes [e.g., *Knott and Turco*, 1991; *van Dijk and Okkes*, 1991; *Cello et al.*, 1996; *Rosseti et al.*, 2001]. Rock units in Calabria were subjected to high-pressure metamorphism during the Eocene (∼44 Ma), and were later exhumed to shallow crustal levels in a period of extension (at ∼30 Ma [*Rosseti et al.*, 2001]). In the framework of the Tyrrhenian-Apennine system, the Calabrian block (including the Peloritan Mountains of northeast Sicily; Figure 1a) is considered to be an allochthonous terrane that originated ∼800 km northwest of its present location, and moved southeastward since the Oligocene (∼30 Ma) to become thrust onto the Adriatic continental margin during the Miocene [*Rosenbaum et al.*, 2002a, and references therein].

[13] Shortening in Sicily involved progressive underthrusting during southeastward movement of the thrust front and clockwise block rotations [*Oldow et al.*, 1990; *Roure et al.*, 1990]. Shortening in western Sicily began in the early middle Miocene (20–15 Ma) [*Oldow et al.*, 1990], which is somewhat earlier than the start of deformation in the southern Apennines.

3.2. Movement of the Extensional Front

[14] The spatial distribution of the earliest synrift sediments in the Tyrrhenian Sea and its margins indicates that extension moved toward the northeast in the northern domain and toward the southeast in the southern domain (Figure 4). The earliest synrift sediments are late Oligocene to Burdigalian (∼25–16 Ma) deposits in the Corsica Basin [*Mauffret and Contrucci*, 1999] (Figure 4). This rifting stage took place prior to or during the opening of the Ligurian-Provençal Basin (Figure 1a) and before Corsica and Sardinia reached their present positions (with respect to Europe) at 16 Ma [*Speranza et al.*, 2002]. The Oligocene-early Miocene extensional deformation in the northern Tyrrhenian Sea may have resulted from subduction rollback of an earlier Oligocene northwest dipping subduction zone [*Rosenbaum et al.*, 2002a]. The locus of that extension was located in the Ligurian-Provencal rift system. In Pianosa Island, there is evidence that synrift sedimentation continued also during the Langhian (16–15 Ma) [*Carmignani et al.*, 1995]. Nevertheless, rifting did not seem to play a major role in the northern Tyrrhenian Sea between 16 and 10 Ma [*Mauffret and Contrucci*, 1999].

[15] The major rifting event associated with the opening of the Tyrrhenian Sea began in the early middle Tortonian (∼10–9 Ma) on the basis of synrift Tortonian sediments in the northern Tyrrhenian Sea and in the western part of the southern Tyrrhenian Sea (Figure 4). Tortonian synrift sediments are widespread in the northern Tyrrhenian Sea and become progressively younger toward the northeast [*Bartole*, 1995]. In the southern Tyrrhenian Sea, the distribution of Tortonian sediments is restricted to a narrow zone offshore of the Sardinian coast [*Spadini et al.*, 1995; *Sartori et al.*, 2001]. This spatial distribution may indicate that during the Tortonian, the movement of extensional deformation in the southern domain was slightly slower than the

movement in the northern domain. A wedge of synrift late Tortonian sediments has also been reported from the rifted margin of northern Sicily [*Pepe et al.*, 2000], which is in a relatively anomalous location compared with the distribution of Tortonian sediments in the southern Tyrrhenian Sea (Figure 4). These Tortonian sediments, as well as older (middle Miocene) synrift sediments found in Calabria [e.g., *Argentieri et al.*, 1998], were probably not deposited where they are now, but in a more westerly position, from which they have moved eastward together with Sicilian and Calabrian allochthonous units. We suggest that such lateral displacements occurred due to a right-lateral strike-slip movement along the North Sicily Fault off the north coast of Sicily (Figure 1a).

[16] The majority of the southern Tyrrhenian Sea was subject to extension from the Messinian to the Pleistocene that culminated in the Pliocene-Pleistocene seafloor spreading of the Vavilov (5–4 Ma) and Marsili Basins (3–2 Ma) [*Kastens et al.*, 1988]. We interpret the wider distribution of synrift sediment as indicating that during this period, the extensional front moved faster in the southern Tyrrhenian Sea than in the northern Tyrrhenian Sea (Figure 4). These differential rates of movement may have been accommodated by left-lateral strike-slip faulting along the 41PL (Figure 4) that was active during the Messinian and the Pliocene [*Spadini and Wezel*, 1994; *Bruno et al.*, 2000]. On the basis of the distribution of synrift sediments in the southern Tyrrhenian Sea, the rates of movement of the extensional front at 7–2 Ma are estimated as $\sim$80 km Myr^{-1}.

4. Constraints on the Role of Subduction Rollback

[17] The strongest evidence on the role of subduction rollback in the Tyrrhenian-Apennine system, derived from the distribution of subduction-related magmatism, indicates a pattern of movement of the magmatic arc that is consistent with rollback of the subduction hinge toward the east and the southeast. In this section, we combine data on magmatic activity with data derived from cross sections that are based on seismic tomography. Using this approach, we can infer changes in the geometry of the subducting slab with time and reconstruct the history of rollback in different segments of the Tyrrhenian-Apennine system.

4.1. Magmatism

[18] Neogene to Quaternary magmatic activity in the Tyrrhenian-Apennine region includes subduction-related calc-alkaline magmatism, intraplate alkaline magmatism and MORB-type basalts [*Savelli*, 1988, 2000, 2001, 2002; *Serri et al.*, 1993; *Argnani and Savelli*, 1999, 2001] (Figure 5 and Table 1). The distribution of subduction-related (mainly calc-alkaline) magmatism defines a geochemical polarity associated with a west dipping subduction zone [e.g., *Savelli*, 2000; *Argnani and Savelli*, 2001]. These magmas become younger from west to east, which we interpret as the response to rollback of the subduction hinge during the opening of the Tyrrhenian Sea.

[19] The oldest volcanic rocks in the Tyrrhenian margin are Oligocene-middle Miocene (32–13 Ma) calc-alkaline rocks in Corsica and Sardinia [*Savelli*, 2002, and references therein]. The youngest of these magmatic centers (16–13 Ma) were active after Corsica and Sardinia stopped rotating and indicate the location of a N-S striking volcanic arc that existed at that time (Figure 5a). The subsequent movement of this magmatic arc is reconstructed in Figure 6.

[20] The earliest step in the movement of the Tyrrhenian-Apennine magmatic arc is documented by a series of N-S striking magmatic centers dated at 13–7 Ma (Figure 5b). These magmatic rocks lie 100–150 km east of the former position of the magmatic arc, indicating rapid rollback that took place during the Tortonian (11–7 Ma). Subduction rollback continued during the Messinian (7–5 Ma) leading to the cessation of calc-alkaline magmatism offshore of Sardinia and southern Corsica, and to the onset of magmatism near the eastern margin of the Tyrrhenian Sea.

[21] A later stage of subduction rollback is inferred from the distribution of post-Messinian (6–0 Ma) calc-alkaline magmatism. During this period, rollback continued in the southern domain, but had slowed down or stopped in the northern domain. The episode of rapid rollback in the southern domain is inferred from the observation that positions of the post-Messinian (<6 Ma) magmatic arc in the southern Tyrrhenian Sea are relatively widely spaced (Figure 6).

4.2. Geometry of the Subducting Slab

[22] Seismic data from the Apennines and the Calabrian Arc support the existence of a segmented, locally detached, west dipping subduction zone in the region [e.g., *Anderson and Jackson*, 1987; *Selvaggi and Amato*, 1992; *Wortel and Spakman*, 1992; *Lucente et al.*, 1999]. The Tyrrhenian-Apennine slab is illustrated in Figure 7, in three segments, which are the northern Apennine slab, the central southern Apennine slab and the Ionian slab.

[23] The existence of a cold lithospheric slab in the northern Apennine Arc is interpreted from few occurrences of intermediate depth earthquakes at depths of up to 90 km [*Selvaggi and Amato*, 1992] and from zones of relatively high seismic velocities recognized in tomographic models [*Wortel and Spakman*, 1992; *Lucente et al.*, 1999] (Figure 7a). Beneath the northern Apennines, it is debateable whether these seismic anomalies represent a continuous slab that is presently subducting [*Lucente et al.*, 1999], or a slab that is separated from the overriding plate by a zone of low velocity asthenosphere [e.g., *Wortel and Spakman*, 1992, 2000]. *Wortel and Spakman* [1992] explained their model by a detachment of the lithospheric slab that has been propagated laterally beneath the Apennines. Our analysis is based on the tomographic model of *Lucente et al.* [1999], which shows a continuous subduction beneath the northern Apennines, but we cannot discard the possibility that the northern Apennine slab has been detached.

