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Coexisting tectonic settings: the example of the southern Tyrrhenian Sea

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Abstract We performed geodetic strain rate analyses in southern Italy, using new GPS velocities. Two-dimensional strain and rotation rate fields were estimated and results show that most of the shortening is distributed in the northern Sicily offshore. Extension becomes more evident and comparable with shortening on the eastern side of the same margin, and greater in the eastern Sicily offshore. Principal shortening and extension rate axes are consistent with long-term geological features: seismic reflection profiles show both active compressive and extensional faults affecting Pleistocene strata. We show evidence for contemporaneous extension and transtension in the Cefalù Basin. Combining geodetic data and geological features point to the coexistence of independent geodynamic processes, i.e., the active E–W backarc spreading in the hangingwall of the Apennines subduction zone and shortening along the southern margin of the Tyrrhenian backarc basin operated by the NNW-motion of Africa relative to Eurasia.

Keywords Southern Tyrrhenian Sea · GPS-derived strain rate · Seismic reflection profiles · Coexisting tectonics

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Introduction

The geology and geodynamics of Sicily represent a cardinal point for the unraveling of the Mediterranean tectonics (Casero and Roure 1994; Catalano et al. 1995, 1996, 2000; Giunta et al. 2000; Monaco et al. 2002). In this article, we use this regional case study as an evidence for the coexistence in the same area of two independent geodynamic processes. A similar, albeit different, setting has been described in the Sicily Channel (Corti et al. 2006).

The offshore of northern Sicily is affected by an intense seismicity, and the available focal mechanisms (Fig. 1) (e.g., Pondrelli et al. 2006, and references therein) show the presence of two different seismogenic behaviors at shallow depth (i.e., above 30 km) west and east of the central Aeolian Islands. The boundary between these two zones is commonly identified with the northern prolongation of the Tindari-Letojanni fault system (Billi et al. 2006) toward the Aeolian Islands, where a broad belt of compressional or transpressional structures has been recognized (Argnani et al. 2007; Visini et al. 2009) in the hagingwall of the southern Tyrrhenian subduction zone (e.g., Chiarabba et al. 2008). This compressional belt has been also interpreted as the indication for the inception of a new subduction zone along the southern Tyrrhenian (Billi et al. 2007). The compressive belt in the northern offshore of Sicily appears

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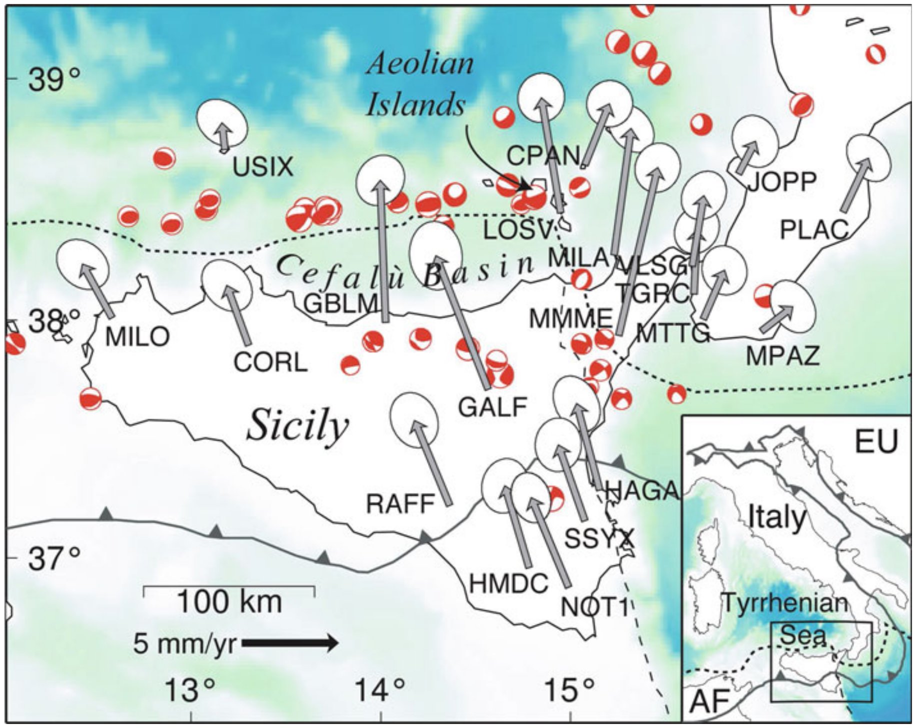

Fig. 1 GPS velocities in southern Italy relative to fixed Eurasia, with their 95% confidence level error ellipses. The *dashed line* represents the Africa-Eurasia margin, and the NW–SE *dashed* one is the Malta Escarpment, whereas the *solid line* is the external deformation front of the Apennines-Maghrebides system. Earthquake focal mechanisms are from the INGV-RCMT catalog provided by Pondrelli et al. (2006)

as the eastern prolongation of the convergence zone characterizing the northwestern Africa margin, from Morocco to Tunisia, where the margin separating continental Africa from the oceanic southwestern Mediterranean Sea has been inverted by compression during the Plio-Quaternary (Déverchère et al. 2005; Domzig, 2006; Yelles et al. 2009).

