

Evolution of the Tyrrhenian Sea-Calabrian Arc system: The past and the present

ALBERTO MALINVERNO (*)

Key words: *Tyrrhenian Sea, Calabrian Arc, trench rollback, orogen extension.*

INTRODUCTION

The Tyrrhenian Sea is an extensional basin that formed in the last 10 Ma in the broad suture between the African and European plates. The convergent plate boundary is evident in the SE corner of the Tyrrhenian Sea, which contains a funnel-shaped Benioff zone (CHIARABBA *et alii*, 2005), a subducting slab imaged by seismic tomography (PIROMALLO & MORELLI, 2003), and the Aeolian islands Quaternary calc-alkaline volcanic arc (SERRI, 1990; FRANCALANCI & MANETTI, 1994; SAVELLI, 2002). Extension in the Tyrrhenian Sea took place at the same time as shortening in the arcuate Apenninic-Maghrebian thrust belt that surrounds the basin to the E and S. The maximum amount of extension is more than 300 km in a WNW-ESE direction between Sardinia and Calabria (MALINVERNO & RYAN, 1986), and is matched by a similar amount of shortening in the Southern Apennines (PATACCA & SCANDONE, 1989).

The key puzzle in the formation of the Tyrrhenian Sea is how large amounts of extension took place in a region of weak plate convergence. Africa and Europe converged by only about 80 km in a NW-SE direction in the last 10 Ma (MAZZOLI & HELMAN, 1994). After reviewing key constraints on the evolution of the Tyrrhenian Sea-Calabrian Arc system, this paper presents a working hypothesis on the outward migration of extension in the Tyrrhenian domain.

EVOLUTION OF THE TYRRHENIAN SEA-CALABRIAN ARC SYSTEM

The two cross-sections in Fig. 1 portray the initial condition of a Sardinia-Calabria transect just before the opening of the Tyrrhenian and its final geometry at the present time. These

cross-sections are mainly constrained by seismic surveys and by the requirement of balancing cross-sectional areas.

The onset of the extension in the Tyrrhenian Sea has been dated to the Tortonian (~10 Ma) from ODP drilling results (KASTENS & MASCLE, 1990). The 10 Ma cross-section of Fig. 1 follows a narrow oceanic seaway that separated the N margin of Africa and the SW margin of the Adriatic platform; the presently subducting slab in the SE Tyrrhenian and the deepest portion of the Ionian Sea are the last remnants of this oceanic corridor (CATALANO *et alii*, 2001). An alternative interpretation places in this oceanic seaway a sliver of continental crust underlying an Apennine-Panormide carbonate platform that connects the Apenninic and Maghrebian domains (ARGNANI, 2005).

Many authors noted that the rifting of the Tyrrhenian took

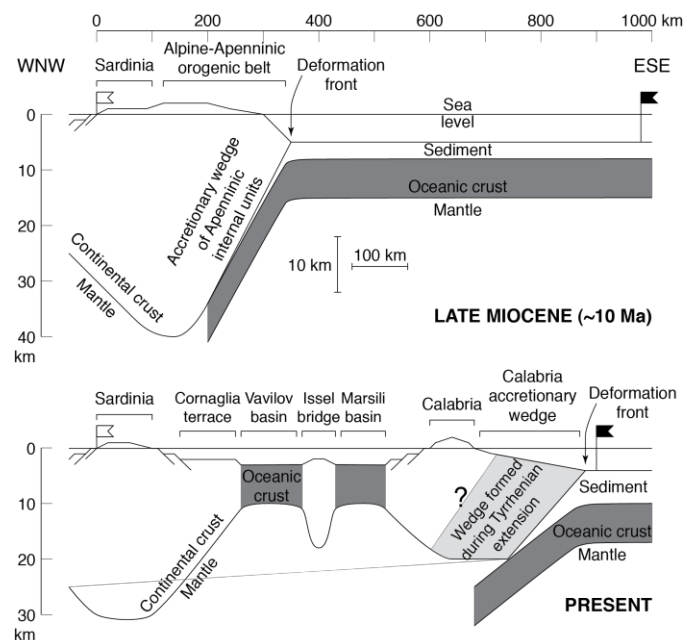


Fig. 1 – Cross-section from Sardinia to the present location of Calabria before the opening of the Tyrrhenian Sea (about 10 Ma; top) and at present (bottom). The Tyrrhenian Sea opens in a pre-existing Alpine-Apenninic orogenic belt, and during extension the accretionary wedge to the E of Calabria grows by incorporating sediments from the subducting plate. The white flag marks the western coastline of Sardinia, and the black flag a point on the subducting plate; because of Africa-Europe motion, the two plates converge by about 80 km in the last 10 Ma (MAZZOLI & HELMAN, 1994).