[24] In the central Apennines, evidence for slab detachment has been inferred both from the models by *Wortel and Spakman* [1992] and *Lucente et al.* [1999]. In both models, there is no high-velocity anomaly at shallow and interme-

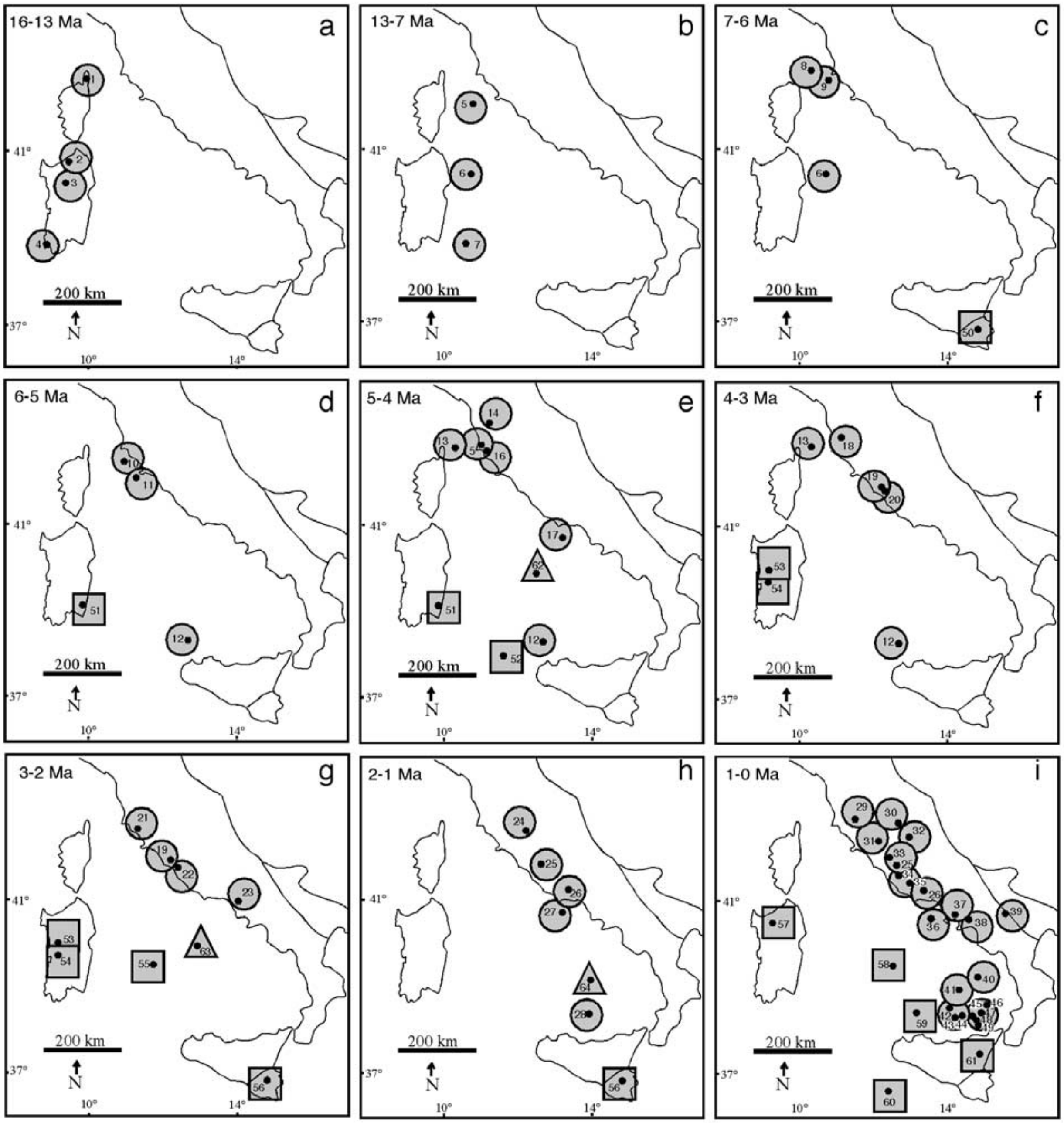

Figure 5. Distribution of subduction-related magmatism (circles), intraplate magmatism (squares), and MORB-type magmatism (triangles) in the Tyrrhenian region. The numbers correspond to the list of references in Table 1.

diate depths (up to 250 km) beneath the central Apennines, which means that subduction does not take place at these depths. However, a zone of high seismic velocities at depths of 400–700 km (Figure 7b) may point to the existence of a detached slab beneath the central Apennines.

[25] The continuous nature of the southernmost segment of the Tyrrhenian-Apennine slab (the Ionian slab) in the Calabrian Arc is in contrast to the fragmented central Apennine slab. In this region, there is a good agreement between different tomographic models [*Wortel and Spakman*, 1992, 2000; *Lucente et al.*, 1999] that show a relatively narrow zone (~300 km) of high seismic velocities. This seismic anomaly indicates a continuous subvertical cold slab dipping toward the northwest. The existence of this slab is also supported by occurrences of deep earthquakes (at depths of up to 500 km) defining the Benioff-Wadati zone [*Anderson and Jackson*, 1987]. The tomographic images (Figure 7c) indicate that the subducted slab does not extend beyond a depth of ~700 km, that is, around the 670 km discontinuity. Remnants of the slab can

Table 1. Magmatic Rocks Throughout the Tyrrhenian-Apennine Region[a]

	Location	Rock Type	Age, Ma	References
		Mainly Calc-Alkaline (Subduction Related)		
1	Sisco, northeast Corsica	lamproite	15–14	*Civetta et al.* [1978]
2	Gallura, west Sardinia	rhyolitic dacite	15	*Savelli* [2002]
3	Logudoro, Sardinia	andesite	13	*Savelli* [2002]
4	south Pietro island (SE Sardinia)	comendite	14–15	*Savelli* [2002]
5	Montecristo	cordierite monzogranite	7.3	*Serri et al.* [1993]
6	Vercelli seamount	monzogranite	7.5–6.5	*Savelli* [2002]
7	Cornacya, seamount	shoshonite	12.9–12.3	*Mascale et al.* [2001]
8	Capraia	andesite, dacite, rhyolite	6.9–6	*Savelli* [2002]
9	Mount Capanne, Elba	granodiorite, monzogranite	6.8–6.2	*Serri et al.* [1993]
10	Porto Azzurro, Elba	cordierite monzogranite	5.1	*Serri et al.* [1993]
11	Giglio	cordierite monzogranites	5.1	*Serri et al.* [1993]
12	Anchise	shoshonitic basalts and dacites	5.3–3.5	*Savelli* [2002]
13	Capraia	high-K andesites, dacites, rhyolites	4.6–3.5	*Serri et al.* [1993]
14	Montecatini, Tuscany	lamproite	4.1	*Savelli* [2002]
15	San Vincenzo	cordierite rhyolite	4.7	*Serri et al.* [1993]
16	Castel di Pietra and Gavorrano	monzogranites, syenogranites	4.4–4.3	*Serri et al.* [1993]
17	Ponza island	rhyolite	4.4	*Savelli* [2002]
18	Monteverdi	cordierite monzogranites	3.8	*Serri et al.* [1993]
19	Tolfa	trachydacite and rhyolite	3.8–2.3	*Savelli* [2000]
20	Manziana	rhyolites	3.6	*Serri et al.* [1993]
21	Roccastrada	cordierite rhyolite	2.5–2.2	*Serri et al.* [1993]
22	Cerite	rhyolite	2.4	*Serri et al.* [1993]
23	Volturno plain	basalt, andesite	>2	*Savelli* [2002]
24	Radicofani	basalts	1.3	*Savelli* [2002]
25	Cimini	trachytic dacite	1.3–0.9	*Savelli* [2002]
26	Raccamonfina	basalt, trachytic basalt, latite	1.2–0.3	*Savelli* [2002]
27	Ponza island	trachyte	1.1	*Savelli* [1988]
28	Lower slope	basalts	1.1	*Savelli* [1988]
29	Mount Amiata	trachytic dacite	0.3–0.2	*Savelli* [2000]
30	south Venanzo	melilitite/carbonatite	0.4	*Stoppa and Wooley* [1997]
31	Torre Alfina	lamproite	0.8	*Savelli* [2002]
32	Cupaello	melilitite/carbonatite	0.4	*Stoppa and Wooley* [1997]
33	Vulsini	basanite, shoshonite, latite, trachyte	0.6–0.1	*Savelli* [2002]
34	Vico, Sabatini	tephrite, leucitite, phonolite, trachyte	0.6–0.1	*Savelli* [2002]
35	Albani Hills	leucitite,	0.6–0.1	*Savelli* [2002]
36	Ventotene volcanic complex	trachytic basalts, phonolite	0.8–<0.2	*Savelli* [2002]
37	Phlegrei fields	basalt	<0.04	*Savelli* [2002]
38	Vesuvius	trachyte, phonolite	<0.03	*Savelli* [2002]
39	Vulture	tephrite, phonolite	0.8–0.13	*Stoppa and Wooley* [1997]
40	Palinuro seamount	basalt	0.8–0.3	*Savelli* [2002]
41	Marsili seamount	andesite	0.8–0	*Savelli* [2002]
42	Enarete and Eolo seamounts	basalts, andesites	0.8–0.6	*Savelli* [1988]
43	Alicudi island	basalts	<0.2	*Savelli* [2002]
44	Filicudi island	basalts	<0.2	*Savelli* [2002]
45	Salina island	basalt, andesite, dacite, rhyolite	0.4–0.01	*Savelli* [2002]
46	Stromboli island	basalt, andesite	<0.06	*Savelli* [2002]
47	Panarea volcanic complex	basalt, andesite	0.8–0.01	*Savelli* [2002]
48	Lipari island	andesite, rhyolite	<0.25	*Savelli* [2002]
49	Vulcano island	basalt, shoshonite, latite, rhyolite	<0.12	*Savelli* [2002]
		Mainly Tholeiitic/Alkaline, Interplate		
50	Hyblean Plateau	toleiitic and alkaline basalts	8–6	*Savelli* [2001]
51	Capo Ferrato, Sardinia	tachytic basalt, trachyte	5	*Savelli* [2002]
52	Aceste	tachyte, rhyolite	5	*Savelli* [1988]
53	Montiferro, Sardinia	basanite, trachytic basalt, phonolite	3.2–2.3	*Savelli* [2002]
54	Monte Arci, Sardinia	basalt, andesite, rhyolite, trachyte	4–2.3	*Savelli* [2002]
55	Magnaghi seamount	basalt	3–2.7	*Savelli* [2002]
56	Hyblean Plateau	tholeiitic and alkaline basalts	3–1.2	*Savelli* [2001]
57	Logudoro, Sardinia	basalt, trachytic basalt	0.9–0.2	*Savelli* [2002]
58	Vavilov seamount	basalts	0.4–<0.1	*Savelli* [1988]
59	Ustica island	basalt, trachyte, rhyolite	0.8–<0.2	*Savelli* [2002]
60	Pantelleria island	alkaline magmas, peralkaline, rhyolites, trachytes	<0.3	*Savelli* [2001]
61	Etna	tholeiitic basalts	0.5–0	*Savelli* [2002]

Table 1. (continued)

	Location	Rock Type	Age, Ma	References
		Oceanic Basalts		
62	ODP 655, Gortani Ridge	basalts	4.6–4	*Feraud* [1990]
63	ODP 651	basalts	3–2.6	*Feraud* [1990]
64	ODP 650 (Marsili Basin)	basalts	1.9–1.6	*Savelli* [2002]

[a]See Figure 5 for locations.

be traced horizontally (toward the northwest) parallel to the 670 km discontinuity over a distance of 600–700 km. The zone of active subduction is localized only in the area where the Tyrrhenian-Apennine subduction system meets the oceanic lithosphere of the Ionian Sea. This may indicate that the Calabrian Arc is the only area within the Tyrrhenian-Apennine system where subduction processes have not yet been impeded by the accretion of continental material [*Rosenbaum and Lister*, 2004].

