



Marsili and Cefalù basins: The evolution of a rift system in the southern Tyrrhenian Sea (Central Mediterranean)

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ABSTRACT

The Marsili Basin (in the southern Tyrrhenian Sea), whose mode of extension is still a controversial issue, is the youngest bathyal basin of the Central Mediterranean. A thin sedimentary cover in the basin permits to image basement fabric and structure by swath mapping and seismic reflection data. We investigate the crustal structure of the southern Tyrrhenian Sea, extending from the bathyal Marsili Basin to the adjacent Sicily continental margin. Interpretation of seismic reflection profiles (calibrated by well and dredge data) and crustal cross-sections were used to identify the stratigraphic infill, structural pattern and large-scale crustal features of the region. We recognized three basins in the southern Tyrrhenian Sea: (1) the Termini basin that is an overfilled sedimentary basin on the continental shelf area; (2) the Cefalù basin, located on the continental slope area and filled by thick deep water turbidite deposits; (3) the distal Marsili basin, filled by hemipelagic and thin distal turbidite deposits. The sequence stratigraphy interpretation permitted us to recognize fourth-order depositional sequences and the stratigraphic signature of the rift stages. An important increase in the sedimentary supply from the continental shelf to the bathyal basin occurred approximately over the last 0.5 Ma and is related to the uplift of the coastal area. The stratigraphic constraints indicate a Lower Pleistocene age for the opening of the southern Tyrrhenian Sea basin. The structural map reveals a complex fault pattern, in which coeval normal faults disclose a triangular basin from the Marsili bathyal basin to the Sicily continental margin, associated to an Euler pole in the northern Sicily. Tacking in account the faults pattern that developed in the whole Southern Tyrrhenian Sea during the Lower Pleistocene, we reconstructed two opposite triangular basins separated by a perpendicular rift. For analogy with the contiguous Vavilov basin, we propose that the extension in the Marsili basin reached the mantle exhumation stage.

1. Introduction

In the last decades, many studies have been carried out on rift formation, in order to understand causes and modes of lithospheric extension (e.g., Neumann and Ramberg, 1978; Coward et al., 1987; Keen, 1987; Ruppel, 1995; Brun, 1999; Corti et al., 2003). The opening of a backarc basin is characterized by lithospheric stretching and thinning through progressive phases of continental rifting, crustal necking, hyper extension, and mantle exhumation (Mohn et al., 2012). Stratigraphic analyses of sedimentary rift basins are fundamental for studying the evolution of rift systems, making it possible to understand the close relationship between sedimentation and tectonics (e.g. Gawthorpe and Leeder, 2000). In particular, stratigraphic analyses permit to reconstruct the development and kinematics of active faults

and variations in fault slip rates, which are the main factors influencing the spatial distribution and architecture of depositional systems adjacent to the fault zones. According to Reston and Pérez-Gussinyé (2007), the complete process of continental break-up can be understood only through detailed 3D studies of the rift evolution. Up to now, only few studies use 3D stratigraphic reconstructions to investigate the variations in the extensional fault geometry and resulting sedimentary record, associated to the evolution of rift basins (e.g. Martin, 1984, 2006; Schellart et al., 2003; Lavier and Manatschal, 2006; Milia et al., 2017a).

The Marsili basin (Fig. 1) is a rectangular bathyal plain formed in the southeastern of the backarc Tyrrhenian basin and has in its central part a homonym volcano. The evolution of this basin has been reconstructed using both paleomagnetic data (Nicolosi et al., 2006;

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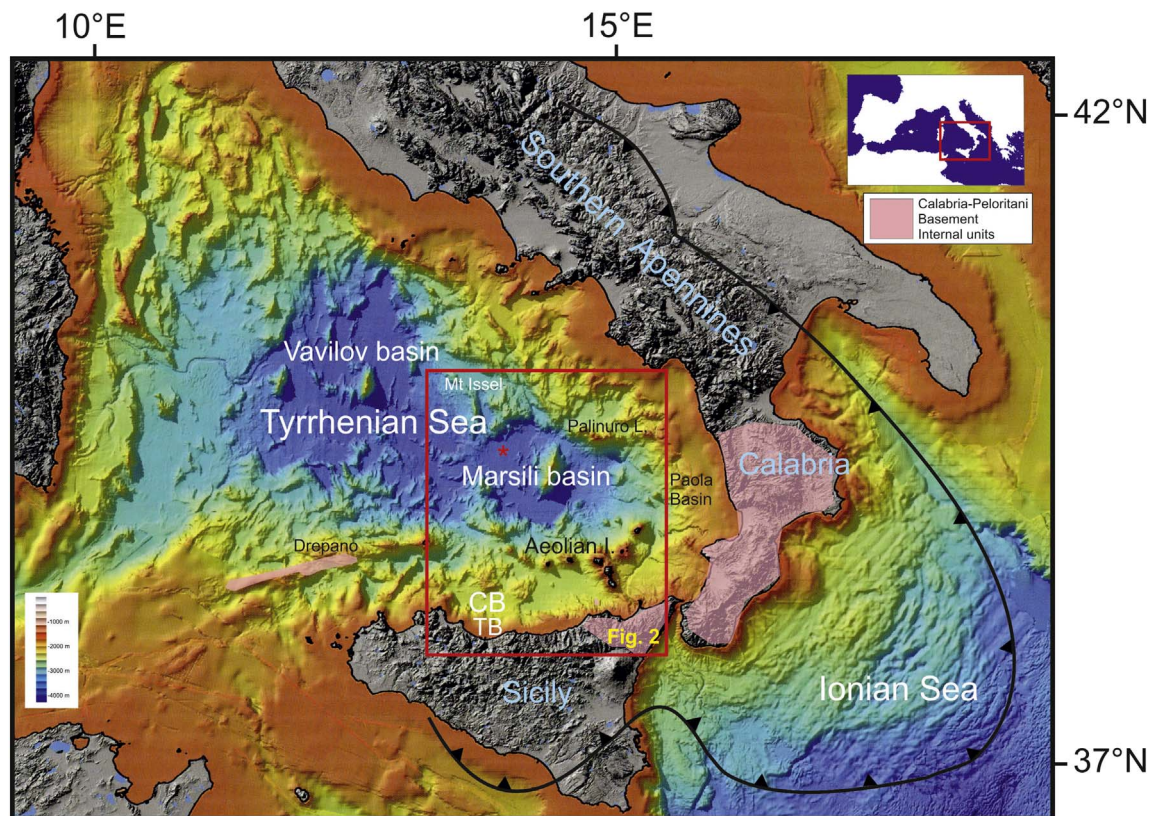


Fig. 1. Morpho-bathymetric map of Italy and surrounding seas (from Brosolo et al., 2012). CB = Cefalù basin, TB = Termini basin. Red asterisk shows location of the ODP 654 site. Thrust fronts are modified from Casero (2004). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Cocchi et al., 2009) and the stratigraphic analysis of Ocean Drilling Project Site 650 (Channell et al., 1990). On the base of these data and of the NNE-trend of the Marsili volcano (Fig. 2), previous studies suggested an ESE extension of the region between 1.8 and 0.7 Ma (Sartori, 1990; Cocchi et al., 2009). The Marsili basin is limited to the south by the Sicily continental margin (Figs. 1, 2), whose structure is poorly constrained. Furthermore, different stress regimes have been proposed for this area: N-S directed extension (e.g. Malinverno and Ryan, 1986; Tavarnelli et al., 2003; Pepe et al., 2004); N-S directed compression (Faccenna et al., 1996; Monaco et al., 1998; Goes et al., 2004); E-W transcurrent regime, with an associated pattern of strike slip faults (Renda et al., 2000; Guarnieri, 2006; Giunta et al., 2009; Gueguen et al., 2010). The physiography of this region (Fig. 2) includes the Cefalù basin that extends from the continental shelf to the continental slope, grading into the bathyal abyssal plain (Marsili basin).

In this study, we reconstruct for the first time the 3D architecture of the Marsili basin and adjacent Sicily continental margin, provide a detailed chronostratigraphic framework in which these basins evolved, and describe the mode of extension of the Southern Tyrrhenian Sea, highlighting the features of crustal thinning. For this purpose, we investigate the structure of the crust and, in particular, of the sedimentary basins of the southern Tyrrhenian Sea, from the Sicily continental margin to the Marsili basin, through the interpretation of seismic reflection profiles, calibrated by well stratigraphy and dredges and the analysis of cross-sections of the crustal model EuCRUST-07 (Tesauro et al., 2008).

2. Geologic framework

The Tyrrhenian Sea is a triangular land-locked extensional basin that formed between Tortonian and Quaternary at the rear of the Neogene Apennines-Maghrebide thrust belt (e.g. Sartori, 1989; Patacca et al., 1990). The evolution of the Tyrrhenian Sea occurred within the

overall context of approximately N-S convergence between the African and Eurasian plates (e.g. Dewey et al., 1989) and has mainly been attributed to the south-eastward roll-back of the Ionian slab (e.g. Malinverno and Ryan, 1986; Faccenna et al., 1996; Cavinato and De Celles, 1999). The paleogeography of the Tyrrhenian Sea changed profoundly between Miocene and Pliocene. In the Miocene the paleogeographic reconstructions of the Lower Oligocene-upper Tortonian suggest that the central Mediterranean was affected by two main rift stages separated by a late Burdigalian-Langhian compressional event linked to a plate's re-organization after the collision occurred along the North African margin. The previous extensional basins are associated to approximately N-S normal faults separated by E-W transfer zones affected widely the Calabria Peloritani terrane, at the time laying approximately north of Sicily (Milia and Torrente, 2014; Milia et al., 2017b). During Pliocene-Quaternary times, the Tyrrhenian basin grew as the result of several extensional sedimentary sub-basins overprinted on the Apennines-Maghrebide thrust belt (e.g. Fabbri et al., 1981; Argnani and Trincardi, 1988; Kastens et al., 1988; Catalano and Milia, 1990; Milia et al., 2013; Milia and Torrente, 2015), already dismembered by the Miocene tectonics. Based on seismic tomographic images, seismological data, petrology of volcanic rocks, and analogue models, several authors (e.g. Serri, 1990; Gvirtzman and Nur, 1999; Faccenna et al., 2003, 2004; Rosenbaum and Lister, 2004; Faccenna et al., 2007; Palano et al., 2017) proposed the existence of a subduction system in southern Italy (Fig. 1) consisting of the (1) Ionian oceanic slab, dipping north-westwards and underlying the Calabria accretionary wedge; (2) Aeolian volcanic arc (1.3–0 Ma), with seven islands and several seamounts (Eolo, Enarete, and Sisifo composed of the oldest rocks of 1.3–0.9 Ma; Beccaluva et al., 1985), lying on the Sicily's continental margin.