(*) Lamont-Doherty Earth Observatory of Columbia University, Palisades NY 10964, USA.
Work supported by grant EAR 06-07687 of the US National Science Foundation.

place in a pre-existing orogenic belt composed of Alpine and Apenninic units (ALVAREZ *et alii*, 1974; SCANDONE, 1979; DERCOURT *et alii*, 1986; KASTENS & MASCLE, 1990; PATACCA *et alii*, 1990; ROSENBAUM & LISTER, 2004). Key evidence for this conclusion is in the results of extensive sampling campaigns summarized by the late Renzo Sartori (SARTORI, 1986, 2005). These results show that the Tyrrhenian seafloor contains outcrops of continental basement and ophiolites metamorphosed during the Alpine cycle and of sedimentary rocks correlated to Apenninic units.

Just before the Tyrrhenian opening, the orogenic belt in Fig. 1 had on its eastern edge an accretionary wedge that formed during the subduction of African oceanic lithosphere up to the Tortonian and that was contained the internal units of the Apennines (ARGNANI, 2005). During the Tyrrhenian opening, the Apenninic deformation front migrated to the E and S and the sedimentary covers of the Adria and African margin were progressively incorporated in the orogenic wedge to form the southern Apennines and the Sicilian Maghrebides (LENTINI *et alii*, 1994; CELLO & MAZZOLI, 1999; PAROTTO & PRATURLON, 2004; ROSENBAUM & LISTER, 2004). Most of the shortening in the southern Apennines took place after 10 Ma, at the same time as extension in the Tyrrhenian basin (ROURE *et alii*, 1991). The deformation front moved the farthest to the southeast toward the subducting Ionian oceanic seaway. Sediments accreted or underplated from the Ionian basin formed a large accretionary wedge to the SE of Calabria (ROSSI & SARTORI, 1981; LENCI *et alii*, 2004; FINETTI, 2005).

Extension did not progress symmetrically in the Tyrrhenian, but migrated from the W to the E with time (KASTENS *et alii*, 1988; GUEGUEN *et alii*, 1997). The earliest center of extension was the Cornaglia Terrace W of Sardinia (Fig. 1), where there is clear evidence on seismic reflection profiles of pre-Messinian sediments. The Cornaglia Terrace had to be the deepest area at the time Messinian salt was deposited (~6 Ma), because the Messinian salt layer is clearly recognizable on seismic reflection lines only W of about 12°E longitude (FABBRI & CURZI, 1979; MALINVERNO *et alii*, 1981). After the deposition of the Messinian salt, extension shifted east to the Vavilov basin (KASTENS *et alii*, 1988). The Vavilov basin is bounded to the E by a bathymetric ridge with a relatively thick crust, the Issel bridge (SARTORI, 2003). A relic Pliocene calc-alkaline volcanic arc has been observed there, coeval to extension in the Vavilov basin (SARTORI, 1986; KASTENS *et alii*, 1988; ROSENBAUM & LISTER, 2004). Starting about 2 Ma, extension moved east once more to the Marsili basin (KASTENS *et alii*, 1988). The Paola basin, located east of the Marsili basin near the coast of Calabria (FABBRI *et alii*, 1981), is a deep sinkhole containing about 5 km of Pliocene and Quaternary sediments (BARONE *et alii*, 1982; FINETTI & DEL BEN, 1986; TRINCARDI *et alii*, 1995) and may be the site where extension has migrated most recently (GUEGUEN *et alii*, 1997).

The direction of maximum extension in the Tyrrhenian was

approximately E-W when extension was active in the Cornaglia terrace and in the Vavilov basin, and then rotated to SE-NW during the formation of the Marsili basin (SARTORI, 2003). Extension rates averaged over the last 10 Ma are 40-50 km/Ma (PATACCA *et alii*, 1990; FACCENNA *et alii*, 1996; FACCENNA *et alii*, 2004). The extension rate was not constant in time, but reached a maximum of 60-100 km/Ma in the Messinian (~6-5 Ma) (ROSENBAUM & LISTER, 2004); this extension rate is matched by Messinian deformation rates of 80 km/Ma in the southern Apennines (PATACCA *et alii*, 1990). GPS data show that Calabria is not presently moving to the SE with respect to Sardinia (D'AGOSTINO & SELVAGGI, 2004; SERPELLONI *et alii*, 2005), suggesting that extension in the Tyrrhenian domain is not active at present.