5. Reconstruction of Subduction Rollback

[26] We have reconstructed the evolution of the slab (Figure 8) on the basis of the assumption that slab segments recognized beneath the Tyrrhenian-Apennine system have been subducted during or before the opening of the Tyrrhenian Sea. The results shown in Figure 8 have been obtained by preserving the length of each slab segment, and by applying an incremental reconstruction of the subduction zone. We assume that the near surface convergence within the downgoing plate and the overriding plate has been negligible so all horizontal motion is attributed to subduction rollback. This assumption is justified because the rates of convergence in the past 10 Myr were considerably slower than the rates of subduction rollback (Figure 9). In the central Mediterranean, the vector of Africa-Europe convergence since 10 Ma is estimated to be 7–7.4 km Myr^{-1} toward the northeast [*DeMets et al.*, 1994; *Rosenbaum et al.*, 2002b]. This implies zero convergence in cross sections perpendicular to the Apennine belt, and ~6 km Myr^{-1} convergence along cross section CC′ (Figure 9). This value is negligible when compared with the rates of subduction rollback (20–100 km Myr^{-1}).

[27] Predictions on the behavior of the slab during subduction rollback are based on results from analogue experiments [*Faccenna et al.*, 2001b; *Schellart*, 2003] that simulated subduction by initiating gravitational sinking of a relatively high-viscosity upper layer (simulating the lithosphere) in a model box filled with low viscosity material simulating the sublithospheric mantle. Both sets of experiments have shown that under these circumstances, the slab was subject to rapid rollback, and that stagnation and flattening of the slab occurred when it reached a mechanical boundary simulating the 670 km discontinuity.

[28] The age of each stage in the reconstruction is deduced from the location of the magmatic arc relative to the subducting slab. These time constraints provide the ability to estimate the length of the slab that has been subducted during the opening of the Tyrrhenian Sea. In the northern transect, the total length of the slab subducted since 13 Ma has been ~200 km (Figure 8a). The deeper parts (>200 km depths) of the northern Apennine slab were therefore subducted earlier, that is, during the opening of the Ligurian-Provençal Basin at the early Miocene. The rates of rollback in this transect were greater at the earliest stages of the Tyrrhenian extension (~10–8 Ma).

[29] The history of the central Apennine slab is relatively poorly constrained (Figure 8b). However, on the basis of its three-dimensional position with respect to the northern and southern slab segments (Figures 8 and 10), we suggest an age of 6–5 Ma for the tearing of the slab. Since then, the subduction processes ceased and the slab has been subjected to gravitational foundering. Therefore it is likely that the origin of younger (3–0 Ma) volcanic rocks in the central Apennines has not been directly derived from subduction processes [e.g., *Lavecchia and Stoppa*, 1996].

[30] The role of subduction rollback is best illustrated in the cross section across the Calabrian Arc (Figure 8c). Here, the length of the slab subducted during the opening of the Tyrrhenian Sea is estimated at ~530 km. The reconstruction shows an increase in the rates of rollback at ~5 Ma, with maximum rollback velocities of ~100 km Myr^{-1}.

[31] The evolution of the subducting lithosphere in the Tyrrhenian-Apennine system in a map view is shown in

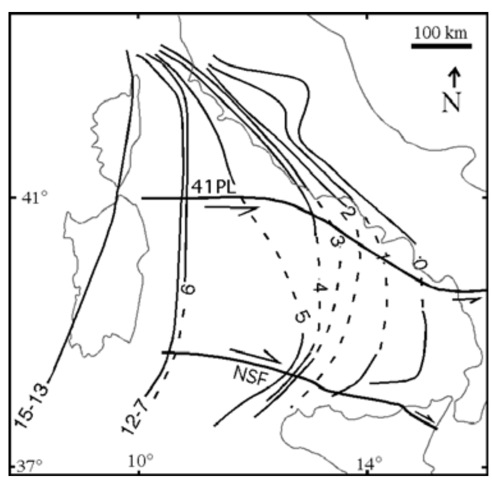

Figure 6. Map showing the approximate location of the magmatic arc through time based on the data of Figure 5. Numbers indicate ages (in Ma). The map shows an eastward movement of the magmatic arc since the late Miocene. Dashed lines indicate inferred locations where no data exist. Abbreviations are 41PL, 41 parallel strike-slip fault zone; NSF, North Sicily Fault.

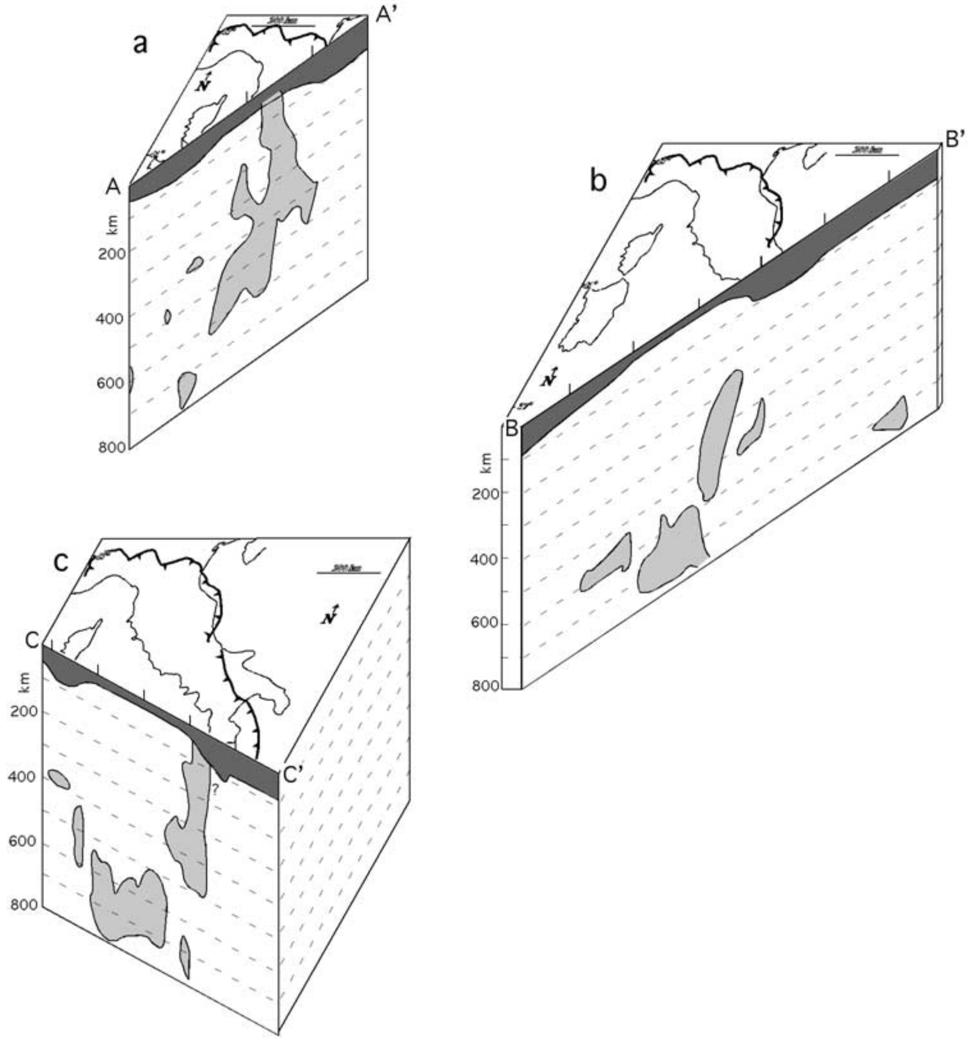

Figure 7. Upper mantle cross sections beneath the (a) northern Apennines, (b) central Apennines, and (c) Calabria. The cross sections show positive (>2%) seismic velocities of *P* waves [after *Lucente et al.*, 1999] (light grey) and estimated lithospheric thickness [after *Della Vedova et al.*, 1991] (dark grey).

Figure 10. We consider that tearing of the slab beneath the central Apennines occurred when the strike-slip faults have initiated, and was followed by a subsequent period of rapid rollback in the southern Tyrrhenian Sea. Furthermore, we suggest that the tearing of the central Apennine slab and the development of lithospheric-scale strike-slip faults may have triggered the episode of rapid rollback.

6. Origin of the Apennines

6.1. Paleomagnetic Constraints

[32] In this section we consider the role of Neogene to Quaternary block rotations in the Tyrrhenian-Apennine region as interpreted from paleomagnetic data (Table 2 and Figure 11). These rotations indicate the sense of motions during deformation in the Apennine-Calabrian-Maghrebide fold-and-thrust belts. Since deformation took place contemporaneously with the opening of the Tyrrhenian Sea, it is possible to combine these rotations within the framework of subduction rollback and back arc extension (Figure 11b).

[33] The pattern of deformation in the Apennines is predominantly governed by counterclockwise rotations (Figure 11a). In general, the degree of rotation increases, and the ages of these rotations become younger, from north to south along the Apennines. There are few exceptions to this deformational pattern, as for example, in the external part of the northern Apennines (Figure 11a), where post-Messinian (<5 Ma) clockwise and counterclockwise rotations correspond to the arcuate bending of the orogen [*Speranza et al.*, 1997; *Lucente and Speranza*, 2001].

