Publisher: GSA
Journal: GEOL: Geology
DOI:10.1130/G46774.1

Recent inversion of the Tyrrhenian Basin

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ABSTRACT

The Tyrrhenian Basin is a region created by Neogene extensional tectonics related to slab rollback of the east-southeast–migrating Apennine subduction system, commonly believed to be actively underthrusting the Calabrian arc. A compilation of >12,000 km of

multichannel seismic profiles, much of them recently collected or reprocessed, provided closer scrutiny and the mapping of previously undetected large compressive structures along the Tyrrhenian margins. This new finding suggests that Tyrrhenian Basin extension recently ceased. The ongoing compressional reorganization of the basin indicates a change of the regional stress field in the area, confirming that slab rollback is no longer a driving mechanism for regional kinematics, now dominated by the Africa-Eurasia lithospheric collision

INTRODUCTION

The Tyrrhenian Basin is a young basin of the Mediterranean (Fig. 1A), commonly assumed to be actively opening (Malinverno and Ryan, 1986; Trua et al., 2018). It is well established that the Tyrrhenian Basin formed as a back-arc ~~(Fig. 1)~~ within a preexisting microcontinent, the Calabrian-Sardinia-Corsica microplate (Alvarez et al., 1974) (Fig. 1C). The lithospheric thinning of the Tyrrhenian region started in the late Miocene, ca. 9–10 Ma (Kastens et al., 1988), and was caused by the east-southeast to southeast retreat of the Apennine subduction system (Malinverno and Ryan, 1986; Doglioni et al., 1997). Continental breakup (Prada et al., 2016) of Corsica-Sardinia from Calabria (Fig. 1D) just after the Messinian (5 Ma) was followed by mantle exhumation in the Magnaghi-Vavilov Basin and, soon after, by the same process in its**[[Clarify what “its” refers to]]** easternmost portion (Figs. 1E, 1F), in the Marsili Basin (Prada et al., 2018). As suggested by the age of the sedimentary cover (Kastens et al., 1988), the mantle unroofing terminated ca. 2 Ma in the Magnaghi-Vavilov Basin and between 1.8 Ma (oldest age of sediments sampled by the International Ocean Drilling Program**[[References?]]**) and 0.8 Ma (age of the volcano) in the Marsili Basin, leading to the formation, from west to east, of deep abyssal plains. These basins are now floored mainly by partially serpentinized mantle and by the homonymous Magnaghi, Vavilov, and Marsili volcanoes at their centers (Figs. 1E, 1F).

Notwithstanding all of the published evidence of past widespread extensional tectonics (Fabbri et al., 1981; Kastens et al., 1988), scattered and local evidence of active compressive structures was described in the Tyrrhenian Basin (Trincardi and Zitellini, 1987; Bigi et al., 1991; Milia et al., 2017), as well as the occurrence of compressive crustal seismicity north of Sicily, offshore Sardinia-Corsica and Lazio-Campania, Italy (Vannucci et al., 2004; Presti et al., 2013). To check the presence of these structures, we reprocessed 8000 km of the Crosta Profonda (CROP) data set of deep-penetrating multichannel seismic (MCS) reflection profiles collected in the late 1980s and 1990s to investigate the crustal structure around Italy**[[References?]]**. This data set was integrated with data from two**[[Three appear to be listed?]]** recent MCS reflection surveys (MEDOC [MEDiterráneo Occidental] in 2010, CHIANTI in 2015, and ISTEGE in 2010**[[Conducted by whom? References?]]**) (Fig. 1B), vintage single-channel data from the 1970s and 1980s (Fig. DR1 in the GSA Data Repository[1]), and multibeam bathymetry covering the basin**[[References?]]** (Figs. 1A and 1B). The seismic images do not show evidence of large active normal faulting that may support current extension of the Tyrrhenian Basin, as commonly assumed, but rather display abundant evidence of previously unrecognized active contractional structures. The new data detected and mapped active large-scale compressive tectonic structures along a large sector of the Tyrrhenian margin of Italy. We describe them and discuss the kinematic and geodynamic implications, providing new constraints for unacknowledged ongoing crustal shortening of the entire basin.