However, while in northern Sicilian offshore the compression is well established by earthquakes and folding of the Pliocene-Pleistocene successions, the oblique, E–W directed extension and transtension in the same area, is subtle and less appreciated. Along the southern border of the Tyrrhenian Sea rift, the roughly N–S convergence between Africa and Eurasia cohabits with the extension associated with the backarc spreading in the hangingwall of the Apennines subduction zone. Differential slab retreat is allowed by a major transfer zone (i.e., the Malta Escarpment), where right-lateral transtension and the Etna volcanism take place (Doglioni et al. 2001). Active shortening due to Africa and Eurasia relative motion in the Ionian accretionary prism is evident by sea-floor folding (e.g., Gutscher et al. 2006), and it has been interpreted as related to the >5 mm/a subduction rate along the Calabrian arc (Devoti et al. 2008). The southern sector of the Tyrrhenian Sea is characterized by the presence of a deep-seated tear, separating the lithosphere subducting below Sicily and Calabria (Gvirtzman and Nur 1999; Goes et al. 2005) developed in the last few million years. This geometry of the lithosphere can be also observed by the combination of geophysical and petrological modeling for the Tyrrhenian basin and surroundings (e.g., Chimera et al. 2003; Panza et al. 2007). While along the Calabrian sector the slab is continuous (Mele 1998), based on tomographic interpretation (Piromallo and Morelli 2003), along northern Sicily there are doubts about its presence. However, continental lithosphere has slower seismic velocity preventing an accurate 3D mantle tomography based on a 1D velocity model. Moreover, the weaker rheology may prevent seismicity (Carminati et al. 2002). Therefore, the deep structure of the southern Tyrrhenian Sea is not unequivocally solved.

We show here that to the west of the subduction transfer zone, the compression coexists with the extension, being the latter not a simple ancillary consequence of the compression, but the result of active extension in the Tyrrhenian backarc basin. Geodetic measurements of site displacements profoundly contributed to the understanding of tectonic processes. However, since the number of GPS stations located in Sicily and Calabria has increased with respect to previous works (e.g., Serpelloni et al. 2007, and reference therein), and a better description of the velocity distribution of the Mediterranean area is now available, in this paper, we compute a new GPS-derived strain rate field. Moreover, the upper plate deformation above a deep-seated lithospheric tear is investigated by integrating the analysis of new GPS data with the interpretation of the available seismic reflection profiles.

GPS data processing and strain rate field analysis

The GPS data processing was carried out on a more extended network composed by 12 regional clusters of about 40 stations with at least 11 common anchor sites, i.e., selected sites based on station performance and geographical distribution, used as core sites for the cluster combination (e.g., Devoti et al. 2008). The whole GPS data span a time interval of 10 years (1998–2007); nevertheless, most of the data come from the recent RING network (http://ring.gm.ingv.it) settled in Italy in the last 5 years by INGV.

We have processed the data with the Bernese Processing Engine (BPE) of the Bernese software, version 5.0 (Beutler et al. 2007) based on the double difference observables. We have estimated each daily cluster in a loosely constrained reference frame, imposing a priori uncertainties of 10 m to obtain the so-called loosely constrained solution. The daily cluster solutions are then merged into global daily solutions of the whole network applying a classical least squares approach (Bianco et al. 2003). The constraints defining the reference frame are imposed only a posteriori at the final stage of the analysis. The velocity field is estimated from the time series of the daily coordinates together with annual signals and sporadic offsets at epochs of instrumental changes, taking into account the whole covariance matrix. Then, the loosely constrained velocity field has been transformed into the ITRF2005 reference system (Altamimi et al. 2007) by applying an 8-parameter Helmert transformation (scale, translation and their derivatives) and the inner constraints to the final solution. GPS site positions and velocities with respect to the fixed Eurasia reference frame, with their 1σ uncertainties, are reported in Table 1 and Fig. 1.

Strain and rotation rate fields in southern Tyrrhenian Sea and northern Sicily were computed solving the two-dimensional velocity gradient tensor equations, with an inverse procedure, based on the standard least squares approach, using 20 GPS velocities (Table 1 and Fig. 1). Several numerical methods exist to solve velocity gradient tensor, e.g., Delaunay triangulation (Calais et al. 2002), or statistical selection of homogeneous field (Pietrantonio and Riguzzi 2004); here, we used a regularly spaced gridded interpolation, with the distance weighted approach (Shen et al. 1996; Allmendinger et al. 2007; Cardozo and Allmendinger 2009). We constructed a uniform grid (5 × 5 km) in the area of the investigations (i.e., southern Tyrrhenian Sea and surroundings), and we estimated strain and rotation rate components at the center of each cell, using all the GPS velocities. The contribution of each station is weighted by the factor $W = \exp(-d^2/2\alpha^2)$, where d is the distance between each GPS site and the center of the cell, and $\alpha = 70$ km is the damping parameter defining how the contribute of each station decays with distance from the cell center.