Starting from 2.0 Ma ago, the rollback of the Ionian slab (Kastens et al., 1988; Kastens and Mascle, 1990) induced the opening of the Marsili backarc basin (Fig. 1), bounded to the north by the Mount Issel

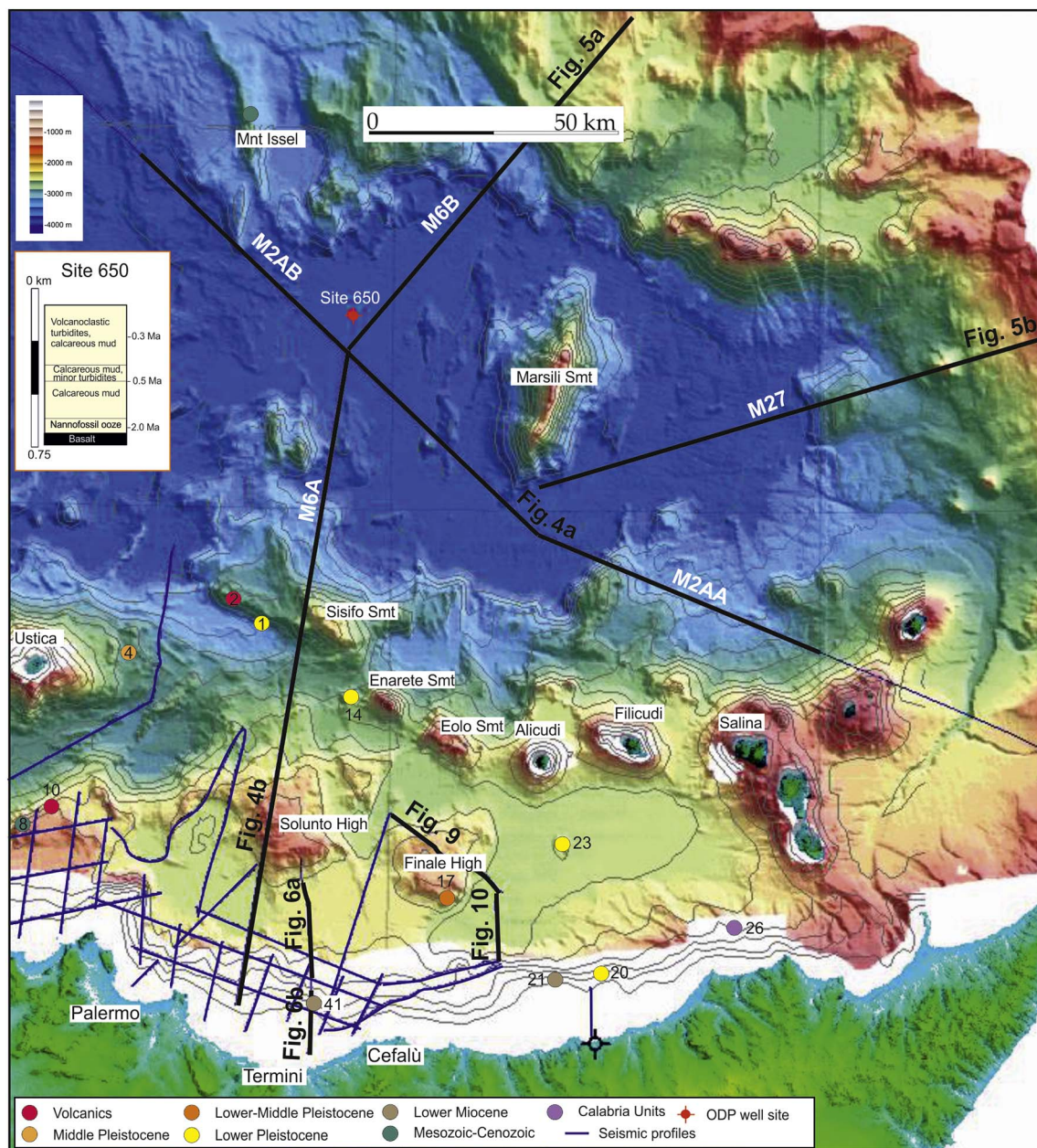


Fig. 2. a. Index map of seismic grid, stratigraphy of the ODP 654 site (Kastens and Mascle, 1990; Channell et al., 1990), and seafloor dredges and cores of the southern Tyrrhenian Sea (Bacini Sedimentari, 1980). Multibeam map of the Tyrrhenian Sea from Marani et al. (2004).

and Palinuro Lineament, to the east by the Paola basin, and to the south by Aeolian volcanic arc and Sicily margin. The Palinuro lineament is an approximately E-W fault located at the boundary with the Campania continental margin. The Paola basin lies on the Calabria continental margin and is characterized by a complex tectonic evolution (Milia et al., 2009): (i) Lower Pleistocene N-S extension; (ii) 1.0–0.7 Ma-old NW-SE left-lateral faulting; (iii) post-500 ka NW-SE right-lateral faults. The Marsili backarc basin features a thinned continental crust (Nicolich, 1981; Florio et al., 2011), asthenosphere upwelling (Cimini, 2004), and heat flow up to 250 mW m^{-2} (Zito et al., 2003). The nature of the crust flooring the Marsili basin is matter of debate: oceanic crust or thinned continental crust, overlying exhumed upper mantle. Ponteivo and Panza (2006) identified a 5–12 km-thick oceanic crust, whereas Florio et al. (2011) reported a pattern of magnetic anomalies at the Marsili basin not compatible with those characterizing oceanic or large backarc basins and concluded that the Marsili seamount cannot be interpreted as a classical spreading ridge. Cocchi et al. (2009)

recognized in the southern Tyrrhenian Sea NNE–SSW magnetization stripes and estimated for the Marsili Basin decreasing spreading rates (3.1 cm/yr, between 1.77 and 1.07 Ma; 2.4–2.15 cm/yr and 1.8 cm/yr, between 1.07 and 0.7 Ma).

The northern part of Sicily corresponds to a Cenozoic accretionary wedge derived from the closure of the Tethys Ocean contemporaneously to the opening of the Central Mediterranean backarc basins (e.g. Handy et al., 2010; Catalano et al., 2013). The south-verging Sicilian-Maghrebian thrust belt is formed from the top by: Miocene Flysch-type nappes, Upper Mesozoic-Paleogene basinal carbonates; thick imbricates of Mesozoic-Cenozoic platform carbonate rocks (Catalano et al., 1985; Compagnoni et al., 1989; Catalano et al., 2013). These nappes are covered in the northeastern part of Sicily (Fig. 1) by the AlKaPeCa crystalline basement units (Calabro-Peloritani terrane). The Cenozoic thrust belt is overprinted by extensional and strike-slip faults in southern Tyrrhenian margin, whose mutual relationships are controversial. Gueguen et al. (2010) proposed that the southern