[34] Paleomagnetic evidence from Calabria and Sicily indicate predominantly clockwise rotations since the late Miocene (Table 2 and Figure 11a). *Speranza et al.* [2000]

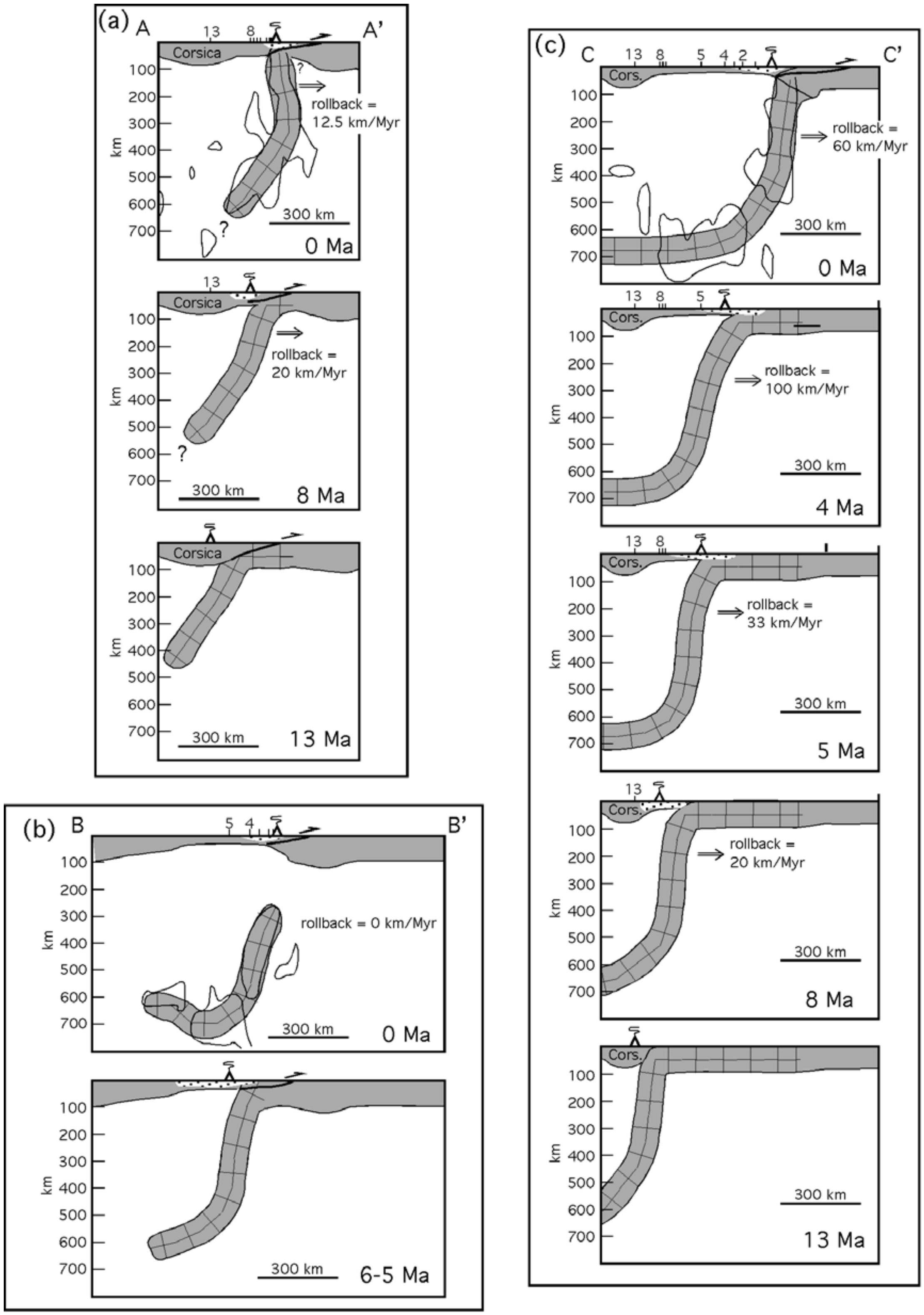

Figure 8. Reconstruction of the slab at different stages during the opening of the Tyrrhenian Sea for (a) Northern Apennine transect, (b) central Apennines transect, and (c) Calabrian Arc transect. The short vertical thin lines and adjacent numbers indicate locations and ages (in Ma) of the magmatic arc. Thick solid lines indicate the approximate location of the thrust front (unknown for the Calabrian transect), and dots indicate areas of synrift sedimentation. Zones of high seismic velocities at 0 Ma are also shown.

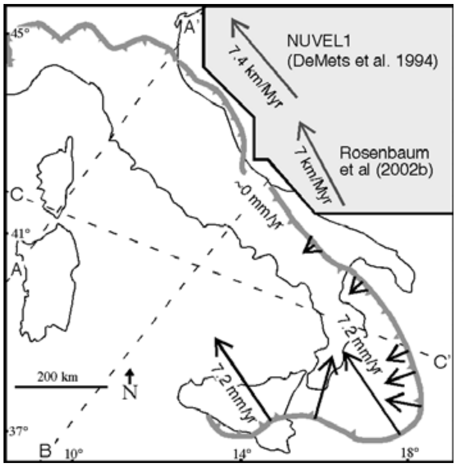

Figure 9. Component of convergence perpendicular to the strike of the subduction zone (black arrows) calculated from the relative motion of Africa and Europe [after *DeMets et al.*, 1994; *Rosenbaum et al.*, 2002b]. Velocities are indicated by the relative lengths of the arrows. The component of convergence is greatest in the Calabrian Arc and in Sicily (7.2 km Myr^{-1}) and is equal to zero in the Apennines. Within the lithosphere, convergence perpendicular to the section CC′ is ∼6 km Myr^{-1}, which is one magnitude of order smaller than the rates of subduction rollback.

have reported on earlier (early middle Miocene?) counterclockwise rotations of the Calabrian block, which were probably associated with the lateral movement of this block from its Oligocene position in the northwestern Mediterranean [*Rosenbaum et al.*, 2002a]. Clockwise rotations in Sicily occurred contemporaneously with nappe emplacement and the opening of the southern Tyrrhenian Sea [*Oldow et al.*, 1990], and correspond to dextral displacements along the North Sicily Fault (Figure 11). The opposite sense of coeval rotations in Sicily and in the southern Apennines indicates the importance of the two major strike-slip faults. The rotations are also associated with the oroclinal bending of the fold-and-thrust belts that took place during the overall rollback of the Ionian slab [*Rosenbaum and Lister*, 2004] (Figure 11b).

6.2. Paleogeography

[35] The evolution of the Apennine-Maghrebide orogen can also be discussed in paleogeographic sedimentary facies distributions (Figure 12). Since the Tortonian, orogenesis has occurred close to the western margin of Adria, which has a heterogeneous sedimentary cover of Mesozoic carbonate platforms and rift basin pelagic deposits (Figure 12b). The Adriatic carbonate platforms were deposited during the Mesozoic in a shallow marine environment [e.g., *Bosellini*, 2002, and references therein]. The most southwestern platform in the central and southern Apennines is the Apulian platform (Figure 12a). More internal platforms (hereinafter ‘‘internal platform’’), such as the Campania-Lucania platform and the Latium-Abruzzi platform, are presently thrust on top of the Apulian platform. The boundary between the Apulian and the internal platform is marked by two basinal domains, which are intracontinental rifts, represented by the Lagonegro and the Molise units [*Mostardini and Merlini*, 1986]. These units consist of Triassic to Oligocene clays, cherts, radiolarites, and limestones, overlain by Miocene turbiditic sequences [*Wood*, 1981; *Marsella et al.*, 1995]. They were deposited in a deep marine environment that was located west of the slope of the Apulian carbonate platform [*Marsella et al.*, 1995] (Figure 12b).

[36] The paleogeography of the northern Apennines differs from the paleogeography of the central and southern Apennines (Figure 12a) (see also discussion by *Lucente and Speranza* [2001]). In the Umbria-Marche region of the northern Apennines, the sedimentary pile predominantly consists of Early Jurassic to Paleogene pelagic limestones deposited on top of Triassic evaporites [*Lavecchia et al.*, 1988, and references therein]. Furthermore, the crust and lithosphere beneath the Umbria-Marche region is thinner in comparison with the central and southern Apennines [*Calcagnile and Panza*, 1980; *Geiss*, 1987]. This indicates that the northern Apennines were not deposited on a ‘‘normal’’ continental crust and that the shape of the

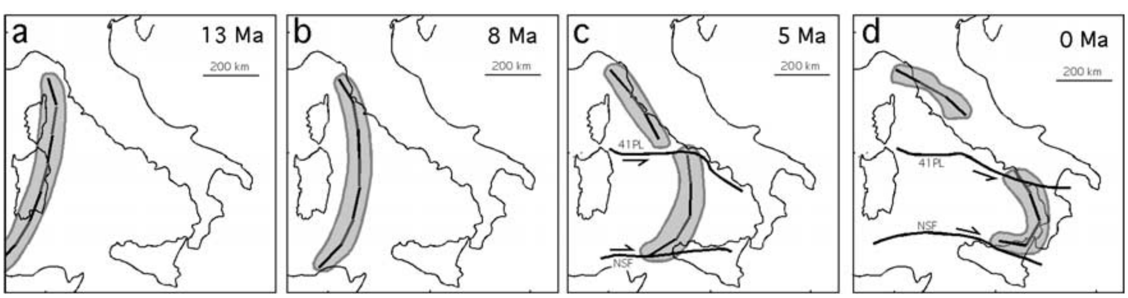

Figure 10. Maps showing the evolution of the subducting lithospheric slab beneath Italy since the late Miocene (relative to present-day coastlines). Shaded areas are surface projections of the slab at depths of 30–100 km based on the tomographic model of *Lucente et al.* [1999] and the results of our reconstruction (Figure 8). Note that the reconstruction predicts tearing of the slab at the latest Messinian (∼6–5 Ma) and a subsequent period of rapid rollback in the southern Tyrrhenian Sea. Abbreviations are 41PL, 41 parallel strike-slip fault zone; NSF, North Sicily Fault.