Results (Figs. 2 and 3) show that most of the shortening of the Africa-Eurasia relative motion is distributed in the northwestern side of Sicily, whereas the extension is greater in the northeastern side of Sicily, and becomes comparable with shortening on the eastern side of the Cefalù Basin. In Fig. 2, strain rate shortening and extension principal axes are reported on a 30 × 30 km uniform grid, whereas in Fig. 3 shortening and extension grid plots are provided on a 5 × 5 km uniform grid with their associated errors. The strain rate field shows a maximum value of 34 nstrain/a and an average error of 7 nstrain/a for the shortening, and a maximum value of 28 nstrain/a and an average error of 10 nstrain/a for the extension. Where shortening and extension become comparable (i.e., eastern side of the Cefalù Basin), a value of ~11 nstrain/a is computed.

Also, 2-D dilatation field computed on a regular grid 5 × 5 km (Fig. 2) records a similar pattern, with negative values (shortening) in the northwestern area of Sicily close to the Ustica island, and positive values (extension) in the northeastern and southeastern ones, respectively, ranging from −22 to 21 nstrain/a with a mean error of 17 nstrain/a.

Moreover, where shortening and extension have mostly a similar order of magnitude, two rotation rate fields can be detected (Fig. 2, upper-right inset), CCW in the northwestern side of Sicily (maximum value of 3.2 × 10^7 deg/a), and CW in the northeastern one (maximum value of

Table 1 GPS site positions, longitude (Lon) and latitude (Lat) are in degrees. East (E) and North (N) velocity components and their associated 1σ uncertainties, (±E and ±N) are in units of mma^{-1}. Corr is the correlation between the East and North velocity components, and Δt is the time span in units of annum

Site	Lon	Lat	E	N	±E	±N	Corr	Δt
CPAN	15.077	38.642	1.28	3.19	0.48	0.49	0.01	3.6
CORL	13.303	37.894	−1.13	3.11	0.53	0.54	−0.27	1.8
GBLM	14.026	37.990	−0.27	7.39	0.51	0.53	0.12	4.8
GALF	14.566	37.710	−2.72	6.95	0.56	0.72	−0.06	1.2
HAGA	15.155	37.285	−1.20	4.50	0.49	0.59	−0.28	1.8
HMDC	14.783	36.959	−1.26	4.26	0.49	0.57	0.08	2.5
JOPP	15.885	38.606	0.88	1.69	0.49	0.55	−0.14	1.4
LOSV	14.948	38.445	−1.00	5.99	0.49	0.52	0.03	2.0
MILA	15.230	38.270	0.88	6.59	0.48	0.51	−0.29	2.1
MILO	12.584	38.008	−1.53	2.78	0.55	0.53	−0.24	6.0
MMME	15.254	37.935	2.03	8.73	0.48	0.52	0.07	2.7
MPAZ	16.006	37.953	1.64	1.28	0.48	0.55	−0.30	1.2
MTTG	15.699	38.003	1.11	2.54	0.47	0.52	−0.07	2.0
NOT1	14.989	36.876	−1.95	4.67	0.49	0.57	−0.16	7.2
PLAC	16.438	38.449	1.32	2.80	0.47	0.49	−0.31	2.3
RAFF	14.362	37.222	−1.83	4.43	0.51	0.58	−0.16	1.0
SSYX	15.076	37.157	−1.38	3.95	0.49	0.57	0.02	2.6
TGRC	15.651	38.108	0.15	3.34	0.47	0.50	0.14	7.0
USIX	13.179	38.707	−0.15	1.38	0.54	0.50	−0.25	2.2
VLSG	15.641	38.224	0.61	3.68	0.47	0.51	0.17	2.5