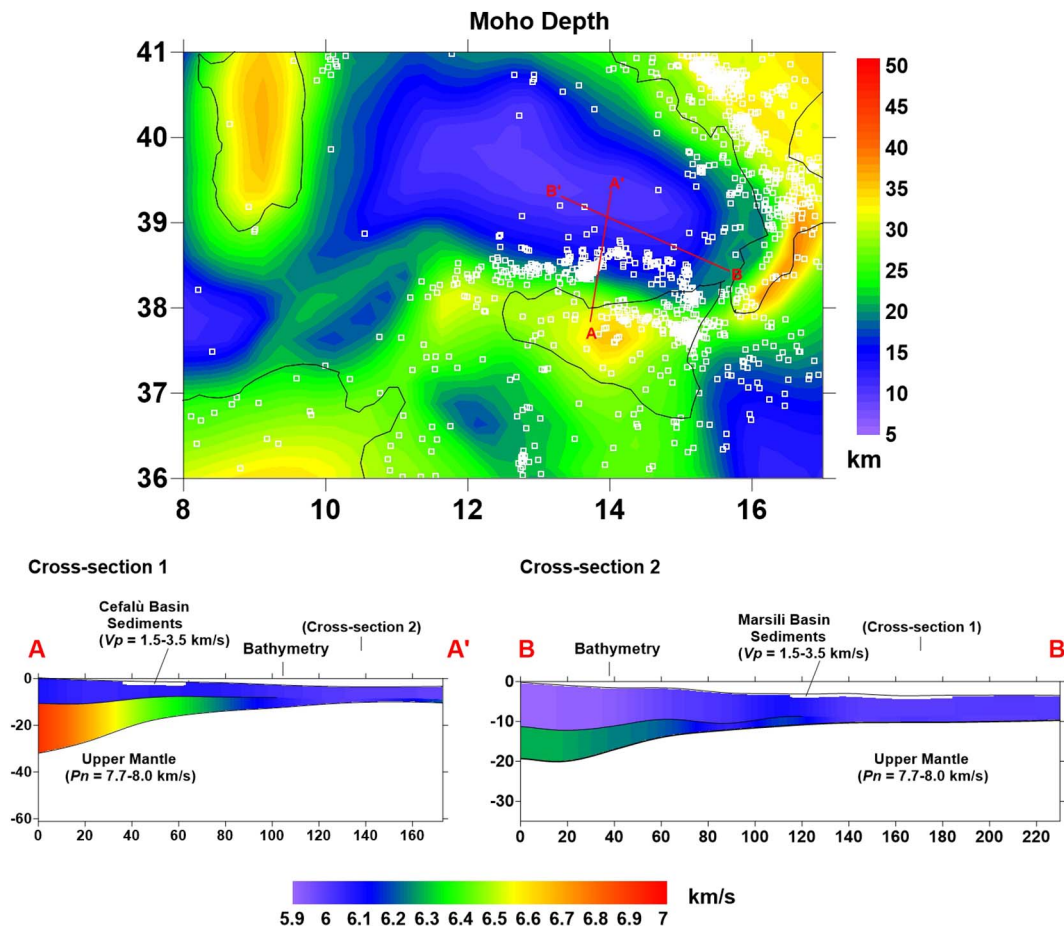


Fig. 3. Moho depth of the Tyrrhenian Sea and surroundings according to the crustal model EuCRUST-07 (Tesauro et al., 2008). White open squares on the map represent the distribution of earthquakes from the USGS seismic catalogue (<http://earthquake.usgs.gov/earthquakes/search/>) at a depth of ≤ 10 km. Red lines depict location of two cross-sections of EuCRUST-07, displaying the crustal thickness and P-wave velocity variations along the northern Sicily margin and Marsili basin. Sedimentary thickness and P-wave velocity variations are derived from the interpretation of the seismic reflection profiles. Pn values are from Cassinis et al. (2003). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Tyrrhenian margin corresponds to an E-W strike-slip duplex. NW-SE dextral strike-slip faults have been documented along the northern margin of Sicily (Catalano et al., 1985; Finetti et al., 1996; Abate et al., 1998; Giunta et al., 2000; Nigro et al., 2000; Renda et al., 2000; Gueguen et al., 2010). Some of these faults are still active and responsible for the shallow seismicity present both inland and offshore (e.g. Cultrera et al., 2016).

Deep Neogene extensional basins, lying on the top of the collisional chain (Catalano et al., 1985; Compagnoni et al., 1989), are filled by several hundred meters thick Pliocene-Pleistocene sediments (Bacini Sedimentari, 1980; Bigi et al., 1992; Agate et al., 1993, 2000). The largest and deepest basin is the Cefalù basin, having a sedimentary thickness > 1.5 km, assuming a V_p of 2 km/s in the depth conversion of the Pliocene-Pleistocene seismic unit (Fig. 1). According to the tectono-stratigraphic model of Pepe et al. (2004) the onset of faults activity bounding the Cefalù basin occurred in the Tortonian. Up to 60 m-thick Lower Pleistocene marine clays, dated 1.5–0.7 Ma, (Argille di Ficarazzi Fm) outcrop discontinuously along the coast of the northern Sicily margin and are present in the subsurface of the plains (Servizio Geologico d'Italia, 2013 and reference therein). These deposits lie unconformably on lower Pliocene deposits, suggesting a Pleistocene age for the extensional tectonic event that originated the basin. The basin's substrate of the southern Tyrrhenian is composed of basalts in the Marsili basin and Calabro-Peloritani crystalline rocks, Lower Miocene clastics, and Mesozoic-Cenozoic carbonates, in the Sicily margin, respectively (Fig. 2). The oldest sediments at ODP site 650 are

represented by Lower Pleistocene nannofossil and foraminiferal-rich muds, dated 2.0 Ma (biozone MPL6/NN18; Channell et al., 1990). The Continental Margin dredges record from older to younger: Lower Pleistocene nannofossil and foraminiferal-rich marls, dated 2.0–1.8 Ma (BS79-1, Inflata Biozone); Lower Pleistocene sandy mudstones, dated 1.8–1.2 Ma, (BS79-14, BS79-23, BS79-20; Globigerina Cariacoensis Biozone); Lower-Middle Pleistocene mudstones, dated 1.2–0.3 Ma (BS79-17); Middle Pleistocene marls, dated 0.5–0.3 Ma (BS79-4, Gephyrocapsa Oceanica Biozone) (Bacini Sedimentari, 1980).

3. Data and methods

We used seismic reflection profiles with different resolution and penetration: multichannel seismic profiles, CROP seismic profiles, and Sparker data. The CROP data differ from the commercial multichannel profiles, as they are Near Vertical Reflection seismic profiles characterized by deep penetration (17 s of two way-travel-time) and low resolution. The Sparker seismic data set was acquired with a Multispot Extended Array System (MEAS). The output power of the MEAS, transmitted through a 36-tip array, was 16 kJ. Vertical recording scales were 2.0 s with a maximum vertical resolution of 6 m. The seismic interpretation was made using seismic stratigraphy and sequence stratigraphy methods: we identified seismic units as groups of seismic reflections, whose parameters (configuration, amplitude, continuity, and frequency) differ from those of adjacent groups. Sedimentary units were defined on the basis of contact relationships and internal and external

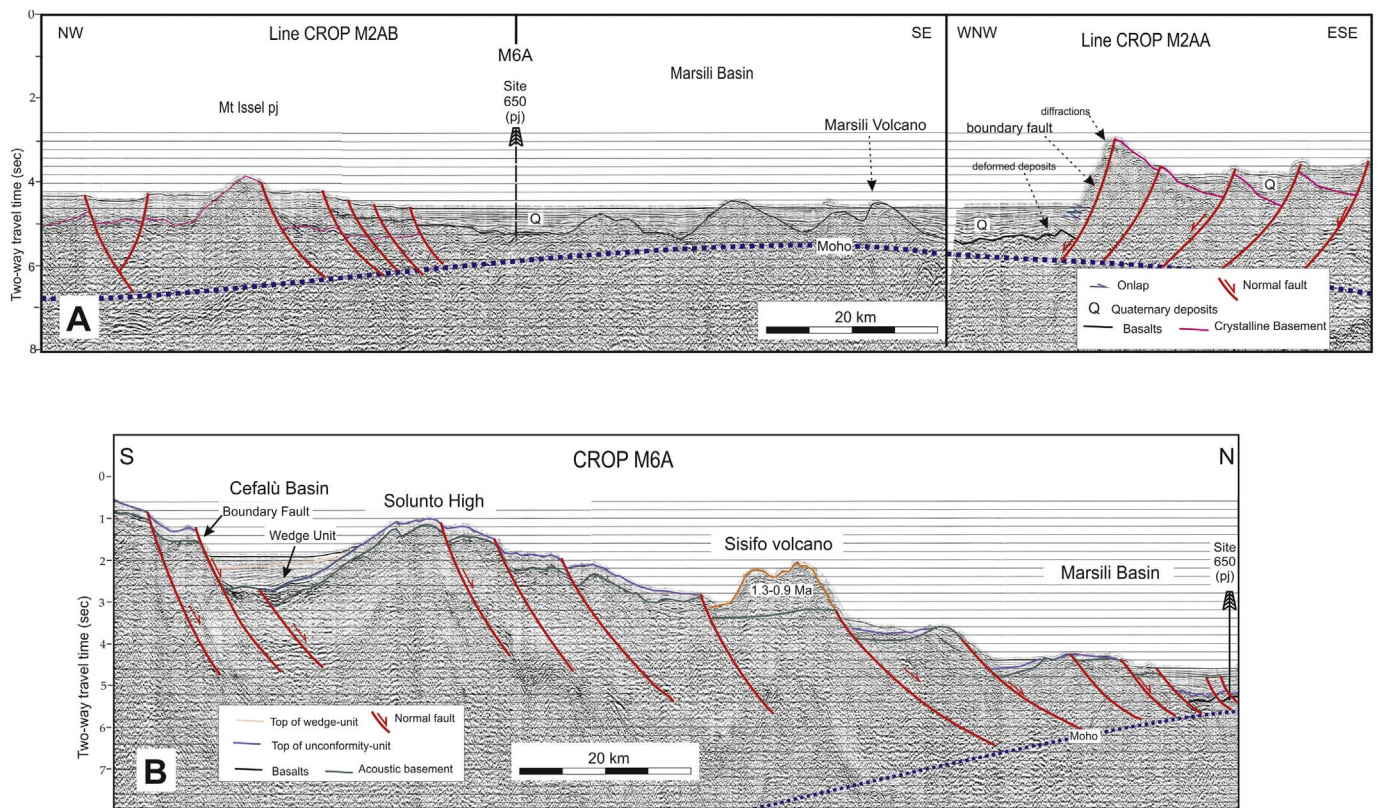


Fig. 4. A) Interpreted seismic sections CROP M2AA-M2AB in the Marsili basin, displaying a symmetrical extensional structure. B) Interpreted seismic section CROP M6A extending from the northern Sicily margin to the Marsili basin.

configurations (Mitchum et al., 1977). The sequence stratigraphy approach (Posamentier and Vail, 1988) made it possible the identification of 4th-order depositional sequences (100 ka), forecasting depositional settings and lithologies. The seismic interpretation was calibrated by the ODP Site 650 (Kastens and Mascle, 1990; Channell et al., 1990) and by dredge data (Bacini Sedimentari, 1980; Trua et al., 2004; Sartori, 2005). The subsurface data were subsequently processed, in order to build a consistent dataset: the seismic line base maps and well position were geo-referenced in a common coordinate system (European Datum 50) and collected in a dedicated geographic information system (GIS) environment (Kingdom, IHS Inc.). We constructed 2D digital models of the subsurface (sections and structure contour maps), providing very accurate tectono-stratigraphic interpretations. We used the crustal model EuCRUST-07 (Tesauro et al., 2008) to identify the main variations of the crustal structure of the southern Tyrrhenian region. EuCRUST-07 has been obtained by assembling a large number of seismic refraction, reflection, and receiver function data. It provides the depth of the main crustal boundaries and velocities of the upper and lower crust on a uniform grid $15' \times 15'$.