METHODS

The data set consists of MCS reflection lines collected on behalf of the Italian CROP project (http://www.crop.cnr.it), which was funded by the Italian National Research Council and by the two Italian leading energy companies (~~EN~~I and ENEL) to explore the crust and upper mantle of Italy and surrounding seas. This project was carried out between 1986 and 1999 in coordination with the French ECORS-CROP, the Swiss NRP20, and the Austrian-German TRANSALP projects **[[spell out the acronyms for these projects]]**. At sea, the MCS lines were acquired using an airgun array as seismic source with a volume of ~4900 c.i.**[[cubic inches? Convert to SI units]]** and shots recorded with a 4500-m-long streamer; see Scrocca et al. (2003) for detailed acquisition parameters. The stack version was published in the form of an atlas in 2003 (http://www.videpi.com/videpi/crop/crop.asp). We carried out the complete reprocessing ~~to~~ the time migration**[[Unclear what this means – reword]]** of the subse~~t of~~ CROP data located in the Tyrrhenian Basin. The processing was done at the Institute of Marine Science (ISMAR) in Bologna, Italy. The processing sequence was: decimation from 2 ms to 4 ms, common-depth-point gathering, spiking deconvolution, velocity analysis every 2.5 km, normal move-out, correction, CDP**[[Spell out]]** staking, spherical,**[[Delete comma? (Otherwise, “spherical” seems to lack an associated noun)]]** divergence correction, finite-difference wave-equation migration using stacking, velocities with reduction of 10%**[[Unclear how this describes a step in the sequence – reword]]**. The CROP data set was supplemented with the MEDOC MCS lines processed at the Institute of Marine Sciences of the Spanish National Research Council in Barcelona, Spain (Prada et al., 2014) and at GEOMAR in Kiel, Germany (Moeller et al., 2014) (Fig. 1B), with the ISTEGE MCS lines processed at the National Institute of Oceanography and Experimental Geophysics (OGS) in Trieste, Italy (Loreto et al., 2013), and with a large collection of single-channel, high-resolution, 30 kJ sparker profiles.**[[What about the CHIANTI survey mentioned above?]]**

RESULTS

We found different types of large structures indicating compression, including folds, anticlines growing above reverse faults, inversion of preexisting normal faults, and compressive reactivation of reverse faults (Fig. 2; Figs. DR2–DR5). Based on stratigraphy, we distinguish three episodes of shortening: two older and currently inactive episodes related to subduction dynamics, and one widespread phase of active basin inversion:

(1) The oldest, pre-rift compressive structures, detected only in the northwestern continental margin of Sicily (Fig. 2A) and in the northern Tyrrhenian Basin (Fig. DR2). These structures belong to the fold-and-thrust belt units shortened from the Oligocene to the middle Miocene during the rotation of the Sardinia-Corsica-Calabria microplate (Sartori et al., 2001). They remain largely undisturbed by the successive episode of extension because they are located in areas affected by minor crustal thinning, i.e., along the northern Tyrrhenian and northern Sicilian margins.

(2) Compressive structures active only during, or soon after, rifting and mantle exhumation that occurred in the Marsili Basin. These structures are present along the western side of the Paola Basin (Fig. 2B), located in the easternmost Tyrrhenian just

west of Calabria, and are sealed by a package of undeformed sediments lapping on either flank of the basin (Fig. 2B; Fig. DR3). The folds formed during the early Pleistocene, ca. 1.8–2.5 Ma (Argnani and Trincardi, 1988), or later (Loreto et al., 2013), probably during the latest stage of the eastward migration of the Calabrian subduction system.

(3) Present-day active compressional structures including folding (Fig. 2A) and rupture of the sedimentary sequence reaching the seafloor (Figs. 2C and 2D), supporting ongoing contractional processes. Several active structures were mapped along the northwestern Sicilian margin and along the western peninsular margin (Figs. DR4, DR5).