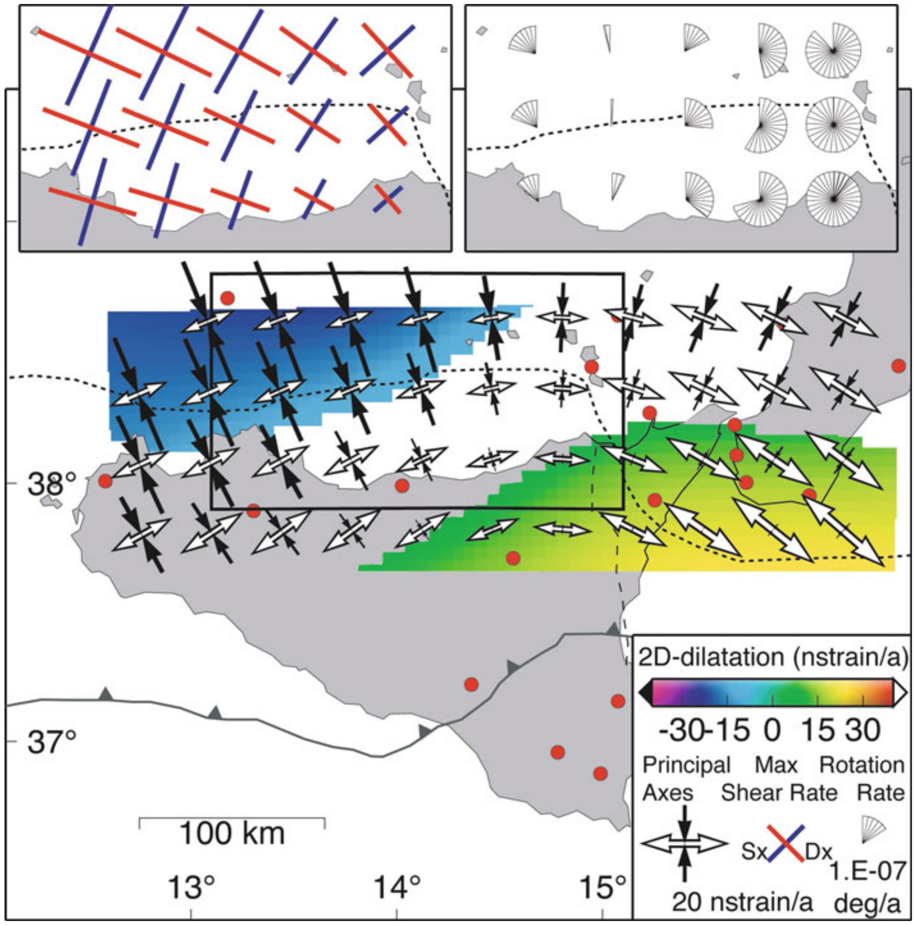

Fig. 2 GPS strain rate field in Sicily reported on a regularly spaced grid (30 × 30 km). *Black* and *white arrows* represent shortening and extension principal axes respectively. *Black rectangle* shows the area where also maximum shear strain—*right*-lateral (*red*) and *left*-lateral (*blue*) planes—and rotation rates were computed (*upper-left* and *upper-right* inset, respectively). Note the variation of rotation rate, from counter-clockwise (CCW) to clockwise (CW), in the western border of the Cafalù Basin. Colors in the plot are the magnitude of two-dilatation rate, computed on regularly spaced grid (5 × 5 km). Negative and positive values represent shortening and extension, respectively. There are *blank boxes* when the magnitude is lower than 1σ error. *Red dots* are the GPS stations of Table 1

9.2×10^{7} deg/a), respectively, having a mean error of 1.3×10^{7} deg/a. Also, maximum shear strain (Fig. 2, upper-left inset) decreases NW–SE from a value of 45 nstrain/a to a value of 13 nstrain/a with a mean error of 18 nstrain/a.

Coexisting tectonic processes in the southern Tyrrhenian Sea

The re-interpretation of seismic reflection profiles available in the southern Tyrrhenian area provides some hints on the structural setting, active tectonic processes, and geodynamic framework of this complex region. Following the development of the Northern Sicilian Maghrebian Chain in Late Oligocene-Middle Miocene (Roure et al. 1990, and references therein; Pepe et al. 2000, 2005, and references therein), the inner northern portion of this chain, corresponding to the present-day Northern Sicilian margin, was affected by the onset of backarc extensional tectonics. Two main fault systems could be recognized, the first is mainly NE-SW oriented, representing the master faults of the late Miocene rifting phase, while the second one is WNW-ESE trending and can be inferred as the correlated left-lateral transfer faults.

After a period of relative tectonic quiescence in the early Pliocene, since late Pliocene and throughout all the Quaternary sediments, the seismic reflection profiles document the presence of a widespread tectonic reactivation, or positive inversion, of previously generated fault systems. Growth strata, tilted onlaps and anomalous thickness of the Plio-Pleistocene units have been detected associated with several structural highs, and they are mainly NE-SW trending with an en-échelon configuration. Tectonic reactivations have been also identified along the WNW-ESE fault systems while typical examples of positive inversion have been recognized only where fault segments rotate toward an E–W orientation.

Based on the above evidence, a significant right-lateral transpressional component along the reactivated faults could be also assumed, and a roughly NNW-SSE-oriented compression may be speculated in agreement with the present-day NW–SE convergence between Africa and Eurasia of a few mm/a (e.g., Jenny et al. 2006, and references therein), which is absorbed along the southern Tyrrhenian belt. For instance, the reprocessing and interpretation of the