4. Main crustal features

The study area (Figs. 1–2) is separated into two sectors by the Aeolian volcanoes (Aeolian Islands and western volcanic seamounts): (i) the southern sector features a narrow continental shelf, passing northward to an articulate continental slope and, at the depth of about 1500 m, into a wide plain, where a couple of substrate seamounts are located (Solunto and Finale highs); (ii) the northern sector (Marsili basin) is characterized by a wide bathyal plain from which a NNE-elongated 3000 m-high submarine volcano rises (Marsili Seamount). The interpretation of the seismic profiles collected across the southern Tyrrhenian Sea has been calibrated by the stratigraphy of ODP Site 650, dredges, and cores data.

To investigate the large-scale features of the crustal structure of the region, we derived two cross-sections from EuCRUST-07 (Tesauro et al., 2008). The first profile trending SSW-NNE, extends from the northern Sicily margin to the bathyal part of the Marsili basin (Cross-section 1, Fig. 3), while the second one (Cross-section 2, Fig. 3), trending ESE-WNW, almost perpendicular to the first one, crosses the bathyal region of the Marsili basin. We can observe from Cross-section 1 (Fig. 3) that the crustal thickness changes quite sharply, decreasing from about 30 km to < 10 km (more than three times of its original value) over a horizontal distance of only ~ 100 km. In contrast, the crust is quite thin and homogeneous along Cross-Section 2, showing only small thickness variations between 7 and 12 km in the bathyal region of the Marsili basin. Toward the Calabria margin the crust gently increases its thickness to almost 20 km. The differences observed imply that the major extensional phases occurred in the direction of Profile 2 (NW-SE).

The strong extension that lead to the crustal thinning in the bathyal region of the Marsili basin, has caused the updoming of the asthenosphere and warmed the overlying lithosphere, as indicated by the high heat flow values of the area. These conditions have likely favored a ductile deformation of the crust, which led to a smoother variation of its thickness. In contrast, along the northern Sicily margin, subjected to less extension (crustal thickness about 25 km) and characterized by an abrupt transition to a very thinned crust (< 10 km) in the bathyal region, the upper crust deforms in brittle conditions. The conversion from a brittle to a ductile regime of deformation is also indicated by the presence of numerous earthquakes at a depth ≤ 10 km along the northern Sicily margin and the almost absence of shallow seismicity in the bathyal region, respectively (Fig. 3). Notably, in both cross-sections, the thinning of the crust occurs with a progressive decrease of seismic P-wave velocities from typical average continental values of about 6.3 km/s to values of 6 km/s. The low seismic velocities in the bathyal region can indicate the presence of a continental or oceanic crust (Christensen and Mooney, 1995), as well as a strong serpentinized

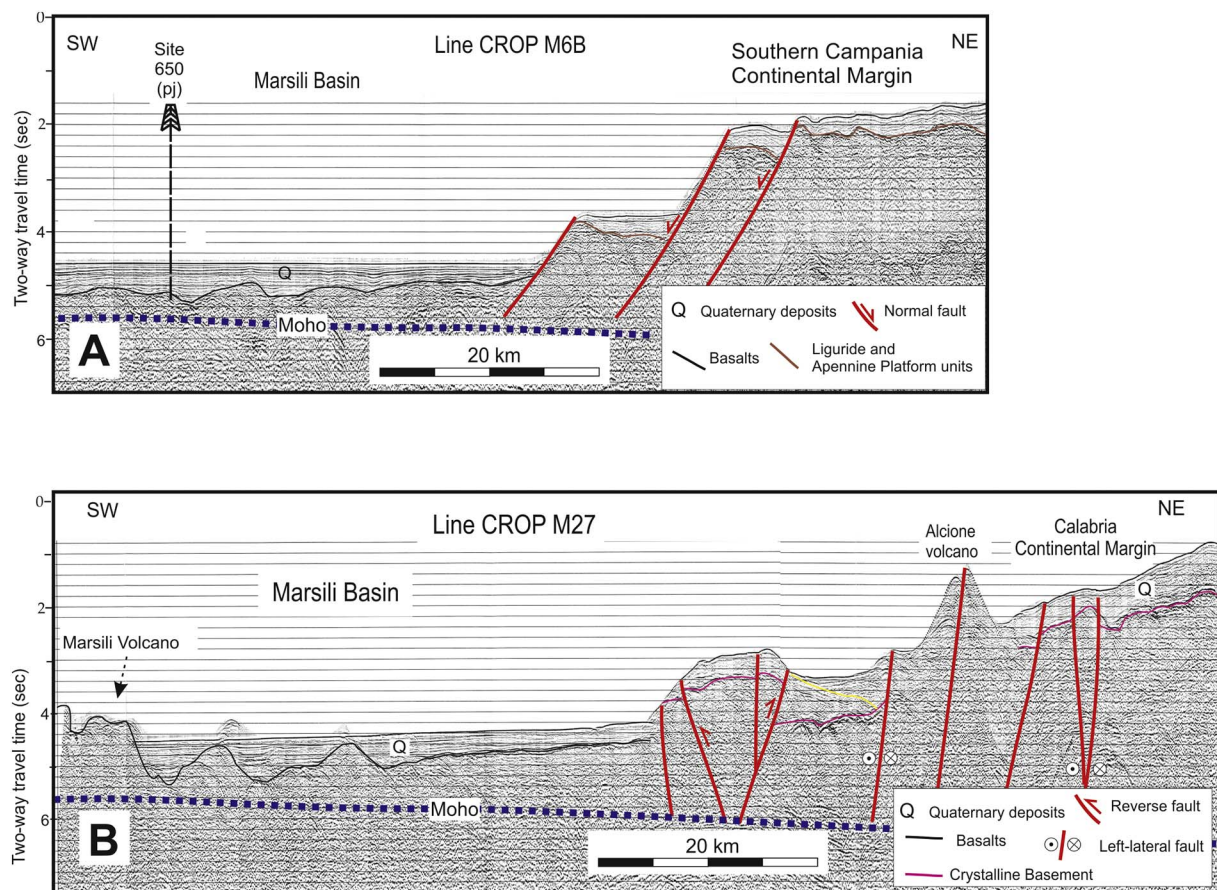


Fig. 5. A) Interpreted seismic section CROP M6B, extending from the Campania margin to the Marsili basin. (after Milia et al., 2017c). B) Interpreted seismic sections CROP M27, encompassing the Calabria margin and the Marsili basin.

upper mantle, as in the Vavilov basin (Milia et al., 2017a). The nature of the shallower part of the crust, was investigated identifying the rocks composing the stratigraphic log of the only ODP well (650 site) located in the Marsili basin. This shallow crust corresponds to an approximately 600 m-thick Quaternary succession overlapping vesicular basalts (Kastens and Mascle, 1990). Volcanic rocks have been also sampled on the seafloor of the Marsili Seamount and nearby (e.g. Trua et al., 2004). On the northern margin of the Marsili basin (Mt. Issel), Liguride and Apennine Platform units have been dredged and in its southern margin (Aeolian Islands) xenoliths of crystalline rocks of the Calabria Peloritani terrane have been sampled (Sartori, 2005).

The CROP M2AA and M2AB seismic profiles cross the whole Marsili basin (Figs. 2, 4) and show an acoustic basement characterized by mounded chaotic seismic facies, overlain by a cover unit (Q) featuring medium-amplitude parallel reflectors. Based on core and dredge data, we interpret the acoustic basement as basalts in the bathyal plain and crystalline basement rocks in the northern and southern margins, respectively. The Marsili bathyal plain is 100 km-wide and is bounded by two sets of normal faults that form an overall symmetrical structural depression (Fig. 4A). Notably, the faults are absent in the central part, supporting the existence of a transition from a brittle to a ductile crustal deformation. The south-eastern part of the Marsili basin displays a 1.2 km-high fault scarp and several WNW-dipping fault blocks. In particular, the sub-basin between the boundary fault and the southern extension of the Marsili volcano is filled by up to 800 m-thick Quaternary deposits formed by older faulted strata and younger ones deposited in onlap on the boundary fault. In contrast, the easternmost basins are covered by thinner Quaternary deposits. The northern part of the basin presents a region of subdued seafloor topography passing to the bathyal plain. The seismic facies reveal a seismic unit with an

approximately constant thickness and characterized by parallel reflectors that cover the acoustic substrate, outcropping in correspondence of Mt. Issel. This topographic high separates a saddle of 15 km-thick continental crust in the north from a region of highly-extended crust in the south (Nicolich, 1981).

The CROP M6A seismic profile (Fig. 4B), trending N-S, displays a complete section of the southern Tyrrhenian Sea, from the northern Sicily margin to the bathyal Marsili basin; it crosses the Cefalù basin, the Solunto High, and the Sisifo volcano (1.3–0.9 Ma-old; Beccaluva et al., 1985). The southern part of this profile shows the Cefalù basin, bounded by the N-dipping normal-separation faults and by the hangingwall block of the Solunto High. The Cefalù basin infill features a tilted unconformity-bounded unit covered by a wedge unit and younger sub-horizontal deposits. Its substrate corresponds to crystalline rocks, Lower Miocene clastics and Mesozoic carbonates (Fig. 2). Because the oldest clastic deposits overlying the substrate (dredge BS 79–1, BS 79 14; Bacini Sedimentari, 1980) have been attributed to the Inflata Biozone (2.0–1.8 Ma) and to the Globigerina Cariacoensis Biozone (1.8–1.2 Ma), the tilted unconformity-bounded unit is post-2 Ma-old and the age of the Cefalù basin infill is Pleistocene. The M6A seismic profile shows an asymmetrical style and normal-separation faults dipping toward the Marsili basin along the whole Sicily margin up to the bathyal plain.