[[Is this paragraph part of episode 3? If so, combine with that list item]]Along the northwestern Sicilian margin, the inversion of rifting-related basins occurs mostly by reactivation in compression of the tectonic structures (Fig. 2A; Fig. DR4) formed during the rotation of Sardinia-Corsica-Calabria. Along this margin, shortening is not focused on individual large structures, but rather distributed on fault sets (Fig. 2A; Fig. DR4). Along the east Tyrrhenian margin, tectonic deformation is mostly associated to transpressive reactivation (Figs. 2C, 2B) or inversion of preexisting, northwest-southeast–trending (see also Milia et al., 2017) and west-northwest–trending normal faults (Fig. 2D; Fig. DR3) along the Latium-Campanian margin (Fig. 1B). Additional evidence of tectonic inversion in this region is found in the southwest offshore of Naples (Fig. 2E) and along the western side of the Palmarola Basin (Fig. DR5). In these two areas, the uplift of one of the flanks of the basin is recorded by the displacement of a pre-compression onlapping sedimentary sequence.

DISCUSSIONS AND CONCLUSIONS

[[This paragraph is very long – can it be broken into multiple paragraphs?]]To frame these observations in a coherent geodynamic context, we take into account the active Eurasia-Africa plate convergence during the opening of the Tyrrhenian. Since the onset of the rifting in the Tyrrhenian Basin ca. 9–10 Ma (Kastens et al., 1988), the trench of the Calabrian arc retreated at a rate of up to 60 km/m.y. (Faccenna et al., 2001) while the regional Eurasia-Africa plate convergence rate in the same period was only ~5 km/m.y. (Nocquet, 2012). Moreover, trench retreat caused a focused lithospheric deformation with the formation of the Tyrrhenian Basin, while the strain generated by the Eurasia-Africa plate convergence was most likely taken up in a much wider area, spanning the whole Apennine system from Sicily to the Alps (Fig. 1A). This implies that during the Tyrrhenian opening, the contractional effect of plate convergence was hardly detectable on local stresses, becoming instead apparent when the Tyrrhenian opening slowed or stopped. A significant slowdown of the subduction process is suggested by the infrequent, mostly strike-slip (Pondrelli et al., 2011) seismicity underneath the Ionian accretionary wedge and by a >1 km Pleistocene uplift of Calabria (Westaway, 1993). In contrast, the active (Argnani and Savelli, 1999; Trua et al., 2018) calc-alkaline Aeolian volcanic arc (AVA in Fig. 1B) and the inferred (Kastens et al., 1988) seafloor spreading–like accretion at the Marsili Basin led to the proposition of an actively moving, but strongly locked subduction fault plane (Gutscher et al., 2006). This view is challenged by the recent discovery of mantle exhumation in place of seafloor spreading (Prada et al., 2016) in the Vavilov Basin. The Vavilov Seamount itself is built as a fissural volcano, as already pointed out by Robin et al. (1987), directly above exhumed mantle, which is covered by undisturbed sediments at least ~2 m.y. old (Kastens et al., 1988). In the Vavilov Basin, extension halted after mantle exhumation, and the same process seems to have occurred in the Marsili Basin (Prada et al., 2018) where the basement is now covered by a sequence of undisturbed sediments as old as ca. 1.8 Ma, ruling out currently active seafloor spreading. In the last decade, the strain and stress regime in Italy has been assessed from focal mechanisms, borehole breakouts, and overcoring data. These data support a present-day compressive to transpressive stress regime affecting the Tyrrhenian (Pondrelli and Morelli, 2008; Olaiz et al., 2009). Devoti et al. (2008) analyzed GPS data collected along the Tyrrhenian coast of Italy and described an "unexpected" southeast-nothwest velocity field with respect to stable Eurasia (Fig. 1A**[[Devoti et al. are not cited in the Fig. 1A caption – please check]]**~~)~~, revealing a southeast-to-northwest compressional component. Also, the present stress field in southern Italy, modeled by Barba et al. (2010) by considering borehole breakouts along with GPS and earthquake data, supports a strike-slip to compressional regime along the Tyrrhenian coasts. Finally, evidence of compressional deformation are recorded by early Pliocene to Quaternary deposits in northeastern Corsica (Fellin et al., 2005) and are indicated by compressive earthquakes in the northern Tyrrhenian Basin (Vannucci et al., 2004; Chiarabba et al., 2015). The results of this research together with the observations presented here imply that, at present, only one plate-driving mechanism is active: the lithospheric collision between Eurasia and Africa in the central Mediterranean. Once the southeastward migration of the Calabrian arc stopped in the Pleistocene, when the exhumation of the mantle terminated in the Marsili Basin, a radical change may have occurred in the stress field, which can account for the moderate ongoing deformation north of Sicily and the more developed deformation of the eastern Tyrrhenian margin (Fig. 1A).