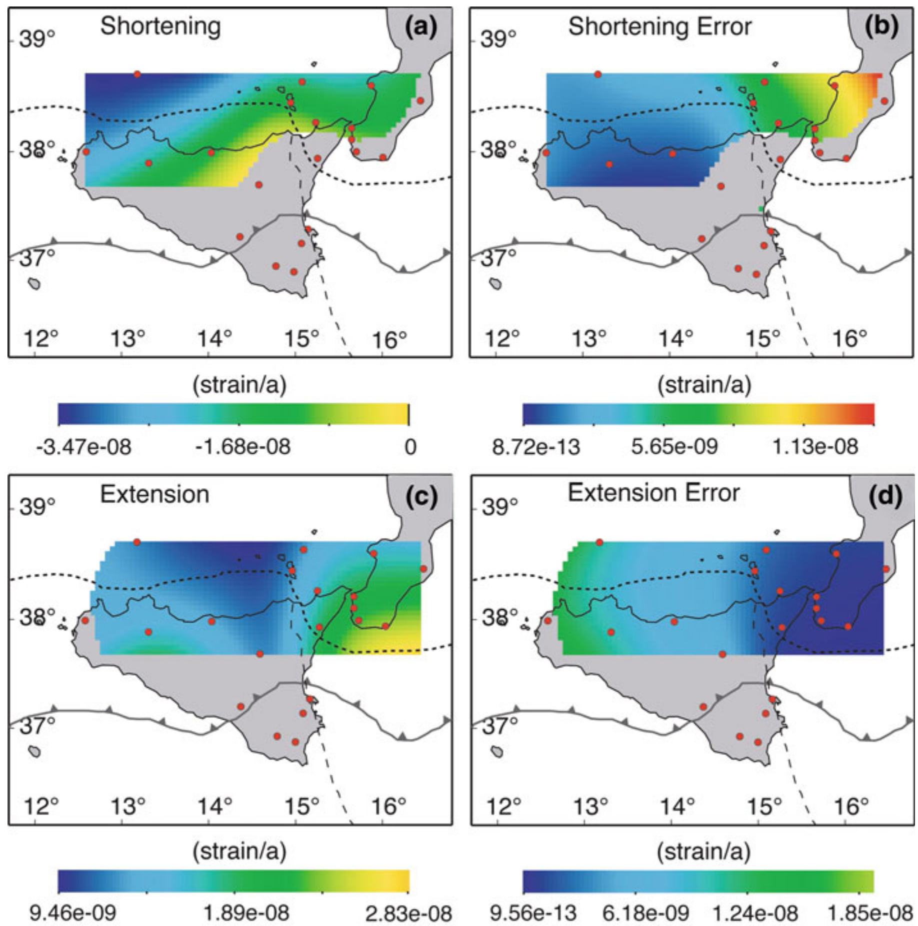

Fig. 3 (**a**) Shortening and (**c**) extension distribution on a 5 × 5 km uniform grid with their associated errors, (**b**) and (**d**), respectively. The strain rate field shows a maximum value of 34 nstrain/a and an average error of 7 nstrain/a for the shortening, and a maximum value of 28 nstrain/a and an average error of 10 nstrain/a for the extension. Where shortening and extension become comparable (i.e., eastern side of the Cefalù Basin), a value of ~11 nstrain/a is computed. There are *blank boxes* when the magnitude is lower than 1σ error. *Red dots* are the GPS stations of Table 1

multichannel seismic reflection section CROP M6A (Scrocca et al. 2006, Fig. 4) show the thrusts and transpressive faults presently shortening the southern Tyrrhenian Sea, with which the aftershocks of the September 2002 seismic sequence can be associated.

Moreover, evidence of extensional faults affecting Pleistocene strata and deforming the seafloor have been also recognized in the eastern sector of the Cefalù Basin on both NE-SW and W-E trending faults, by the interpretation of the section of the single-channel "Sparker" profile BC10 (Fig. 5). Single-channel "Sparker" profiles (BC and SS campaigns) were acquired during the 1970s by the italian "Bacini Sedimentari" team (1980), within the framework of the "Progetto Finalizzato Oceanografia e Fondi Marini" funded by the Italian National Research Council (CNR).

These old data are of quite good quality and provide a pretty homogeneous coverage across the study area. Although their shallow penetration does not permit to resolve the fault geometry at depth, these data allow a detailed analysis of deformations affecting Late Miocene-Pleistocene deposits. The goodness of the data can be shown in Fig. 5, where multiples are not prevalent, and they can be only recognized from 0 to 1 s TWT, at shot point 24, typical of "single-fold" Sparker reflection data.

This evidence is in good agreement with the present-day extension in the northeastern side of the study area revealed by GPS velocity vectors (e.g., Fig. 1), showing a larger E-ward component of sites located in Calabria with respect to sites located either in northern Sicily or in the Ustica-Aeolian islands. These trends are also well described by strain rate field obtained in the previous section, therefore suggesting that the two independent mechanisms might coexist together in the southern Tyrrhenian Sea, i.e., the NNW-SSE Africa-Eurasia convergence and the E–W extension associated with the Apennines subduction backarc spreading (Fig. 6).

Conclusions

Tectonic settings are paradigmatically considered as singularly representing a given area. In this paper, we have described how, in the southern Tyrrhenian Sea, two different geodynamic settings may coexist in the same area.