The Marsili basin and its northern margin are imaged by a couple of CROP seismic profiles (Fig. 5). The oldest structure bounding the Tyrrhenian bathyal zone and the Campania margin (Fig. 5A) corresponds to a NW-SE normal fault swarm (Sartori Lineament Auct.) that down throws the basement at a depth > 5 s (approximately 3800 m). Because the age of the oldest sediments that onlap the basalts is 1.8 Ma, this structure started to form in the Lower Pleistocene (Milia et al.,

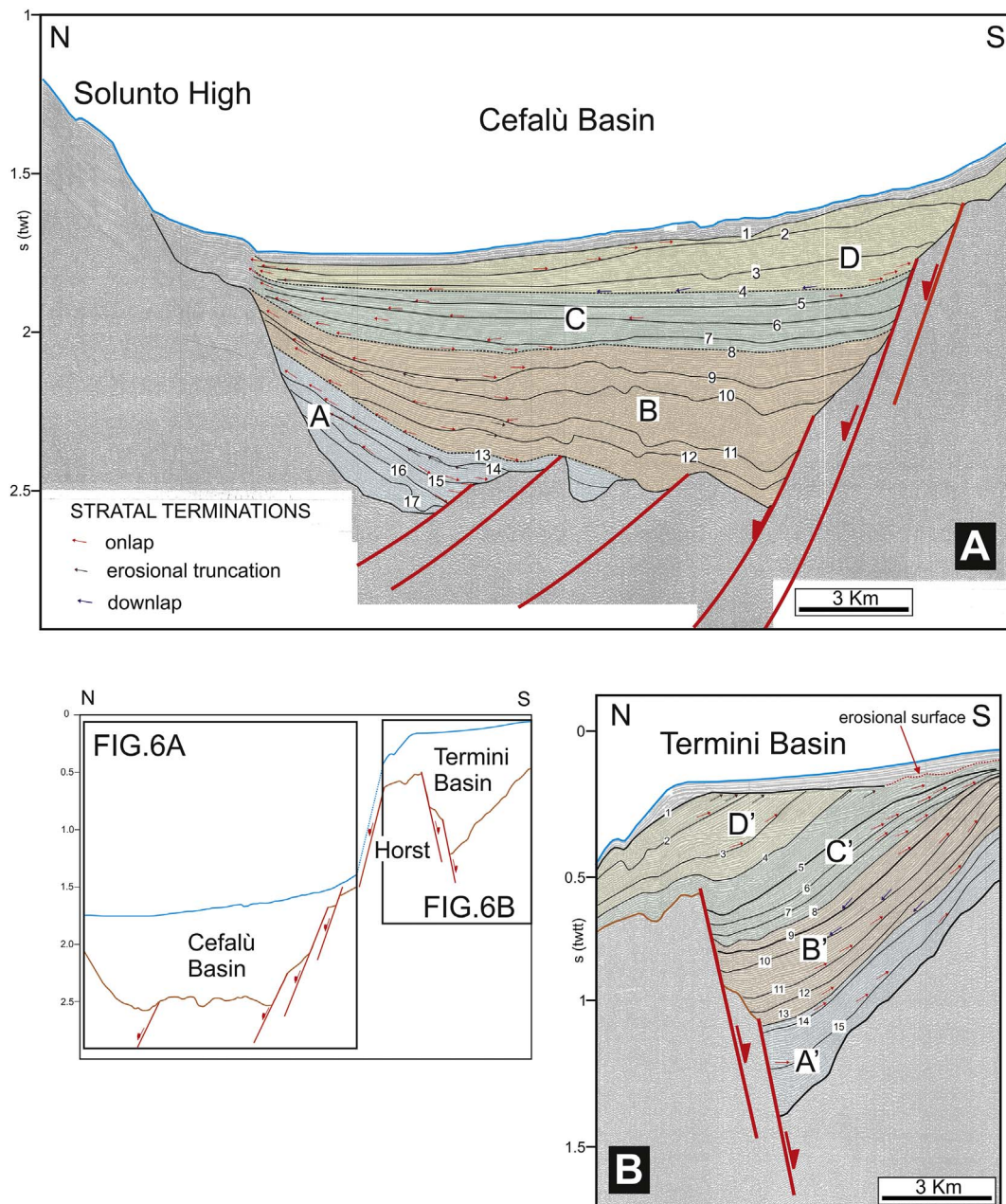


Fig. 6. Interpreted Sparker seismic profile, crossing the Cefalù and Termini basins.

2017c). Instead a pop-up structure confined by high-angle reverse faults displacing Quaternary folded deposits is present at the edge between the Calabria margin and Marsili basin (Fig. 5B). We interpret such a pop-up structure as associated to a system of left-lateral faults that were active on the Calabria margin between 1 and 0.7 Ma (Milia et al., 2009).

5. Stratigraphic architecture and fault geometry

The architecture of the sedimentary basins formed in the southern Tyrrhenian Sea, north of Sicily, was investigated in greater detail through the analysis of a high-resolution Sparker profile (Figs. 6–7), near and parallel to the Crop M6A, showing a horst of substrate (Lower Miocene rocks) that separates the distal Cefalù basin from the proximal Termini basin. The sedimentary infill of these basins is characterized by reflectors with variable frequencies and amplitude and variable to very-good continuity. Submarine fan deposits are characterized by high-

amplitude and continuous reflections, onlapping the basin margin and defining the pinch-out of the fan. This seismic response probably reflects the same type of lithology, while the high-impedance contrasts commonly characterize the fan made of sediments of variable grain size, from pelagic mud to coarse sands, producing variable seismic velocities. Continuous seismic horizons are recognized repeatedly in the fan. The continuity of these boundaries suggests the presence of hemipelagic sediments, which were presumably deposited across the entire fan in the Pleistocene during phases of relatively high sea level. These conditions favored hemipelagic sedimentation since large amounts of terrigenous sediments could not reach the distal fan. The continuous horizons are commonly locally eroded, as witnessed by erosional truncation of stratal terminations, and covered in downlap and onlap by the overlying sequence. The erosional surface and the top of the underlying hemipelagic section represent the sequence boundary. Laterally the hemipelagic horizons correspond to the correlative conformable surface of the erosional sequence boundary. The seismic facies

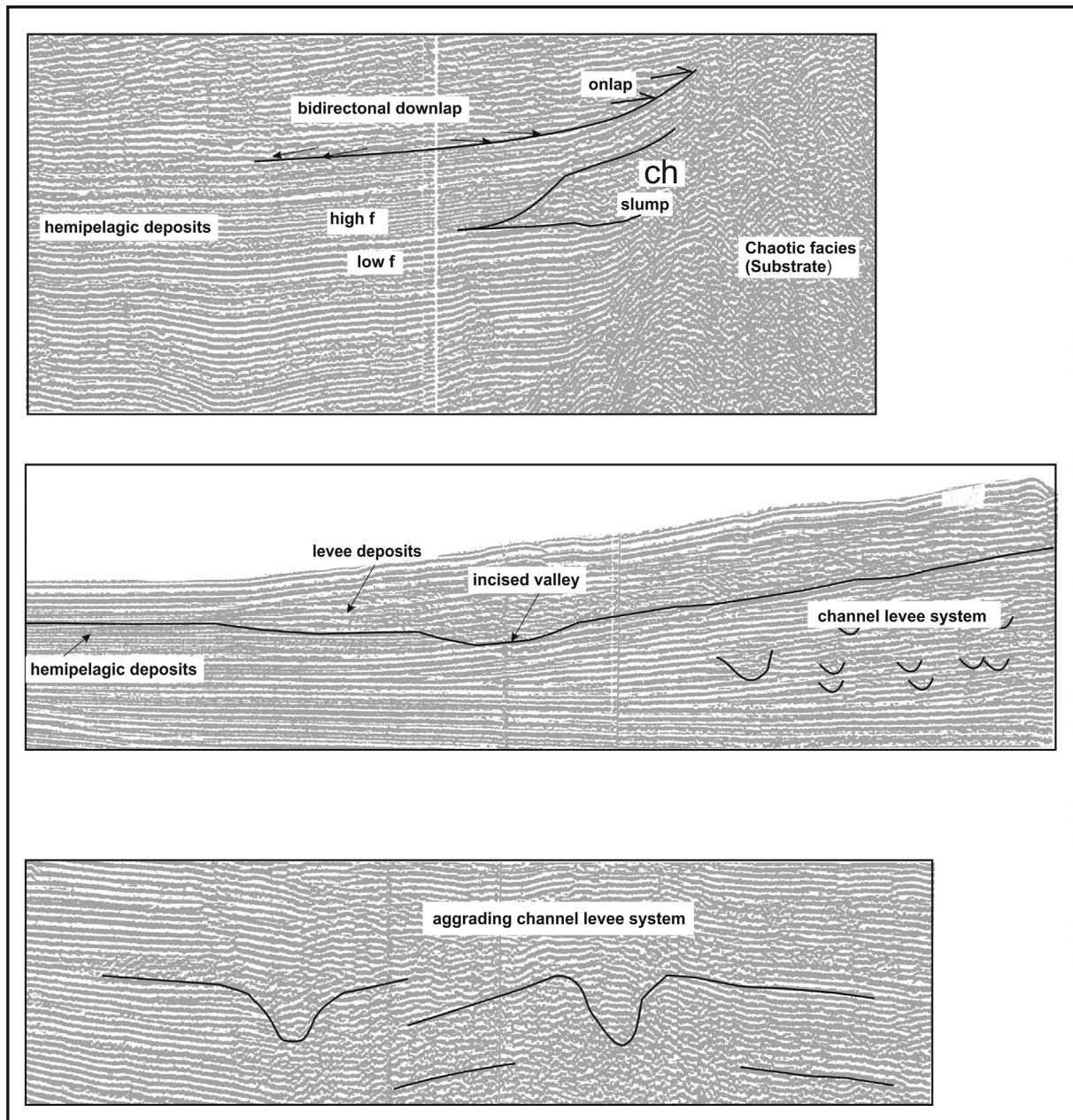


Fig. 7. Seismic facies of the deep-water Cefalù basin.

analysis of the Cefalù basin (Fig. 7) documents a succession made of deep-water turbidite deposits with characteristics distributary channels and levee deposits (sensu Weimer and Link, 1991). Notably, in the last depositional sequence of the Cefalù basin a system of NW-trending canyons (Fig. 2) that evolves down-slope into an active channel-levee depositional system occur (Gamberi and Marani, 2004).