Table 2. Rotations in the Apennines-Maghrebides Since the Tortonian[a]

	Inferred Rotation	Time Span	Reference
		Northern Apennines	
1	28° CCW	since Tortonian	*Muttoni et al.* [2000]
2	20–60° CCW	since Messinian	*Speranza et al.* [1997]
3	20° CCW	since Messinian	*Speranza et al.* [1997]
4	15° CW	since Messinian	*Speranza et al.* [1997]
5	no rotation	since late Messinian	*Mattei et al.* [1996]
		Central Apennines	
6	no rotation	since late Pliocene	*Sagnotti et al.* [1994]
7	28° CCW	since late Miocene	*Mattei et al.* [1995]
8	35° CCW	since Messinian	*Speranza et al.* [1998]
		Southern Apennines	
9	22–23° CCW	late Pliocene-early Pleistocene	*Scheepers et al.* [1993]
10	80° CCW	<15 Ma	*Gattacceca and Speranza* [2002]
11	15° CCW	during late Pliocene	*Scheepers and Langereis* [1994]
11	15° CCW	during middle Pleistocene	*Scheepers and Langereis* [1994]
11	9° CCW	since middle Pleistocene	*Scheepers and Langereis* [1994]
		Calabria-Peloritan	
12	19° CW	Tortonian-Messinian	*Speranza et al.* [2000]
13	25° CW	during Tortonian	*Duermeijer et al.* [1998]
14	15–20° CW	Pleistocene	*Mattei et al.* [1999]
15	10–20° CW	during middle Pleistocene	*Scheepers et al.* [1994]
16	14° CW	Plio-Pleistocene	*Aifa et al.* [1988]
		Sicily	
17	25° CW	since lower Pliocene	*Grasso et al.* [1989]
18	34° CW	since early Pliocene	*Scheepers and Langereis* [1993]
19	55° CW	since early Pliocene	*Speranza et al.* [1999]

[a]See locations in Figure 11a; CW, clockwise; CCW, counterclockwise. Note that rotations are integrated with time.

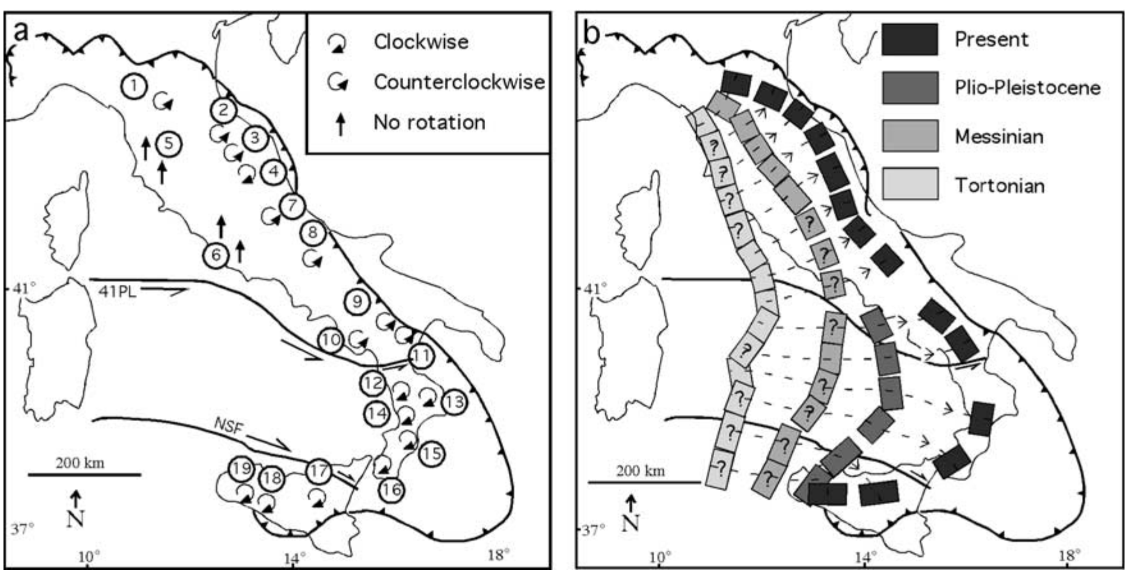

Figure 11. (a) Sense of block rotations in the Apennines-Maghrebides as inferred from paleomagnetic data. Numbers correspond to the list of paleomagnetic rotations in Table 2. (b) Restoration of rigid blocks with respect to history of extension in the Tyrrhenian Sea (Figures 6 and 10) and the amount of inferred paleomagnetic rotations. Dashed lines and arrows indicate the sense of tectonic transport. Rotations that are not based on paleomagnetic data are indicated by question marks. Abbreviations are 41PL, 41 parallel strike-slip fault zone; NSF, North Sicily Fault.

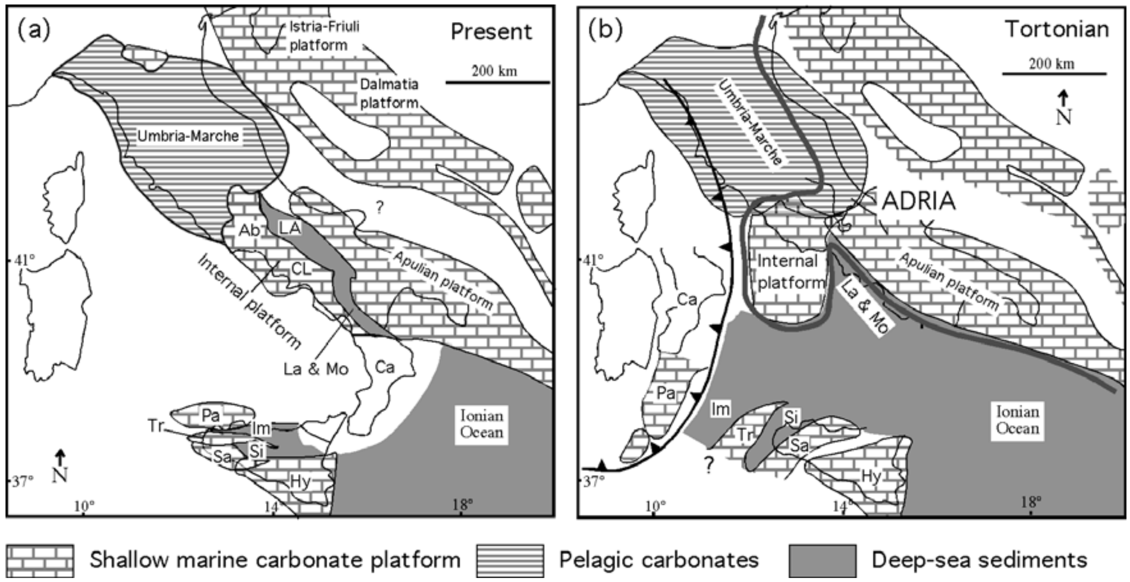

Figure 12. (a) Spatial distribution of sedimentary facies in the western margin of Adria (modified after *Oldow et al.* [1990], *Marsella et al.* [1995], and *Bosellini* [2002]). (b) Restored positions of Apennine-Maghrebide terranes prior to the opening of the Tyrrhenian Sea. The thick grey line indicates the irregular continental margin of Adria. Abbreviations are Ab, Abruzzi; Ca, Calabria; CL, Campania-Lucania platform; Hy, Hyblean platform; Im, Imerese; La, Lagonegro; Mo, Molise; Pa, Panormide platform; Sa, Saccense; Si, Sicanian; Tr, Trapanese.

continental margin of Adria, when it was incorporated in Apennine-Maghrebide orogeny, was irregular (Figure 12b).

[37] The sedimentary facies in Sicily is characterized by several lithotectonic assemblages of Mesozoic carbonate platforms (Panormide, Trapanese, Saccense, and Hybley) and two basinal units with pelagic deposits (Imerese and Sicanian Basins) [*Catalano and D'Argenio*, 1978; *Oldow et al.*, 1990]. In the most internal part of the fold-and-thrust belt and at the highest structural position, the Panormide carbonate platform is separated from the underlying platform and seamount of Trapanese by sediments of the Imerese Basin (Figure 12a). The Sicanian Basin, in turn, is located between the Trapanese unit and the Saccense platforms [*Channell et al.*, 1990; *Oldow et al.*, 1990]. This tectonic configuration indicates that the imbrication of thrust sheets involved closure of rift basins that now form shortened zones between the carbonate tectonic allochthons (Figure 12b).

[38] The suggested palinspastic reconstruction (Figure 12b) combines the paleogeographic data with our constraints on the kinematic evolution of the orogen (see Figure 11b). We suggest that the incorporation of heterogeneous crustal material resulted in an uneven distribution of strain during deformation. Carbonate platforms moved as relatively rigid blocks, whereas basinal units were subjected to intense shortening deformation. We further speculate that the arrival of the platform at the subduction zone impeded subduction and led to (1) the establishment of the 41PL strike-slip fault and (2) tearing of the central Apennine slab. Closure of deep-sea rift basins (Lagonegro, Molise, Imerese and Sicanian Basins) farther west facilitated continuing rollback in the southern Apennines, Calabria and Sicily.

7. Discussion

7.1. Tectonic Evolution of the Tyrrhenian Basin

[39] The results of our analysis indicate that the major stages of opening in the Tyrrhenian Sea did not begin before the late Miocene (~13–10 Ma). Oligocene-early Miocene extensional episodes in the Corsica Basin [e.g., *Mauffret and Contrucci*, 1999] and in the northern Apennines [e.g., *Carmignani et al.*, 1994] are attributable to the opening of the earlier Ligurian-Provençal Basin, with rift basin sediments outcropping in the uplifted margin of the earlier rift. The opening of the Ligurian-Provençal Basin was accompanied by the counterclockwise rotation of Corsica and Sardinia, which reached their present positions with respect to Europe by 16 Ma [*Speranza et al.*, 2002].

[40] During the middle Miocene (16–10 Ma), extension in the Tyrrhenian Sea stopped, as indicated by the absence of middle Miocene synrift sediments in the region (Figure 4), Moreover, during this period, the position of the magmatic arc remained relatively fixed (Figure 6), indicating that the subduction zone did not then rollback.

[41] Rifting in the Tyrrhenian Sea began again during the Tortonian (~10–9 Ma) and was localized along the margins of Corsica and Sardinia. This event, which is recorded in the occurrence of Tortonian synrift sediments, occurred contemporaneously with rapid eastward movement of the magmatic arc (Figure 6). For that reason, Tortonian exten-

sional tectonics in the Tyrrhenian Sea are interpreted as a direct tectonic response to subduction rollback. These constraints on the early stages of back arc extension are significant, because some previous workers have debated whether subduction rollback has actually played a role in the opening of the northern Tyrrhenian Sea [e.g., *Faccenna et al.*, 1996; *Mantovani et al.*, 1996].