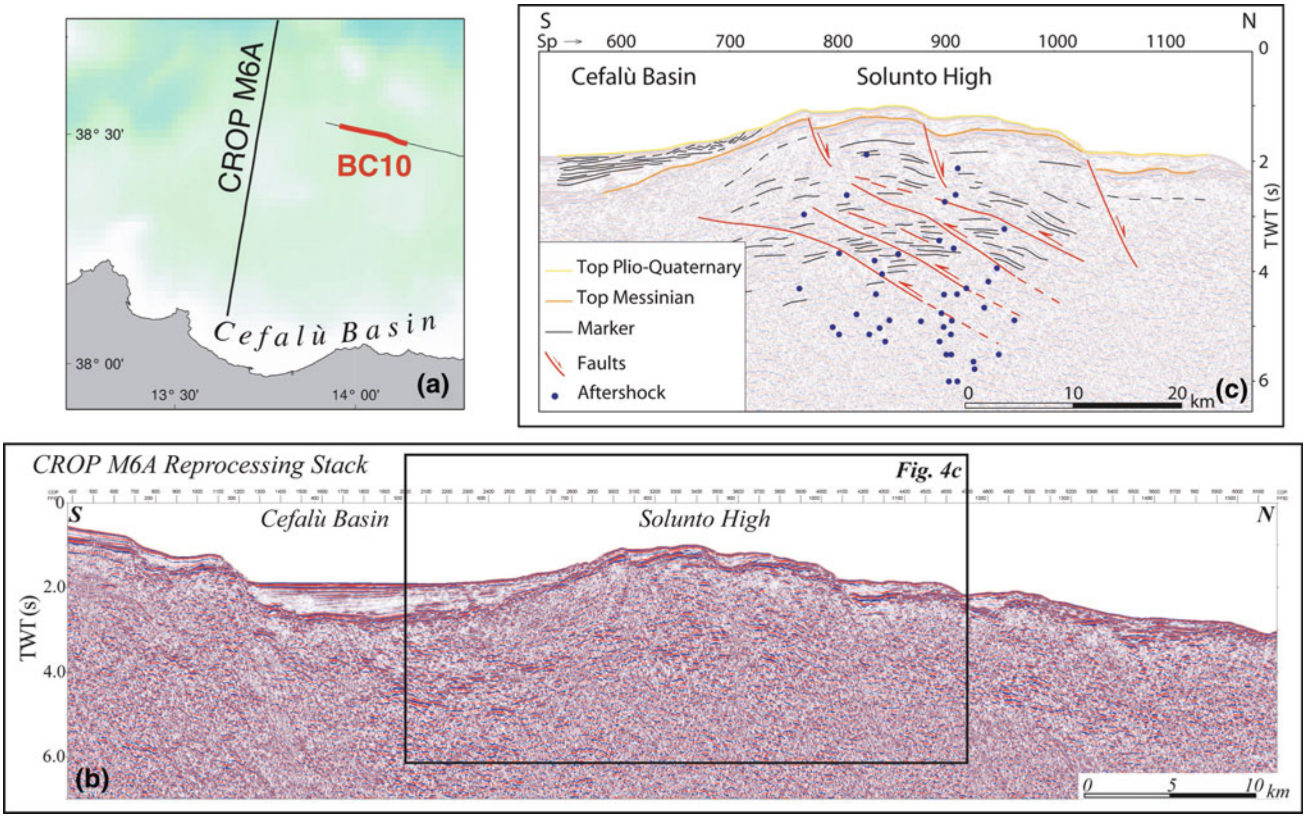

Fig. 4 **a** Location of the CROP M6A multichannel seismic profile (*thick black line*). **b** Reprocessed CROP M6A cross-section and **c** interpretation of the Solunto High, in the northern side of the Cefalù Basin. The relocated aftershocks of the September 2002 seismic sequence (Scrocca et al. 2006) could be associated with the reactivation of inherited thrust structures, which were likely generated during the building of the northern Sicilian Maghrebian Chain. However, deeper N-verging thrust planes are also expected. The *thin black line* in (**a**) is the single-channel "Sparker" profile BC10, and the *red* section is reported and interpreted in Fig. 5

This interpretation is based on new geodetic data and computed GPS-derived strain rate field that are consistent with long-term geological features, obtained by the re-interpretation of the available seismic reflection profiles.

The shortening produced by the Africa-Eurasia NW—directed relative motion is combined with the faster retreat of the Ionian segment of the Apennines subduction zone relative to Sicily and Sardinia, that requires a deep-seated lithospheric tear, expressed by right-lateral transtension along the Malta escarpment, and its northward prolongation in the western sector of the Peloritani mountains in the NE Sicily (Fig. 6). It can be inferred that E–W left-lateral transtensional faults allowed the fast opening of the Vavilov basin during early Pliocene times. To the south, the Apennines accretionary prism in Sicily was characterized by right-lateral transpression (Pepe et al. 2005).

The later tectonic evolution is characterized by a widespread compressional reactivation of the pre-existing normal or transtensional fault network of the southern Tyrrhenian backarc basin. The shortening was gradually decreasing along the southern Sicily accretionary prism, and the Africa-Eurasia convergence was possibly transferred to the north, along the southern Tyrrhenian basin. There may have focused the strain due to the newly formed passive margin of the backarc basin, containing a major lithospheric discontinuity, which separates to the south the continental lithosphere of Sicily from the oceanic lithosphere of the Tyrrhenian basin to the north. The available evidences provided by seismic reflection and GPS data suggest that this transition does not occur along a well-defined narrow tectonic boundary but it is rather distributed over a relatively wide zone in the upper plate.