The present-day compressional vector between Eurasia and Africa is almost perpendicular to the strike of the northern Sicilian margin, while it is almost parallel to the northwest-southeast strike of the faults located in the Tyrrhenian margin of the Italian Peninsula. In Figure 3, we present a schematic model of the tectonic inversion occurring in the Latium-Campanian margin. During the Tortonian to middle Pliocene opening of Vavilov Basin, several normal faults trending northwest-southeast developed in this area (Bigi et al., 1991), implying a stress vector with the σ_1 component directed along the vertical and the σ_3 component parallel to the extension direction (Fig. 3B). The present-day main stress vector σ_1 is oriented NNW-SSE due to the prevailing Europe-Africa convergence. This implies that the inherited normal faults are reactivated (Sibson, 1995) under a transpressive regime as dextral strike-slip faults, with diffuse uplift and folding (Figs. 2D and 3C). The same process does not occur in the northern Sicilian margin, where the stress vector is almost perpendicular to the east-west–trending structures, rendering their inversion more difficult**[[In what repect?]]** and less developed. The proposed new tectonic framework is regionally widespread: the effect of the Eurasia-Africa lithospheric collision in the realm of the Oligocene-Miocene western Mediterranean back-arc basins has been reported in the Ligurian Sea (Larroque et al., 2016) and along the coasts and continental margin of Algeria (Kherroubi et al., 2009) with the occurrence of compressive earthquakes and the presence of active tectonic structures. Also, in the Alboran Sea, which formed in response of the westward migration of the Gibraltar arc subduction system, extension no longer active (Zitellini et al., 2009) and the strain caused by Eurasia-Africa convergence is also observed along oblique-slip NNE- and ESE-trending transpressive faults that crosscut the Alboran Basin (Martínez-García et al., 2013) as well as in the Algero-Balearic Basin (Giaconia et al., 2015). The regional tectonic inversion of the Tyrrhenian Basin along with the evidence of compressive and/or transpressive deformation in the Ligurian and Alboran Seas shows that the entire central Mediterranean is presently affected by intraplate deformation driven by the Africa-Eurasia collision.

ACKNOWELDGMENTS

We thank Enrico Bonatti for reviewing of the manuscript and for his useful suggestions. A special thanks are due to Michael Marani for English revision and fruitful advice. We thank Camilla Palmiotto and Flavio Priore for their support during MEDOC data acquisition. We also thank the reviewers for comments that helped us to significantly improve the manuscript.**[[Would you like to name the reviewers, or state that they were anonymous?]]** We acknowledge the project FRAME (ref. CTM2015-71766-R) funded by the Spanish Ministry of Science, Innovation, and Universities for supporting the work in the Tyrrhenian Sea. We also thank the CROP database (http://www.crop.cnr.it) for providing the seismic data used in our work. This is ISMAR contribution number 2014.

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FIGURE CAPTIONS

Figure 1. Structural setting and location map of study area. (A) Geodynamic sketch map of the central Mediterranean. Base map is from EMODnet bathymetry portal (EMODnet Consortium, 2016: EMODnet Digital Bathymetry, http://doi.org/10.12770/c7b53704-4721-b1a3-4ec60c87238**[[Is this intended to be in the reference list? DOI appears to be invalid]]**); main structures are as synthetized by Bigi et al. (1991). Instrumental seismicity (yellow dots) <30 km depth is from EMSC**[[Spell out]]**