[42] A major change in the style of subduction rollback and back arc extension occurred during the late Messinian (~6–5 Ma) in the Tyrrhenian-Apennine system. This change is recognized both in the distribution of synrift sediments and the distribution of magmatic activity. These independent data sources indicate that at ~6–5 Ma, the rates of subduction rollback and back arc extension slowed down in the northern Tyrrhenian Sea, but increased considerably in the southern Tyrrhenian Sea. The differential velocities of extension were accommodated by the two lithosphere penetrating strike-slip faults of 41PL and off the north coast of Sicily, that were active as strike-slip faults during the Pliocene and the Pleistocene [*Lavecchia*, 1988; *Boccaletti et al.*, 1990b; *Spadini and Wezel*, 1994; *Bruno et al.*, 2000]. During this extensional episode, the extreme rates of subduction rollback (60–100 km Myr^{-1}) induced sufficient lithospheric attenuation in the overriding plate to form possible new oceanic crust in the Vavilov and Marsilli Basins.

7.2. Tectonic Response to Accretion of Continental Crust

[43] An important aspect of this study is the possible relationships between paleogeography and the geometry of the subducting slab. Apart from the uncertain role of present-day subduction in the northern Tyrrhenian Sea [e.g., *Selvaggi and Amato*, 1992; *Lucente and Speranza*, 2001], current subduction in the Tyrrhenian-Apennine system is restricted to a narrow zone bounded by two lithospheric-scale strike-slip fault in the Calabrian Arc. The reason for this geometry is that the Calabrian Arc is the only area within the Tyrrhenian-Apennine system that still consumes oceanic lithosphere (that of the Ionian Sea). In contrast, there is no evidence for active subduction in the central Apennines, where detached remnants of a slab are found only at depths greater than 250–300 km (Figure 7b). In this region, the paleogeography was dominated by a carbonate platform (the internal platform; Figure 12b). We suggest that the arrival of that relatively buoyant continental block at the subduction zone impeded the subduction processes, leading to a detachment of the subducting slab from the surface, and to tearing of the slab at the boundary between the continental block and the oceanic lithosphere (Figure 13). This mechanism is essentially an example of the formation of slab tears as a result of the docking of allochthonous block and fragments of subduction systems [*Ben-Avraham et al.*, 1981; *Nur and Ben-Avraham*, 1982].

[44] The formation of the slab tears was a crucial trigger for change in the history of rollback. In the Tyrrhenian Sea, time constraints on the tearing of the slab and the accretion of the internal platform indicate that these events took place at ~6–5 Ma. These events were followed by a period of

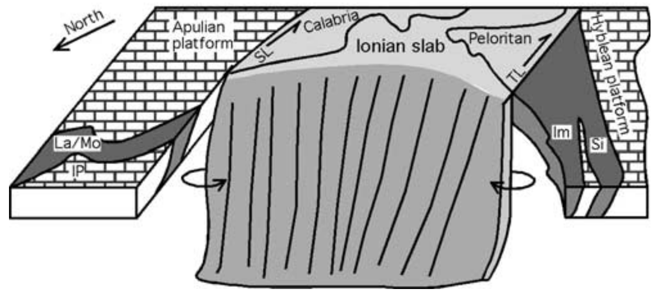

Figure 13. Schematic illustration showing possible relationships between the geometry of the subducting slab and the rheological properties of the crust and lithosphere. Tearing of the slab occurred as a result of the arrival of thick continental material (the internal platform) at the subduction system, combined with ongoing subduction of oceanic lithosphere (the Ionian Sea) in the Calabrian Arc. Following tearing, rollback is further accelerated by sideways asthenospheric flow (arrows). Abbreviations are Im, Imerese; IP, internal platform; La, Lagonegro; Mo, Molise; Si, Sicanian; SL, Sangineto line; TL, Taormina line.

rapid rollback in the southern Tyrrhenian Sea (in excess of 100 km Myr^{-1}), and the formation of an oceanic back arc basin. We suggest that slab tearing was the trigger for the subsequent Plio-Pleistocene episode of increased rapid rollback/back arc extension in the southern Tyrrhenian Sea. The tearing resulted in the formation of a relatively narrow slab [e.g., *Dvorkin et al.*, 1993] remaining beneath the southern Tyrrhenian Sea. Consequently, this slab was subjected to a reduced hydrodynamic suction from asthenospheric flow (Figure 13), which is a lifting force that prevents sinking of the slab into the asthenosphere [*Dvorkin et al.*, 1993; *Nur et al.*, 1993]. We expect that the decrease of this force would act to accelerate subduction rollback.

[45] From this example, it appears that episodes of back arc extension related to subduction rollback are strongly influenced by the rheological properties of the lithosphere and the interaction with relatively rigid continental blocks. Subduction rollback is likely to follow the geometry of existing oceanic crust. Thus, while docking of thick continental material in the subduction system may impede subduction, the incorporation of deep basins at the subduction zone could provide a relatively free boundary for further rollback. A similar assumption has led *Sengör* [1993] to suggest that the closure of small, possibly oceanic, basins, such as the Lagonegro Basin, may have facilitated further subduction rollback of Adria. Our reconstruction shows (Figure 12b) that these basins, the Lagonegro, Molise, Imerese and Sicanian Basins, probably accommodated subduction rollback, although the main component of subduction rollback is attributable to the closure of the narrow Ionian Sea.

8. Conclusions

[46] We have used sets of spatiotemporal constraints in order to obtain a better resolution of crustal and lithospheric

processes associated with the evolution of the Tyrrhenian Sea and the Apennine-Maghrebide belt. The earliest evidence for extensional tectonism is associated with Oligocene-early Miocene (~25–16 Ma) synrift sediments in the northern Tyrrhenian Sea. This extensional episode occurred prior or during the opening of the Ligurian-Provençal Basin, and before Corsica and Sardinia stopped rotating (at ~16 Ma). The major extensional episode associated with the opening of the Tyrrhenian Sea began only at ~10–9 Ma, after a period of 6–7 Myr of relative quiescence in extensional processes during the middle Miocene.

[47] The first stage of opening in Tyrrhenian Sea, between ~10–9 Ma and ~6–5 Ma, was characterized by widespread extension in the northern domain, and rifting in the western part of the southern domain. In contrast, the second stage of opening (after ~6–5 Ma) was localized in the southern Tyrrhenian Sea, and involved extreme rates of subduction rollback (in excess of 100 km Myr^{-1}) and the formation of new oceanic crust in the back arc region. The transition between the two stages of opening at ~6–5 Ma, was triggered by docking of the Internal carbonate platform in the central Apennine subduction system, which we propose, led to the formation of major strike-slip faults and a related slab tear. Subsequently, the remaining Ionian slab beneath Calabria was narrower and was consequently subjected to accelerated rates of subduction rollback, accommodated by the two major strike-slip faults, the sinistral 41 parallel line and the dextral North Sicily Fault.

[48] **Acknowledgments.** We wish to thank W. P. Schellart, M. Raetz, I. M. A. Vos, and P. G. Betts for providing comments on the manuscript and A. M. C. Sengör for a stimulating discussion on the topic. The manuscript has also benefited from the comments made by the reviewers, K. Burke, D. Cowan, and C. Faccenna, and the Editor, B. Wernicke.

References

Aifa, T., H. Feinberg, and J. P. Pozzi (1988), Pliocene-Pleistocene evolution of the Tyrrhenian arc: Paleomagnetic determination of uplift and rotational deformation, *Earth Planet. Sci. Lett.*, *87*, 438–452.

Anderson, H., and J. Jackson (1987), The deep seismicity of the Tyrrhenian Sea, *Geophys. J. R. Astron. Soc.*, *91*, 613–637.

Argentieri, A., M. Mattei, F. Rossetti, A. Argnani, F. Salvini, and R. Funiciello (1998), Tectonic evolution of the Amantea Basin (Calabria, southern Italy): Comparing in-land and off-shore data, *Ann. Tectonicae*, *12*, 79–96.

Argnani, A., and C. Savelli (1999), Cenozoic volcanism and tectonics in the southern Tyrrhenian: Space-time distribution and geodynamic significance, *J. Geodyn.*, *27*, 409–432.

Argnani, A., and C. Savelli (2001), Magmatic signature of episodic back-arc rifting in the southern Tyrrhenian Sea, in *Peri-Tethyan Rift/Wrench Basins and Passive Margins*, *Peri-Tethys Mem. 6*, edited by P. A. Ziegler et al., *Mem. Mus. Natl. Hist. Nat.*, *186*, 735–754.

Bartole, R. (1995), The North Tyrrhenian-northern Apennines post-collisional system: Constraints for a geodynamic model, *Terra Nova*, *7*, 7–30.

Ben-Avraham, Z., A. Nur, D. Jones, and A. Cox (1981), Continental accretion: From oceanic plateaus to allochthonous terranes, *Science*, *213*, 47–54.

Boccaletti, M., et al. (1990a), Migrating foredeep-thrust belt system in the northern Apennines and southern Alps, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *77*, 3–14.

Boccaletti, M., R. Nicolich, and L. Tortorici (1990b), New data and hypothesis on the development of the Tyrrhenian Basin, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *77*, 15–40.

Bosellini, A. (2002), Dinosaurs "re-write" the geodynamics of the eastern Mediterranean and the paleogeography of the Apulia platform, *Earth Sci. Rev.*, *59*, 211–234.

Bruno, P. P., V. Di Fiore, and G. Ventura (2000), Seismic study of the '41st parallel' fault system offshore the Campanian-Latial continental margin, Italy, *Tectonophysics*, *324*, 37–55.

Calcagnile, G., and G. F. Panza (1980), The main characteristics of the lithosphere-asthenosphere system in Italy and surrounding regions, *Pure Appl. Geophys.*, *119*, 865–879.

Carmignani, L., F. A. Decandia, L. Fantozzi, A. Lazzarotto, D. Liotta, and M. Meccheri (1994), Tertiary extensional tectonics in Tuscany (northern Apennines, Italy), *Tectonophysics*, *238*, 295–315.