Therefore, the results of our analysis support the coexistence in this zone of two different tectonic processes (Fig. 7), (i) the compression related to the convergent plate kinematics and (ii) the far field effect of the backarc extension related to the slowed but likely still active subduction of the Ionian lithosphere below the Calabrian arc. This coexistence, suggested by strain rate regime, could be correlated with the present three-dimensional geodynamic geometry in the southern Tyrrhenian Sea, also obtained by the mean S-wave velocity in the crust and the upper

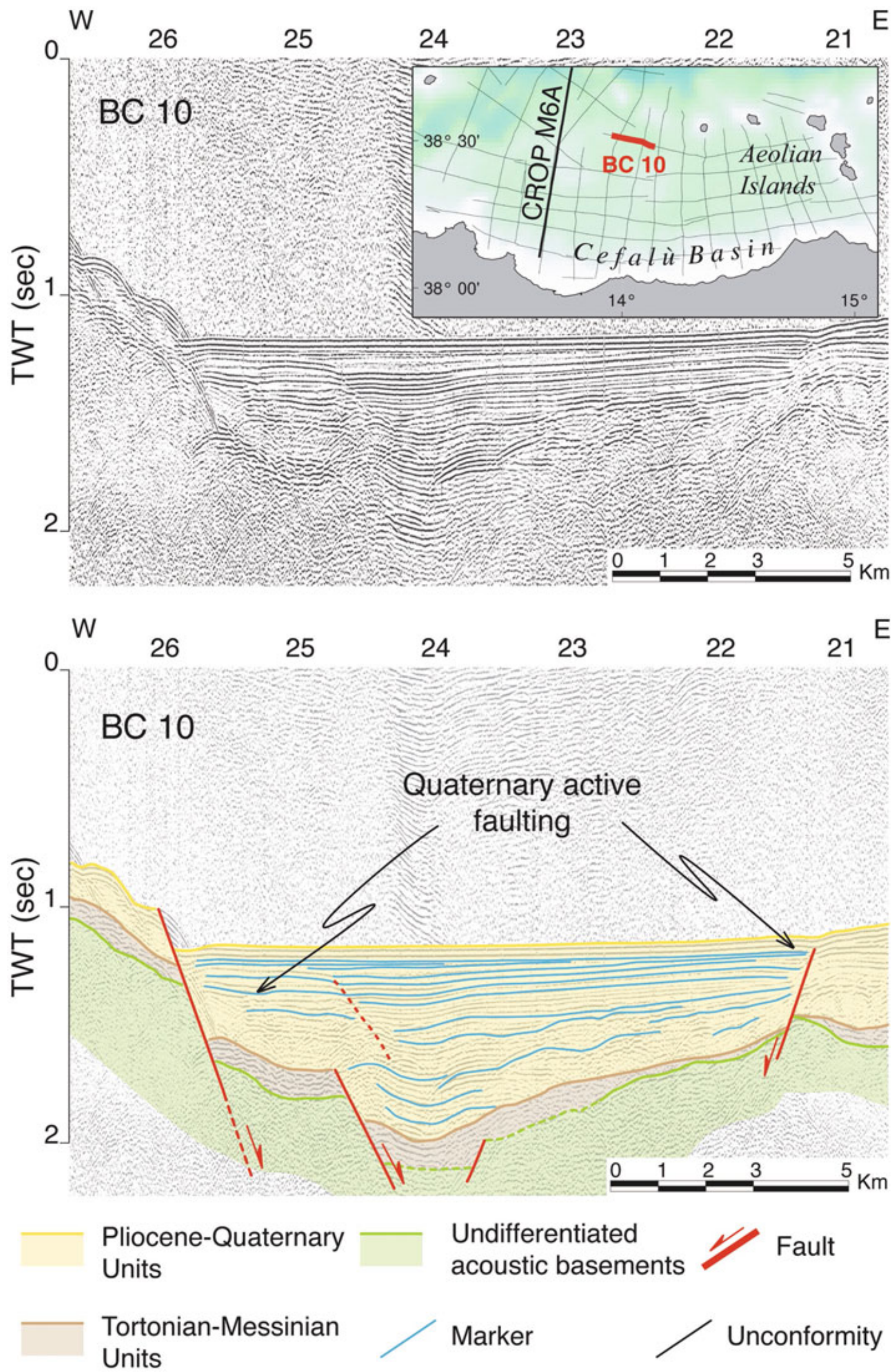

Fig. 5 Section of the single-channel "Sparker" profile BC10 (location in the *inset*) acquired in southern Tyrrhenian Sea in the western sector of the Cefalù Basin within the framework of the "Progetto Finalizzato Oceanografia e Fondi Marini" funded by the Italian National Research Council (CNR). Interpretation shows evidence of extensional faults affecting Pleistocene strata and deforming the seafloor. *Thin black lines* in the *inset* are all the single-channel "Sparker" BC profiles. The *thick black line* is the CROP M6A multichannel seismic profile of the Fig. 4

mantle, for that sector (e.g., Panza et al. 2007). Moreover, the recent identification of a link between volcanic eruptions and seismic events in this area (Walter et al. 2009) corroborates the coexisting geodynamics and it may have lasted for at least the Pleistocene and possibly also for part of the upper Pliocene. The southern arm of the Apennines subduction and related accretionary prism are displaced northward in Sicily, due to the convergence between Africa and Europe. However, this sort of indenter occurred while the Tyrrhenian basin was and is still opening in the west to east direction (Fig. 7). A similar pattern seems to have occurred in the southern Caribbean Sea, where the northward motion of South America associated with its clockwise rotation deformed and pushed to the north the southern side of the Caribbean backarc and accretionary prism, while the associated Barbados subduction was, and still is, eastward retreating.