The detailed stratal patterns analysis makes it possible to distinguish eighteen depositional units that can be grouped in four sets (sets A–D in the Cefalù basin and A'–D' in the Termini basin; Fig. 6). Taking into account the oldest age (not older than 2.0 Ma) of the sedimentary deposits, we interpreted these stratigraphic units as depositional sequences formed during fourth-order (100 ka) sea-level fluctuations. The oldest sequence set (A–A') covers an irregular unconformity at the top of the substrate. These strata show approximately parallel reflection configuration, thus suggesting a gradual infill during the onset of the basin formation. The sequence set B' is represented by subparallel reflectors that progressively onlap the substrate landward and are clearly

divergent toward the faults. In contrast, the Sequence set B displays a sedimentary wedge that significantly thins seaward. The rapid thickening of the depositional sequences toward the fault indicates a fast increase in the accommodation space. This increase suggests a period of syn-rift and/or climax stage of the fault activity linked to the main extensional event of the Cefalù basin. This tectonic event, occurred during the deposition of sequences 18–8, produced the hangingwall rotation and the tilting of both older units and bounding faults. The deposition of a thick turbidite deep-sea fan suggests an increase of the sediment source area, probably due to a relative footwall uplift. The sequence set C (corresponding to sequences 7–4) is characterized by subparallel and sub-horizontal reflectors, indicating a relative tectonic stability. In contrast, the sequence set C' is characterized by an abrupt landward thinning and a sigmoid progradational configuration, suggesting fault block tilting and relative uplift of the coastal area. Sequence set D–D' (sequences 3–1) corresponds to a thick regressive wedge that overfilled the Termini basin and to a deep-sea fan in the Cefalù

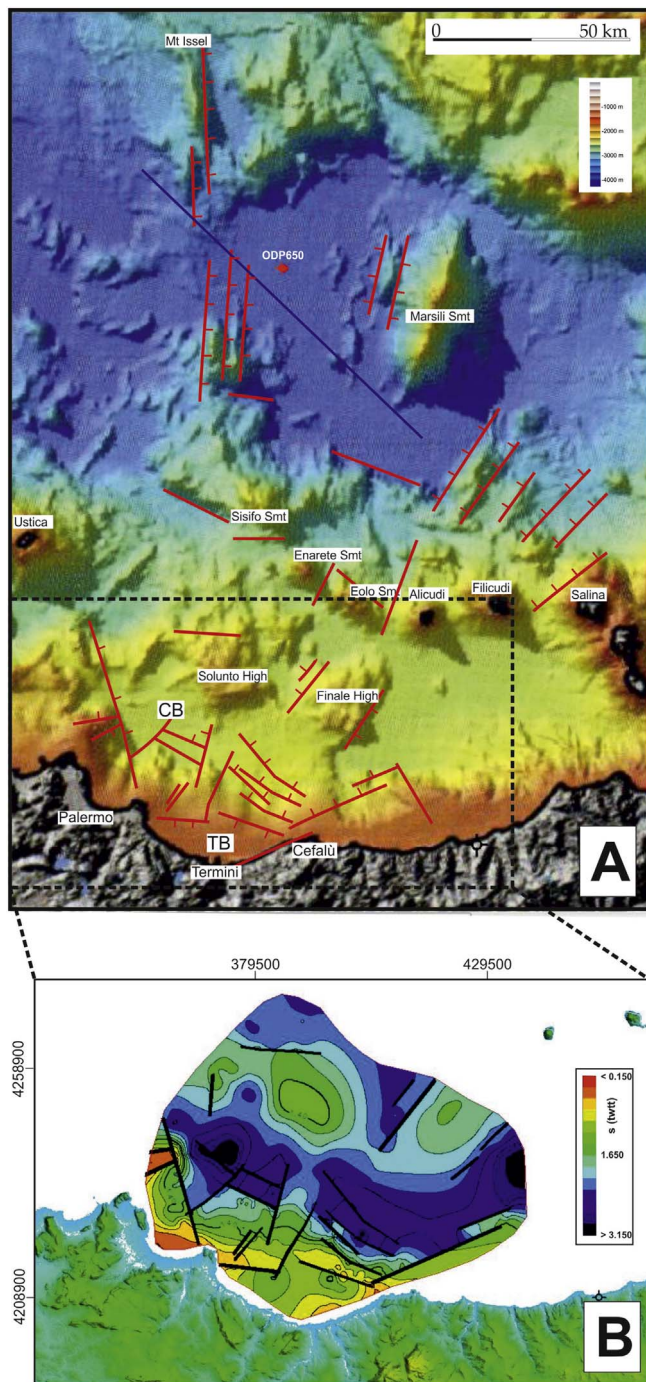


Fig. 8. A) Tectonic map of the southern Tyrrhenian Sea. B) Structure contour map of the acoustic basement in the Cefalù basin.

basin. Consequently, it records the end of extensional tectonics in the basinal area and the uplift of the coastal area.

We produced a structural map using both seismic and bathymetric data. In the Marsili Basin it shows (Fig. 8) several faults trends (NNW-SSW, N-S, NE-SW, ENE-WSE and NW-SE). For example, N-S and NE-SW normal faults occur, respectively, in the western and eastern boundary of the bathyal plain (Fig. 4) and altogether the normal faults of the Marsili basin reveals a triangular pattern. The Sicily continental margin displays instead the same fault sets of the Marsili basin plus an additional orthogonal set trending E-W/NNW-ESE (Fig. 8). A Sparker profile shows NE-SW normal faults bounding the Finale High that are covered in onlap by younger deposits (Fig. 9). Furthermore, a ENE-

trending normal fault swarm bounds the Sicily slope near Cefalù and displaces Lower Pleistocene deposits (Fig. 10). These faults are covered in onlap by younger basinal deposits. The WNW-ESE faults present in the western part of the Cefalù basin (Fig. 8) were active in the Lower Pleistocene (sequence sets A–B) until the deposition of “sequence 8” (Fig. 6A); they are concealed by sequence sets C–D. In contrast, the E-W fault bounding to the north the Termini basin (Fig. 6B), recorded an initial subsidence stage (until “sequence 8”), followed by the tilting and uplift of the crest of the block, contemporaneously to the deposition of the prograding wedge (sequence sets C’–D’). Indeed, the significant erosional surface formed at the same time of the forced regression succession (sequence set D’), witnesses a significant uplift of the coastal area, which lead to the emersion of the Lower Pleistocene marine clays (Argille di Ficarazzi Fm; 1.5–0.7 Ma-old), outcropping along the coast.

6. Discussion and conclusions

The geodynamic interpretation of the Marsili Basin as backarc basin linked to the rollback of the subducting plate is widely accepted. It is well known that the opening of the Marsili basin occurred with variable extension rates between 1.8 and 0.7 Ma, along a WNW-ESE direction, based on the elongation of the central volcano, representing the main physiographic feature of the Southern Tyrrhenian Sea, magnetic anomaly recorded on the bathyal area, and elongation of the tectonic block remnants (Kastens et al., 1988; Kastens and Mascle, 1990; Sartori, 1990; Cocchi et al., 2009). However, the mode of extension of the basin and its link with the Sicily margin, where the crust significantly thickens (Fig. 3), is still poorly understood. Our stratigraphic and structural results documented a wide extensional area between Marsili basin and Sicily continental margin active between 1.8 and 0.7 Ma. The oldest sedimentary deposits above the volcanic substrate of the Marsili Basin are not older than 2 Ma (Kastens et al., 1988), while the oldest sedimentary deposits of the Sicily continental margin offshore and onshore Cefalù area are 1.8 Ma-old. Based on these stratigraphic constraints and the absence of any important tectonically-enhanced erosional truncation and stratigraphic gap, we interpreted the stratigraphic infill of the Cefalù Basin as the stratigraphic record of Quaternary fourth order sea level fluctuations, which has been already identified along the Tyrrhenian and Adriatic margins (Chiocci, 1993; Milia, 1999; Milia et al., 2009; Ridente et al., 2012). Taking into account that a fourth-order sea level fluctuation develops approximately into 100 ka and we identified 18 depositional sequences, we could associate a Lower Pleistocene age to the basin fill of both Cefalù and Termini basins.

The strict relationships between sedimentation and tectonics permitted us to reconstruct the evolution of the faults from basin architecture. Indeed, the Quaternary deposits of the Cefalù basin represent genetically the sediments grown along the bounding fault, while the horizons included may be used as markers of the fault slip rate and fault geometry. On the base of different stratal architecture and external form, the Sicily margin's Quaternary depositional sequences are grouped into four sequence sets (A–D; Fig. 6) linked to the evolution of the faults bounding the basin. Unit A covers the acoustic substrate and is slightly divergent toward the fault. In the Termini basin, this unit onlaps the margin of a subsiding basin. The architecture suggests an early stage of activity of the faults bounding the basins. The occurrence of the unconformity 13 in the Cefalù basin, corresponding to the lower boundary of the wedge-shaped Unit B (13–8), can be interpreted as the onset of the fault's climax stage. Unit B indicates the activity of a syn-sedimentary growth-fault and a rapid subsidence and rotation of the hangingwall block.