Carmignani, L., F. Decandia, A. Disperati, L. Fantozzi, P. L. Lazzarotto, A. Liotta, D. Oggiano, G. Tavarnelli, and E. Relaziaoni (1995), Relationship between the Balearic Basin, the northern Tyrrhenian Sea and the Neogene evolution of the northern Apennines, in *Geodynamics and Active Tectonics of the Tyrrhenian-Apennines System*, edited by G. Cello, G. Deiana, and P. P. Pierantoni, pp. 255–268, Univ. degli Studi di Camerino, Camerino, Italy.

Catalano, R., and B. D'Argenio (1978), An essay of palinspastic restoration across western Sicily, *Geol. Romana*, *17*, 145–159.

Cavinato, G. P., and P. G. De Celles (1999), Extensional basins in the tectonically bimodal central Apennines fold-thrust belt, Italy: Response to corner flow above a subducting slab in retrograde motion, *Geology*, *27*, 955–958.

Cello, G., and S. Mazzoli (1999), Apennine tectonics in southern Italy: A review, *J. Geodyn.*, *27*, 191–211.

Cello, G., C. Ivernizzi, and S. Mazzoli (1996), Structural signature of tectonic processes in the Calabrian Arc, southern Italy: Evidence from the oceanic-derived Diamante-Terranova Unit, *Tectonics*, *15*, 187–200.

Channell, J. E. T., J. S. Oldow, R. Catalano, and B. D'Argenio (1990), Paleomagnetically determined rotations in the western Sicilian fold and thrust belt, *Tectonics*, *9*, 641–660.

Cipollari, P., D. Cosentino, and E. Gliozzi (1999), Extension- and compression-related basins in central Italy during the Messinian Lago-Mare event, *Tectonophysics*, *315*, 163–185.

Civetta, L., G. Orsi, P. Scandone, and R. Pece (1978), Eastwards migration of the Tuscan anatectic magmatism due to anticlockwise rotation of the Apennines, *Nature*, *276*, 604–606.

Della Vedova, B., G. Pellis, J. P. Foucher, and J. P. Rehault (1984), Geothermal structure of the Tyrrhenian Sea, *Mar. Geol.*, *55*, 271–289.

Della Vedova, B., I. Marson, G. F. Panza, and P. Suhadolc (1991), Upper mantle properties of the Tuscan-Tyrrhenian area: A framework for its Recent tectonic evolution, *Tectonophysics*, *195*, 311–318.

DeMets, C., R. G. Gordon, D. F. Argus, and S. Stein (1994), Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions, *Geophys. Res. Lett.*, *21*, 2191–2194.

Dewey, J. F. (1980), Episodicity, sequence, and style at convergent plate boundaries, *Geol. Assoc. Can. Spec. Pap.*, *20*, 553–573.

Duermeijer, C. E., N. van Vugt, C. G. Langereis, J. E. Meulenkamp, and W. J. Zachariasse (1998), A major late Tortonian rotation phase in the Crotone basin using AMS as tectonic tilt correction and timing of the opening of the Tyrrehenian basin, *Tectonophysics*, *287*, 233–249.

Dvorkin, J., A. Nur, G. Mavko, and Z. Ben-Avraham (1993), Narrow subducting slabs and the origin of backarc basins, *Tectonophysics*, *227*, 63–79.

Elsasser, W. M. (1971), Sea-floor spreading as thermal convection, *J. Geophys. Res.*, *76*, 1101–1112.

Faccenna, C., et al. (1996), The dynamics of back-arc extension: An experimental approach to the opening of the Tyrrhenian Sea, *Geophys. J. Int.*, *126*, 781–795.

Faccenna, C., M. Mattei, R. Funiciello, and L. Jolivet (1997), Styles of back-arc extension in the central Mediterranean, *Terra Nova*, *9*, 126–130.

Faccenna, C., T. W. Becker, F. P. Lucente, L. Jolivet, and F. Rosseti (2001a), History of subduction and back-arc extension in the central Mediterranean, *Geophys. J. Int.*, *145*, 809–820.

Faccenna, C., F. Funiciello, D. Giardini, and P. Lucente (2001b), Episodic back-arc extension during restricted mantle convection in the central Mediterranean, *Earth Planet. Sci. Lett.*, *187*, 105–116.

Feraud, G. (1990), ^{39}Ar-^{40}Ar analysis on basaltic lava series of Vavilov Basin, Tyrrhenian Sea (Ocean Drilling Program, Leg 107, holes 655B and 651A), *Proc. Ocean Drill. Program Sci. Results*, *107*, 93–97.

Finetti, I. R., et al. (2001), Crustal section based on CROP seismic data across the North Tyrrhenian-northern Apennines-Adriatic Sea, *Tectonophysics*, *343*, 135–163.

Gamberi, F., and A. Argnani (1995), Basin formation and inversion tectonics on top of the Egadi foreland thrust belt (NW Strait of Sicily), *Tectonophysics*, *252*, 285–294.

Garfunkel, Z., C. A. Anderson, and G. Schubert (1986), Mantle circulation and the lateral migration of subducted slabs, *J. Geophys. Res.*, *91*, 7205–7223.

Gattacceca, J., and F. Speranza (2002), Paleomagnetism of Jurassic to Miocene sediments from the Apenninic carbonate platform (southern Apennines, Italy): Evidence for a 60° counterclockwise Miocene rotation, *Earth Planet. Sci. Lett.*, *201*, 19–34.

Geiss, E. (1987), A new compilation of crustal thickness data for the Mediterranean area, *Ann. Geophys.*, *5*, 623–630.

Grasso, M., M. Manzoni, and A. Quintili (1989), Misure magnetiche su Trubi infrapliocenici della Sicilia orientale: Possibili implicazioni stratigrafiche e strutturali, *Mem. Sci. Geol. It.*, *38*, 459–474.

Gvirtzman, Z., and A. Nur (1999), The formation of Mount Etna as the consequence of slab rollback, *Nature*, *401*, 782–785.

Gvirtzman, Z., and A. Nur (2001), Residual topography, lithospheric structure and sunken slabs in the central Mediterranean, *Earth Planet. Sci. Lett.*, *187*, 117–130.

Jolivet, L., et al. (1998), Midcrustal shear zones in postorogenic extension: Example from the Tyrrhenian Sea, *J. Geophys. Res.*, *103*, 12,123–12,160.

Kastens, K., et al. (1988), ODP leg 107 in the Tyrrhenian Sea: Insights into passive margin and back-arc basin evolution, *Geol. Soc. Am. Bull.*, *100*, 1140–1156.

Knott, S. D., and E. Turco (1991), Late Cenozoic kinematics of the Calabrian Arc, southern Italy, *Tectonics*, *10*, 1164–1172.

Lavecchia, G. (1988), The Tyrrhenian-Apennines system: Structural setting and seismotectogenesis, *Tectonophysics*, *147*, 263–296.

Lavecchia, G., and F. Stoppa (1996), The tectonic significance of Italian magmatism: An alternative view to the popular interpretation, *Terra Nova*, *8*, 435–446.

Lavecchia, G., G. Minelli, and G. Pialli (1988), The Umbria-Marche arcuate fold belt (Italy), *Tectonophysics*, *146*, 125–137.

Lucente, F. P., and F. Speranza (2001), Belt bending driven by lateral bending of subducting lithospheric slab: Geophysical evidences from the northern Apennines (Italy), *Tectonophysics*, *337*, 53–64.

Lucente, F. P., C. Chiarabba, G. B. Cimini, and D. Giardini (1999), Tomographic constraints on the geodynamic evolution of the Italian region, *J. Geophys. Res.*, *104*, 20,307–20,327.

Malinverno, A., and W. B. F. Ryan (1986), Extension on the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the lithosphere, *Tectonics*, *5*, 227–245.

Mantovani, E., D. Albarello, C. Tamburelli, and D. Babbucci (1996), Evolution of the Tyrrhenian basin and surrounding regions as a result of the Africa-Eurasia convergence, *J. Geodyn.*, *21*, 35–72.

Mariucci, M. T., A. Amato, and P. Montone (1999), Recent tectonic evolution and present stress in the northern Apennines (Italy), *Tectonics*, *18*, 108–118.

Marsella, E., A. W. Bally, G. Cippitelli, B. D'Argenio, and G. Pappone (1995), Tectonic history of the Lagonegro Domain and southern Apennine thrust belt evolution, *Tectonophysics*, *252*, 307–330.

Mascle, G. H., et al. (2001), Evolution of the Sardinia Channel (western Mediterranean): New constraints from a diving survey on Cornacya Seamount off SE Sardinia, *Mar. Geol.*, *179*, 179–201.

Mattei, M., R. Funiciello, and C. Kissel (1995), Paleomagnetic and structural evidence for Neogene block rotations in the central Apennines, Italy, *J. Geophys. Res.*, *100*, 17,863–17,883.

Mattei, M., C. Kissel, and R. Funiciello (1996), No tectonic rotation of the Tuscan Tyrrhenian margin (Italy) since late Messinian, *J. Geophys. Res.*, *101*, 2835–2845.

Mattei, M., F. Speranza, A. Argentieri, F. Rosseti, L. Sangotti, and R. Funiciello (1999), Extensional tectonics in the Amantea basin (Calabria, Italy): A comparison between structural and magnetic anisotropy data, *Tectonophysics*, *307*, 33–49.

Mauffret, A., and I. Contrucci (1999), Crustal structure of the North Tyrrhenian Sea: First result of the multichannel seismic LISA cruise, in *The Mediterranean Basins: Tertiary Extension Within the Alpine Orogen*, edited by B. Durand et al., *Geol. Soc. Spec. Publ.*, *156*, 169–193.

Molnar, P., and T. Atwater (1978), Interarc spreading and Cordilleran tectonics as alternates related to the age of subducted oceanic lithosphere, *Earth Planet. Sci. Lett.*, *41*, 330–340.

Montone, P., and A. Amato (1999), Active stress map of Italy, *J. Geophys. Res.*, *104*, 25,595–25,610.

Mostardini, F., and S. Merlini (1986), Appennino centro-meridionale: Sezioni geologiche e proposta di modello strutturale, *Mem. Sci. Geol. It.*, *35*, 177–202.

Muttoni, G., et al. (2000), Paleomagnetic evidence for a Neogene two-phase counterclockwise rotation in the northern Apennines (Italy), *Tectonophysics*, *326*, 241–253.