The concurrence of more than one geodynamic setting in the same area could suggest the idea that plate

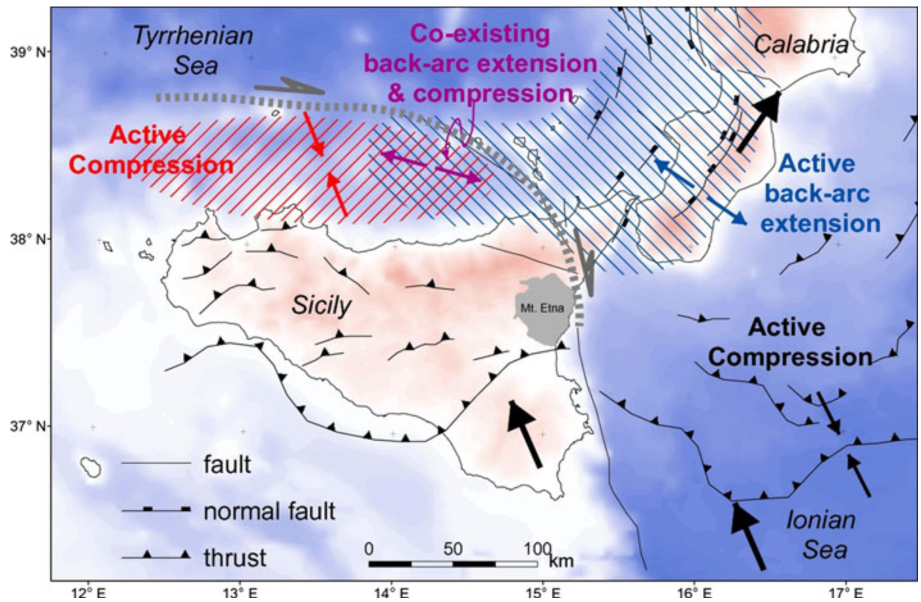

Fig. 6 Coexisting geodynamic settings in the southern Tyrrhenian Sea. The shortening associated with the Africa-Eurasia relative motion is combined with the SE-ward retreat of the Ionian segment of the Apennines subduction and the contemporaneous Tyrrhenian backarc stretching. *Gray arrows* represent the lithospheric tear, and *large black arrows* show general direction of motions (not in scale), based on GPS velocities relative to Eurasia

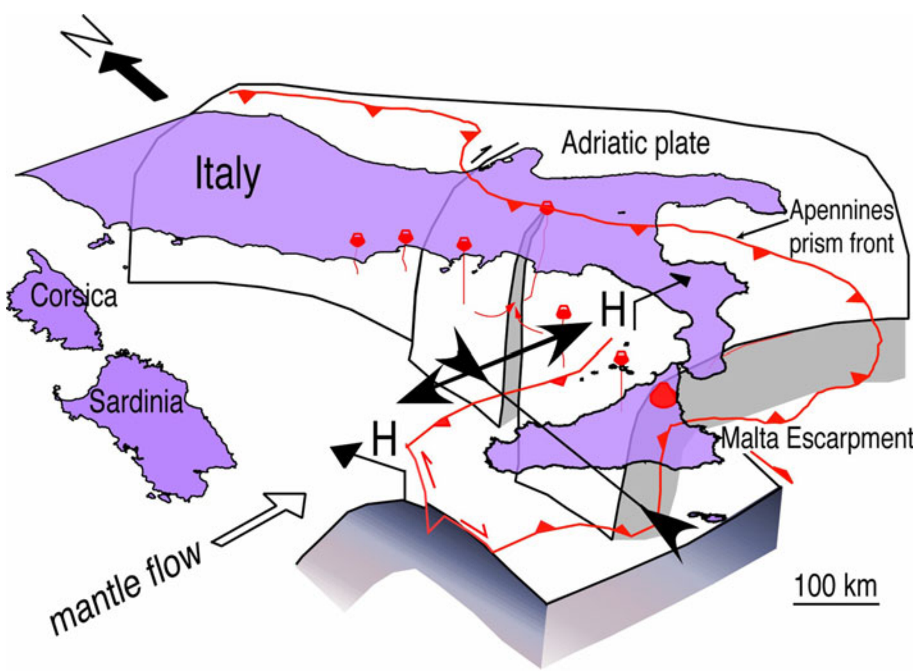

Fig. 7 In a simplified sketch, the Apennines subduction hinge *H* is retreating relative to Sardinia, whereas *H* in Sicily is moving toward Sardinia. This kinematic frame predicts a 3D coexistence in the southern Tyrrhenian basin of E–W extension (the rift of the backarc basin), and about NNW-SSE convergence in Sicily and its northern offshore. The compression generated a pop-up limiting to the north and to the south Sicily. This conjugate thrust system disappears eastward of the Malta Escarpment (and its northern prolongation), which allows faster SE-ward retreat of the Calabrian slab with respect to the Sicilian lithosphere. The N–S convergence of Africa and the Sicilian lithosphere determines a sort of indenter into the Tyrrhenian Sea, deforming and pushing N-ward the southern arm of the Apennines arc and the associated backarc basin

boundaries may be passive features, and they could not substantially drive plate tectonics (Doglioni et al. 2007; Cuffaro et al. 2010).

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