The bottom cross-section in Fig. 1 shows the present-day geometry, with a large orogenic wedge composed of Ionian Sea sediments accreted or underplated while the oceanic seaway between the African and Adria margin was being subducted. The present-day crustal structure is given by the results of seismic experiments (STEINMETZ *et alii*, 1983; SCARASCIA *et alii*, 1994). The crustal structure in the deepest part of the Ionian Sea (4 km water depth) consists of approximately 6 km of sediments and 7 km of igneous crust, so that the Moho is 17 km below sea level (MAKRIS *et alii*, 1986; DE VOOGD *et alii*, 1992). The 20 km thickness of the Calabria accretionary wedge near the coast of Calabria is also constrained by seismic experiments that show the Ionian Moho at 30-35 km depth near the SE coast of Calabria (FERRUCCI *et alii*, 1991; SCARASCIA *et alii*, 1994). By offsetting the crustal section in the deep Ionian Sea to have a Moho 35 km deep and assuming that no sediment was added to the wedge, the minimum wedge thickness is 13-18 km. The cross-sectional area of the wedge formed during the Tyrrhenian extension in the bottom cross-section of Fig. 1 (light gray region) corresponds to approximately 80% of the sediment that covered the length of the Ionian basin subducted in the last 10 Ma. The total cross-sectional area of continental crust in the overriding plate in the 10 Ma cross-section balances the area of extended continental crust in the present-day cross-section. The total amount of extension in the Tyrrhenian Sea implied by the cross-sections of Fig. 1 is 370 km. If the Tyrrhenian started forming 10 Ma, this gives an average extension rate of 37 km/Ma, which matches the averages estimated by other authors (PATACCA *et alii*, 1990; FACCENNA *et alii*, 1996; FACCENNA *et alii*, 2004).

SUBDUCTION HINGE ROLLBACK AND OROGENIC EXTENSIONAL COLLAPSE

A widely proposed explanation for the formation of the Tyrrhenian Sea is based on the observation that the hinge of a subducting plate will migrate away from the overriding plate if the subducting plate has a vertical component of motion into the mantle (ELSASSER, 1971; RITSEMA, 1979). If the subduction

hinge migrates, or “rolls back” faster than the plates converge, extension will take place in the overriding plate (DEWEY, 1980). Extension in the Tyrrhenian has therefore been explained by a SE rollback of the subduction hinge (DERCOURT *et alii*, 1986; FINETTI & DEL BEN, 1986; MALINVERNO & RYAN, 1986; REHAULT *et alii*, 1987; PATACCA & SCANDONE, 1989; PATACCA *et alii*, 1990; DOGLIONI, 1991; NUR *et alii*, 1991; FACCENNA *et alii*, 1996; FACCENNA *et alii*, 2004; ROSENBAUM & LISTER, 2004). This explanation has a solid kinematic basis: if two plates do not converge significantly while subduction continues, the hinge of the subducting plate has to roll back, causing extension in the overriding plate. Conversely, if hinge migration does not take place, subduction has to stop and leave an oceanic remnant.

Another mechanism proposed for the Tyrrhenian extension invokes the extensional collapse of a pre-existing orogenic belt (HORVÁTH & BERCKHEMER, 1982; DEWEY, 1988; CHANNELL & MARESCHAL, 1989). The driving force for extension in this case is the greater potential energy of an elevated mountain range with thick crust compared to nearby regions at lower elevations (ARTYUSHKOV, 1973; BOTT, 1982; MOLNAR & LYON-CAEN, 1988). Thinning of the lithospheric mantle beneath the mountain range (e.g., by small-scale convection) will additionally favor extension (PLATT & ENGLAND, 1993).

Rollback and orogenic collapse are often presented as alternatives, but in the Tyrrhenian region they acted together. In general, mountain belts can be kept at high elevations by boundary compressive forces due to plate convergence; an orogenic belt located at the edge of an overriding plate, however, will be able to extend by pushing away the subducting plate hinge (LE PICHON, 1982; DEWEY, 1988). Analog experiments by FACCENNA *et alii* (1996) confirm that an overriding lithospheric plate that is thicker and more buoyant than the subducting plate exerts an additional force on the subduction hinge that increases the rollback velocity. If the subduction hinge tends to roll back on its own, extension in the overriding plate will concentrate in the regions of thicker crust and higher elevation.

A HYPOTHESIS ON THE MIGRATION OF EXTENSION IN THE TYRRHENIAN SEA

The two mechanisms of subduction hinge rollback and orogenic collapse suggest a working hypothesis for the outward migration of extension in the Tyrrhenian Sea. The extension leading to the formation of the Tyrrhenian basin started ~10 Ma in the higher elevation areas of an embryonic Apenninic-Maghrebian orogenic belt. As the subduction hinge rolled back, the Apenninic-Maghrebian accretionary wedge grew at its outer edge by adding material scraped off from the thick sedimentary covers of the Ionian Sea and of the Adria and African margins. Hence, the site of maximum elevation in the overriding plate shifted outward, which could have led to a corresponding migration of the focus of extension. The rapid Late Pleistocene

uplift of Calabria (FERRANTI *et alii*, 2006) may be an episode in this progressive shift of the maximum uplift in the Tyrrhenian domain. A related outward shift of the volcanic arc could also have played a role, increasing the local geothermal gradient and weakening the lithosphere. This working hypothesis can be tested by analog and computational geodynamic modeling.

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