The faults in the Cefalù basin show steeper dips going southwards, suggesting a landward migration of the faults (with southern younger faults and northern older rotated faults). A striking change of the Cefalù basin's infill occurred during the deposition of Unit C (8–4), showing a parallel seismic configuration and an approximately constant thickness,

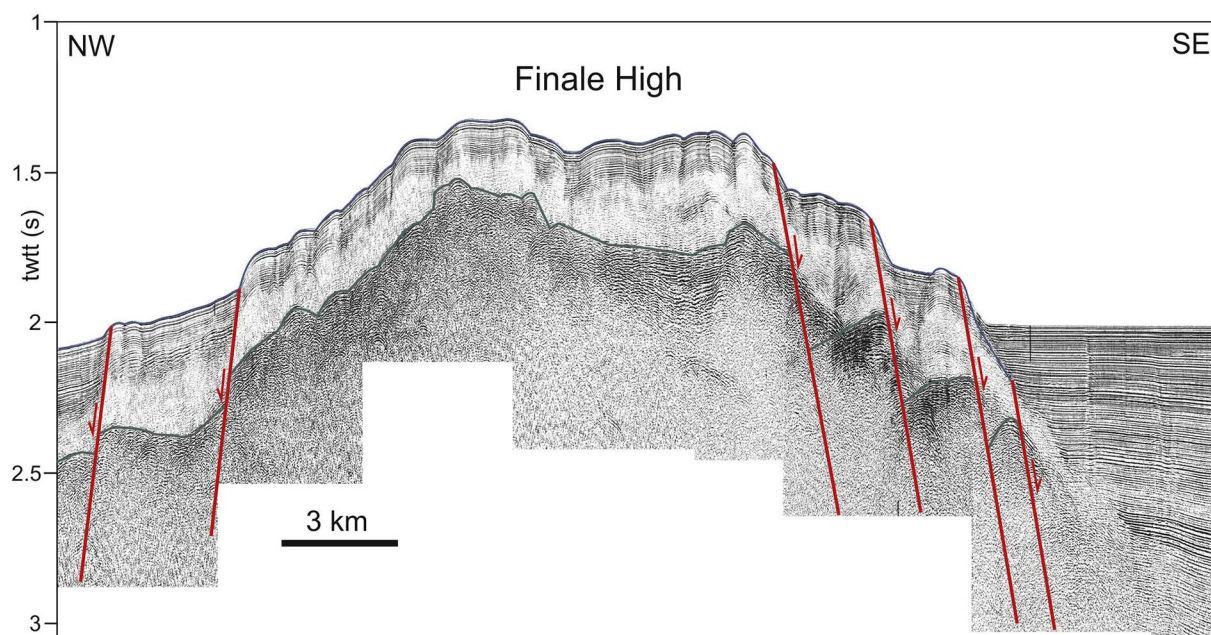


Fig. 9. Interpreted Sparker seismic profile displaying the NE-trending normal faults and the Finale High horst.

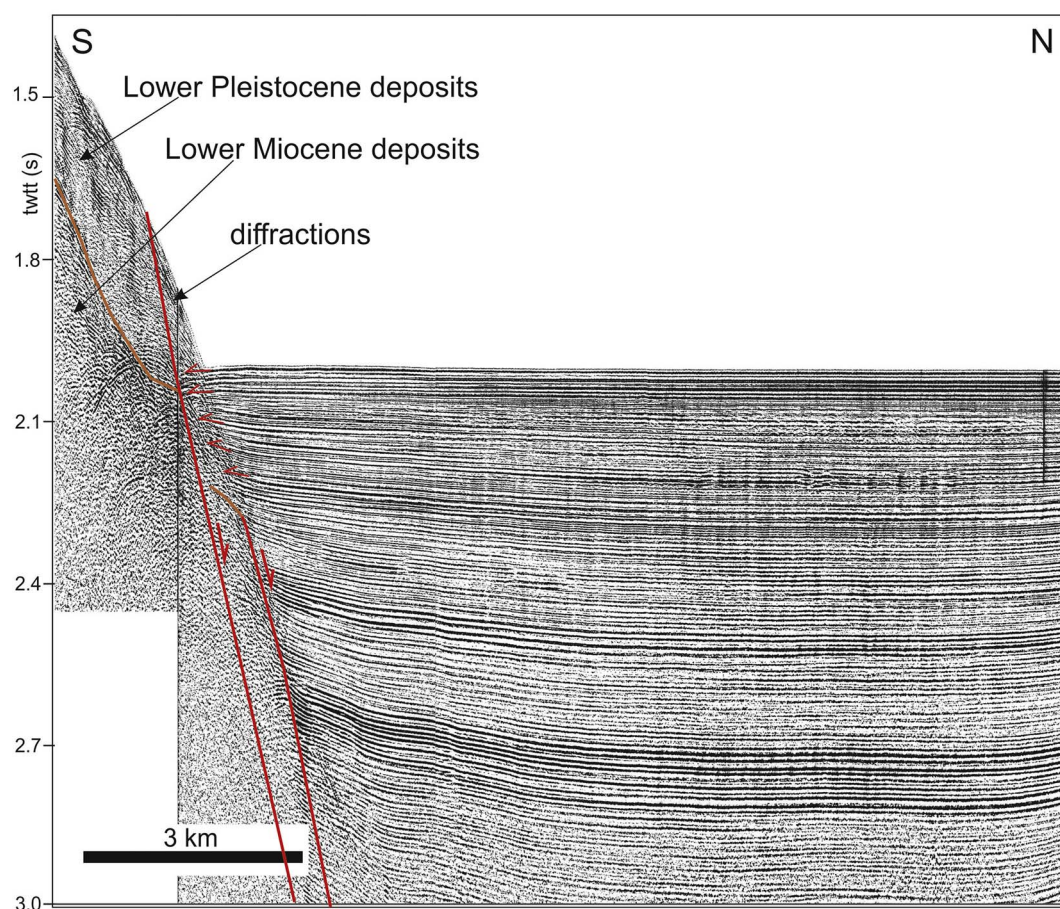


Fig. 10. Interpreted Sparker seismic profile showing the ENE-WSW normal faults bounding the Cefalù basin to the South.

that records a horizontally basin filling and a tectonic stability. In contrast, in the Termini basin a fault-block tilting occurred during the deposition of the Unit C' characterized by the development of a depositional wedge that prograde from the south. An important erosional surface at the top of Unit C' and the deposition of thick regressive

wedge (Unit D') marks an uplift of the continental area and a seaward migration of the deposition. The uplift of the Sicily margin is documented by the emergence of the Lower Pleistocene deposits. The forced regression of Unit D' witnesses the bypass of sediments from inland to deep basin. These features are in agreement with the deposition of the

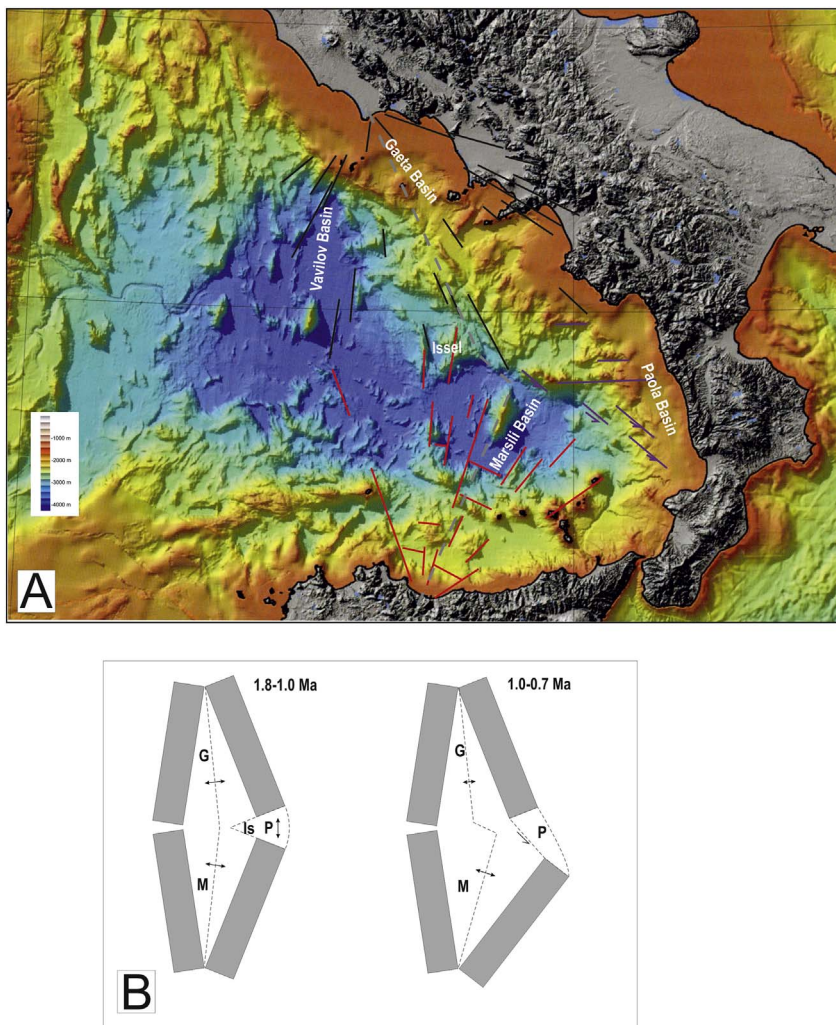


Fig. 11. A) Morpho-structural sketch map, showing faults lasting 1.8–0.7 Ma in the southern Tyrrhenian. Faults located in the Gaeta Basin-Campania margin, Marsili basin, and Paola basin are displayed as black, red and blue lines, respectively. B) Two-stage evolution of the southern Tyrrhenian rifting; G = Gaeta basin, M = Marsili basin, P = Paola basin, Is = Mt. Issel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

front fill unit in the Cefalù basin. Indeed, the deposition of the younger front fill unit indicates an important source of sediments from the South. A coeval front-fill stratal configuration, indicating the uplift of the continental margin, has been already reported in the Paola basin offshore Calabria (Milia et al., 2009). In addition, an increase in the clastic sedimentary supply is documented since 0.46 Ma also in the Marsili basin (ODP site 650; Channell et al., 1990).