Nigro, F., and A. Sulli (1995), Plio-Pleistocene extensional tectonics in the western Peloritani area and its offshore (northeastern Sicily), *Tectonophysics*, *252*, 295–305.

Nur, A., and Z. Ben-Avraham (1982), Oceanic plateaus, the fragmentation of continents, and mountain building, *J. Geophys. Res.*, *87*, 3644–3661.

Nur, A., J. Dvorkin, G. Mavko, and Z. Ben-Avraham (1993), Speculations on the origins and fate of backarc basins, *Ann. Geofis.*, *36*, 155–163.

Oldow, J. S., J. E. T. Channell, R. Catalano, and B. D'Argenio (1990), Contemporaneous thrusting and large-scale rotations in the western Sicilian fold and thrust belt, *Tectonics*, *9*, 661–681.

Patacca, E., and P. Scandone (1989), Post-Tortonian mountain building in the Apennines. The role of the passive sinking of a relic lithospheric slab, in *The Lithosphere in Italy*, edited by A. Boriani et al., pp. 157–176, It. Natl. Comm. for the Int. Lithosphere Program, Rome.

Patacca, E., R. Sartori, and P. Scandone (1990), Tyrrhenian basin and Apenninic arcs: Kinematic relations since Late Tortonian times, *Mem. Sci. Geol. It.*, *45*, 425–451.

Patacca, E., R. Sartori, and P. Scandone (1993), Tyrrhenian basin and Apennines. Kinematic evolution and related dynamic constraints, in *Recent Evolution and Seismicity of the Mediterranean Region*, *NATO ASI Ser., Ser. C*, vol. 402, edited by E. Boschi, E. Mantovani, and A. Morelli, pp. 161–171, Kluwer Acad., Norwell, Mass.

Pepe, F., G. Bertotti, F. Cella, and E. Marsella (2000), Rifted margin formation in the south Tyrrhenian Sea: A high-resolution seismic profile across the north Sicily passive continental margin, *Tectonics*, *19*, 241–257.

Remane, J., et al. (2000), International stratigraphic chart and explanatory note, 16 pp., Int. Union of Geol. Sci., Trondheim, Norway.

Rollet, N., J. Déverchère, M.-O. Beslier, P. Guennoc, J.-P. Réhault, M. Sosson, and C. Truffert (2002), Back arc extension, tectonic inheritance, and volcanism in the Ligurian Sea, western Mediterranean, *Tectonics*, *21*(3), 1015, doi:10.1029/2001TC900027.

Rosenbaum, G., and G. S. Lister (2004), Formation of arcuate orogenic belts in the western Mediterranean region, in *Orogenic Curvature*, edited by A. Sussman and A. Weil, *Spec. Pap. Geol. Soc. Am.*, in press.

Rosenbaum, G., G. S. Lister, and C. Duboz (2002a), Reconstruction of the tectonic evolution of the western Mediterranean since the Oligocene, *J. Virtual Explorer*, *8*, 107–130.

Rosenbaum, G., G. S. Lister, and C. Duboz (2002b), Relative motions of Africa, Iberia and Europe during Alpine orogeny, *Tectonophysics*, *359*, 117–129.

Rosseti, F., et al. (2001), Alpine structural and metamorphic signature of the Sila Piccola Massif nappe stack (Calabria, Italy): Insights for the tectonic evolution of the Calabrian Arc, *Tectonics*, *20*, 112–133.

Roure, F., D. G. Howell, C. Mueller, and I. Moretti (1990), Late Cenozoic subduction complex of Sicily, *J. Struct. Geol.*, *12*, 259–266.

Roure, F., P. Casero, and R. Vially (1991), Growth processes and melange formation in the southern Apennines accretionary wedge, *Earth Planet. Sci. Lett.*, *102*, 395–412.

Royden, L. H. (1993), The tectonic expression of slab pull at continental convergent boundaries, *Tectonics*, *12*, 303–325.

Sagnotti, L., M. Mattei, C. Faccenna, and R. Funiciello (1994), Paleomagnetic evidence for no tectonic rotation of the central Italy Tyrrhenian margin since upper Pliocene, *Geophys. Res. Lett.*, *21*, 481–484.

Sartori, R., G. Carrara, L. Torelli, and N. Zitellini (2001), Neogene evolution of the southwestern Tyrrhenian Sea (Sardinia Basin and western bathyal plain), *Mar. Geol.*, *175*, 47–66.

Savelli, C. (1988), Late Oligocene to Recent episodes of magmatism in and around the Tyrrhenian Sea: Implications for the processes of opening in a young inter-arc basin of intra-orogenic (Mediterranean) type, *Tectonophysics*, *146*, 163–181.

Savelli, C. (2000), Subduction-related episodes of K-alkaline magmatism (15–0. 1 Ma) and geodynamic implications in the north Tyrrhenian - central Italy region: A review, *J. Geodyn.*, *30*, 575–591.

Savelli, C. (2001), Two-stage progression of volcanism (8–0 Ma) in the central Mediterranean (southern Italy), *J. Geodyn.*, *31*, 393–410.

Savelli, C. (2002), Time-space distribution of magmatic activity in the western Mediterranean and peripheral orogens during the past 30 Ma (a stimulus to geodynamic considerations), *J. Geodyn.*, *34*, 99–126.

Scheepers, P. J. J., and C. G. Langereis (1993), Analysis of NRM directions from the Rossello composite: Implications for tectonic rotations of the Caltanissetta basin, *Sicily, Earth Planet. Sci. Lett.*, *119*, 243–258.

Scheepers, P. J. J., and C. G. Langereis (1994), Paleomagnetic evidence for counter-clockwise rotations in the Southern Apennines fold-and-thrust belt during the late Pliocene and middle Pleistocene, *Tectonophysics*, *239*, 43–59.

Scheepers, P. J. J., C. G. Langereis, and F. J. Hilgen (1993), Counter-clockwise rotations in the southern Apennines during the Pleistocene: Paleomagnetic evidence from the Matera area, *Tectonophysics*, *225*, 379–410.

Scheepers, P. J. J., C. G. Langereis, J. D. A. Zijderveld, and F. J. Hilgen (1994), Paleomagnetic evidence for a Pleistocene clockwise rotation of the Calabro-Peloritan block (southern Italy), *Tectonophysics*, *230*, 19–48.

Schellart, W. P. (2003), Subduction rollback, arc formation and back-arc extension, Ph.D. thesis, 243 pp., Monash Univ., Melbourne, Australia.

Selvaggi, G., and A. Amato (1992), Subcrustal earthquakes in the northern Apennines (Italy): Evidence for a still active subduction?, *Geophys. Res. Lett.*, *19*, 2127–2130.

Sengör, A. M. C. (1993), Some current problems on the tectonic evolution of the Mediterranean during the Cainozoic, in *Recent Evolution and Seismicity of the Mediterranean Region*, *NATO ASI Ser., Ser. C*, vol. 402, edited by E. Boschi, E. Mantovani, and A. Morelli, pp. 1–51, Kluwer Acad., Norwell, Mass.

Serri, G., F. Innocenti, and P. Manetti (1993), Geochemical and petrological evidence of the subduction of delaminated Adriatic continental lithosphere in the genesis of the Neogene-Quaternary magmatism of central Italy, *Tectonophysics*, *223*, 117–147.

Spadini, G., and F.-C. Wezel (1994), Structural evolution of the "41st parallel zone": Tyrrhenian Sea, *Terra Nova*, *6*, 552–562.

Spadini, G., G. Bertotti, and S. Cloetingh (1995), Tectono-stratigraphic modelling of the Sardinian margin of the Tyrrhenian Sea, *Tectonophysics*, *252*, 269–284.

Speranza, F., L. Sagnotti, and M. Mattei (1997), Tectonics of the Umbria-Marche-Romagna arc (central northern Apennines, Italy): New paleomagnetic constraints, *J. Geophys. Res.*, *102*, 3153–3166.

Speranza, F., M. Mattei, G. Naso, D. Di Bucci, and S. Corrado (1998), Neogene-Quaternary evolution of the central Apennine orogenic system (Italy): A structural and palaeomagnetic approach in the Molise region, *Tectonophysics*, *299*, 143–157.

Speranza, F., R. Maniscalco, M. Mattei, D. Stefano, and R. W. H. Butler (1999), Timing and magnitude of rotations in the frontal thrust systems of southwestern Sicily, *Tectonics*, *18*, 1178–1197.

Speranza, F., M. Mattei, L. Sagnotti, and F. Grasso (2000), Rotational differences between the northern and southern Tyrrhenian domains: Palaeomagnetic constraints from the Amantea Basin (Calabria, Italy), *J. Geol. Soc. Lon.*, *157*, 327–334.

Speranza, F., et al. (2002), Age of the Corsica-Sardinia rotation and Liguro-Procençal Basin spreading: New paleomagnetic and Ar/Ar evidence, *Tectonophysics*, *347*, 231–251.

Stoppa, F., and A. R. Woolley (1997), The Italian carbonatites: Field occurrence, petrology and regional significance, *Mineral. Petrol.*, *59*, 43–67.

van Dijk, J., and M. Okkes (1991), Neogene tectonostratigraphy and kinematics of Calabrian basins: Implications for the geodynamics of the central Mediterranean, *Tectonophysics*, *196*, 23–60.

Wood, A. W. (1981), Extensional tectonics and the birth of the Lagonegro Basin (southern Italian Apennines), *Neues Jahrb. Geol. Paläeontol. Abh.*, *161*, 93–131.

Wortel, M. J. R., and W. Spakman (1992), Structure and dynamics of subducted lithosphere in the Mediterranean region, *Proc. K. Ned. Akad. Wet.*, *95*, 325–347.

Wortel, M. J. R., and W. Spakman (2000), Subduction and slab detachment in the Mediterranean-Carpathian region, *Science*, *290*, 1910–1917.

G. S. Lister, Research School of Earth Sciences, The Australian National University, Mills Road, Canberra ACT 0200, Australia. (gordon.lister@anu.edu.au)

G. Rosenbaum, Australian Crustal Research Centre, School of Geosciences, Monash University, P.O. Box 28E, Melbourne, Victoria 3800, Australia. (gideon.rosenbaum@sci.monash.edu.au)