(http://www.seismicportal.eu/). Thick arrows are displacement vectors between Africa with respect to **[[and?]]** Eurasia: green are from GPS measurements (Serpelloni et al., 2007); white and black**[[Explain the difference between the white and black arrows]]** are GPS residual velocity (Serpelloni et al., 2005); and red are GPS measurements from ~~free accessible website (~~https://www.unavco.org~~)~~**[[Provide a more specific URL to the data used]]**. Med—Mediterranean. (B) Location map of reprocessed multichannel seismic reflection data set (black lines). Isobaths ~~are~~ downloaded from EMODnet bathymetry portal **[[What contour interval?]]**. Compressive focal mechanisms (CFM) and compressive earthquakes (red stars) are modified by**[[from?]]** Vannucci et al. (2004) and Presti et al. (2013). Black thick segments mark seismic profiles shown in Figure 2 (Figs. 2A–2E) and in the Data Repository (Figs. DR2–DR5 [see footnote 1]). (C–G) Cartoons of southeastward Apennines system migration, modified from Gvirtzman and Nur (2001) and Reitz and Seeber (2012).**[[Explain the light blue and dark blue regions and the associated arrows** Sa, Sard—Sardinia; Co—Corsica; Ca—Calabria; Si—Sicily; Ma—Magnaghi **[[Basin?]]**; V—Vavilov **[[Basin?]]**; M—Marsili **[[Basin?]]**; AVA—Aeolian volcanic arc.

[[In the figure, panel A, include “°N” and “°E” on latitude/longitude; capitalize instances of “Basin”; change “ea” to “Sea”. In panel B, include a north arrow; label bathymetric contours with depths; in the legend, correct the spelling of “Reverse”; change instances of “faults” to “fault”. In panel G, should “Compressions” be “Compressive structures”?]]

Figure 2. Multichannel seismic (MCS) profiles in the Tyrrhenian Basin showing compressional structures; see Figure 1B for location.**[[Explain the values shown on the horizontal axes]]** (A) Anticline-syncline structures buried below well-stratified sediments detected to the northwest of Sicily, presently reactivated in compression. (B) Inverted sediments of the Paola Basin, located offshore of the western Calabria region. MES—Messinian erosional surface. (C) Sirene Seamount located offshore of the Campanian margin, showing compressive and/or transpressive structure growing in the middle of the former extensional sedimentary basin. (D) Inverted sedimentary basin located offshore of the Lazium-Campanian margin. (E) Progressive displacement of pre-compression sedimentary sequences onlapping the western flank of the basin. TWT—two-way traveltime~~;~~ CDP—**[[common depth point?]]**.

[[In the figure, make all instances of “CROP”, “TWT”, and “CDP” uppercase; insert commas in all values 10,000 and above; include units in horizontal-axis description, if applicable; on scale bars, change comma to decimal in “2.5 km”. In panel B, capitalize “Basin”. In panel C, make instances of “compression” lowercase; spell out and capitalize “Seamount”; correct the spelling of “Buried”. In panel E, align the “18,700” value with the other axis values. Beneath panel E, capitalize Figure; correct the spelling of “exaggeration”]]

Figure 3. Fault reactivation due to stress regime changes in the Tyrrhenian Basin. (A) Topography of the Latium-Campanian margin derived from EMODnet grid data**[[Cite reference or provide URL]]**, displaying the Sirene Seamount inverted structure shown in Figure 2C. This structure has been related to stress-field reorganization due to

prevailing Africa-Eurasia plate convergence during the Pleistocene. Image shows highly selective fault reactivation during inversion. Only individual and weak segments of the normal fault system affecting the margin underwent compressional reactivation (red triangles), as observed elsewhere (Sibson, 1995).**[[Explain the color shading]]** (B) During back-arc opening of the Tyrrhenian Sea, a rift-related extensional fault system striking NW-SE generated a set of subparallel, steeply dipping normal faults perpendicular to the opening direction. Black hatched thick solid line indicates normal fault.**[[Explain "+" and "−" symbols]]** Stress-field components due to pure extensional regime are shown on horizontal (x,y) and vertical (x,z) planes. FP—fault plane. (C) Fault reactivation with transpressive regime (red triangles) due to NNW-SSE Africa-Eurasia convergence that induced diffuse uplift and basin inversion along the margin. Stress-field components on the horizontal (x,y) and vertical (x,z) planes indicate dominant strike-slip component, according to the hypothesis that reactivation of steeply dipping normal faults, not well-oriented under compression, is easier than formation of new, favorably oriented thrusts (Sibson, 1995).

[[In the figure, panel A, include a north arrow; include a scale to explain the color shading; spell out "Seamount". In panels B and C, italicize instances of "*x*", "*y*", and "*z*"]]

[1] GSA Data Repository item 2020xxx, **[[Please provide DR item title(s) and brief descriptions here]]**, is available online at http://www.geosociety.org/datarepository/2020/, or on request from editing@geosociety.org.