In the Marsili basin and Sicily margin normal faults are oriented N-S, NNE-SSW and NE-SW and this fault pattern corresponds to a triangular extensional basin with a rotation pole located in Sicily. The orthogonal WNW-ESE faults can be interpreted as transfer faults, characterized by normal throw that accommodated the thinning of the continental crust from the Maghrebian thrust belt to Marsili basin. This interpretation is confirmed by the contemporaneous activity of extension in two adjacent areas, the Marsili basin and Sicily continental margin, indicating a common origin for the opening of the two regions.

On the basis of the reconstruction of fault pattern and fault timing in the southern Tyrrhenian region (Fig. 11), we propose a two-stage kinematic evolution of the area, following the double-saloon-door model of Martin (2006). This model postulates, during the subduction rollback, the formation of two arc-parallel rifts and a third rift orthogonal to the subduction zone. A northern triangular extensional basin, with a rotation pole located in Latium, also formed at the same time in the Gaeta basin and Campania margin (Milia et al., 2013, 2017c; Milia and Torrente, 2015). In between these two triangular rifts lies the Paola basin, featuring NW-SE left-lateral faults and E-W normal faults.

During the first stage of evolution of the southern Tyrrhenian region

(1.8–1.0 Ma; Fig. 11b) the Marsili and Gaeta basins formed as two opposite triangular extensional basins representing the backarc region of the Maghrebian-Appennines thrust belts, whose formation was accompanied by contrary sense vertical axis rotations (counterclockwise in the Southern Apennines and clockwise in the Sicilian Maghrebides; Cifelli et al., 2004 and bibliography therein) and the Paola basin (Fig. 11b) as a rift perpendicular to the Calabria accretionary prism (Milia et al., 2009). The simultaneous rifting of the two opposing backarc basins between 1.8 and 1.0 Ma and associated opposite rotation of the thrust belts are the response to the rollback of the subducting plate. The isolation of blocks of relatively thick continental crust during backarc rifting can occur between two opposite triangular basins in a sector affected by only minor extension. In the southern Tyrrhenian region this sector of minor extension matches the Mt. Issel saddle of 15 km-thick continental crust (Is; Fig. 11b) corresponding to the apex of the perpendicular rift (P; Fig. 11b).

The second stage of evolution of the southern Tyrrhenian region (1.0–0.7 Ma; Fig. 11b) was characterized by a continuous extension of the southern triangular basin (M; Fig. 11b) and a decrease of the opening rate in the northern one (G; Fig. 11b), where NW-trending normal faults were active until 1.0 Ma (Milia et al., 2017c); this fact induced asymmetric deformation and nucleation of a transfer zone within the Paola basin (P; Fig. 11b) (Milia et al., 2009). This stage also records the continental collision and stall of southern Apennines thrust belt toward the Apulia foreland. These overall features can reflect significant changes in the geodynamics of the Central Mediterranean and were interpreted as the response in the upper plate of a Subduction-

Transform-Edge-Propagator fault along the northern margin of the Ionian slab (Milia et al., 2017c).

The bathyal zone of the Tyrrhenian Sea is formed by the Vavilov and Marsili basins (Fig. 1). As already discussed, the type of the crust flooring the Marsili basin is controversial (oceanic crust or thinned continental crust, overlying exhumed upper mantle) because the ODP well 650 did not drill the substrate underlying the basalts. The bathyal region of the Marsili basin is characterized by (Profile 2, Fig. 3) a quite thin and homogeneous crust, showing a progressively decrease of seismic P-wave velocities from typical continental values of about 6.3 km/s to values of 6 km/s. These low seismic velocities can indicate the presence of a thinned continental or oceanic crust (Christensen and Mooney, 1995), as well as a strong serpentinized upper mantle. The presence of oceanic crust has been postulated on the basis of the symmetric magnetic anomaly pattern, considered as isochrones formed at a steady-state spreading ridge recording the reversals of the geomagnetic field (Nicolosi et al., 2006; Cocchi et al., 2009). However, these data may not be sufficient to definitely identify the crust as oceanic type. Indeed, at the Iberia–Newfoundland conjugate rifted margins, linear magnetic anomalies have been observed in non-oceanic domains, characterized by exhumed mantle or hyper-extended continental crust (Whitmarsh and Miles, 1995; Funck et al., 2003; Russell and Whitmarsh, 2003).

Based on the above discussion, the ODP data and the occurrence of mantle exhumation in the opposite triangular Vavilov basin (Milia et al., 2017a and bibliography therein), we prefer to support the existence of an exhumed and serpentinized mantle in the whole bathyal zone of the Tyrrhenian Sea.

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References

- Abate, B., Incandela, A., Nigro, F., Renda, P., 1998. Plio-Pleistocene strike slip tectonics in the Trapani mts. (NW Sicily). *Boll. Soc. Geol. Ital.* 117, 555–567.
- Agate, M., Catalano, R., Infuso, S., Lucido, M., Mirabile, L., Sulli, A., 1993. Structural evolution of the northern Sicily continental margin during the Plio-Pleistocene. In: Max, M.D., Colantoni, P. (Eds.), *Geological Development of the Sicilian-Tunisian Platform*. UNESCO Reports in Marine Science Vol. 58, pp. 25–30.
- Agate, M., Beranzoli, L., Braun, T., Catalano, R., Favali, P., Frugoni, F., Pepe, F., Smriglio, G., Sulli, A., 2000. The 1998 offshore NW Sicily earthquakes in the tectonic framework of the southern border of the Tyrrhenian Sea. *Mem. Soc. Geol. Ital.* 55, 103–114.
- Argnani, A., Trincardi, F., 1988. Paola slope basin: evidence of regional contraction on the eastern Tyrrhenian margin. *Mem. Soc. Geol. Ital.* 44, 93–105.
- Bacini Sedimentari, 1980. Dati geologici preliminari sul bacino di Cefalù (Mar Tirreno). *Ateneo Parmense Acta Nat.* 16, 3–18.
- Beccaluva, L., Gabbianelli, G., Lucchini, F., Rossi, P.L., Savelli, C., 1985. Petrology and K/Ar ages of volcanics dredged from the Eolian seamounts: implications for geodynamic evolution of the southern Tyrrhenian basin. *Earth Planet. Sci. Lett.* 74, 187–208.
- Bigi, G., Cosentino, D., Parotto, M., Sartori, R., Scandone, P., 1992. Structural Model of Italy, Sheet N. 4; Scale 1:500,000. Consiglio nazionale delle ricerche (CNR). Progetto finalizzato geodinamica, Roma.
- Brosolo, L., Mascle, J., Loubrieu, B., 2012. Morpho-bathymetry of the Mediterranean Sea. Scale: 1:4000000. Publication CGM/CGMW. UNESCO, Paris.
- Brun, J.P., 1999. Narrow rifts versus wide rifts: inferences for the mechanics of rifting from laboratory experiments. *Philos. Trans. R. Soc. Lond. A* 357, 695–712.
- Casero, P., 2004. Structural setting of Petroleum exploration plays in Italy. In: Crescenti, V., D'Offizi, S., Merlino, L. (Eds.), *Geology of Italy. Spec. vol. It. Geol. Soc. IGC 32*. Florence, pp. 189–199.
- Cassinis, R., Scarascia, S., Lozej, A., 2003. The deep crustal structure of Italy and surrounding areas from seismic refraction data; a new synthesis. *Boll. Soc. Geol. Ital.* 122 (3), 365–376.
- Catalano, R., Milia, A., 1990. Late Pliocene-Lower Pleistocene structural inversion in offshore Western Sicily. In: Pinet, B., Bois, C. (Eds.), *Potential of Deep Seismic Profiling for Hydrocarbon Exploration*. Edition Technip, Paris, pp. 445–449.
- Catalano, R., D'Argenio, B., Montanari, L., Morlotti, E., Torelli, L., 1985. Marine geology of the NW Sicily offshore (Sardinia Channel) and its relationships with mainland structures. *Boll. Soc. Geol. Ital.* 104, 207–215.
- Catalano, R., Valenti, V., Albanese, C., Accaino, F., Sulli, A., Tinivella, U., Morticelli, M.G., Zanolla, C., Giustiniani, M., 2013. Sicily's fold/thrust belt and slab roll-back: the SI.RI.PRO. Seismic crustal transect. *J. Geol. Soc.* 20, 1–14. <http://dx.doi.org/10.1144/jgs2012-099>.
- Cavinato, G.P., De Celles, P.G., 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.
- Channell, J.E.T., Rio, D., Sprovieri, R., Glacon, G., 1990. Biomagnetostratigraphic correlations from Leg 107 in the Tyrrhenian Sea. In: Kastens, K.A., Mascle, J. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results*. 107, pp. 669–682.
- Chiocci, F.L., 1993. Very high-resolution seismics as a tool for sequence stratigraphy applied to outcrop scale – examples from eastern Tyrrhenian margin Holocene/Pleistocene deposits. *Am. Assoc. Pet. Geol. Bull.* 78, 378–395.
- Christensen, N.I., Mooney, W.D., 1995. Seismic velocity structure and composition of the continental crust: a global view. *J. Geophys. Res.* 100 (B7), 9761–9788.
- Cifelli, F., Rossetti, F., Mattei, M., Hirt, A.M., Funicello, R., Tortorici, L., 2004. An AMS, structural and paleomagnetic study of quaternary deformation in eastern Sicily. *J. Struct. Geol.* 26 (1), 29–46.
- Cimini, G.B., 2004. Tomographic studies of the deep structure of the Tyrrhenian–Apennine system. In: *Mem. Descr. Carta Geol. d'It.* 44, pp. 15–28.
- Cocchi, L., Caratori Tontini, F., Muccini, F., Marani, M.P., Bortoluzzi, G., Carmisciano, C., 2009. Chronology of the transition from a spreading ridge to an accretional seamount in the Marsili backarc basin (Tyrrhenian Sea). *Terra Nova* 21, 369–374. <http://dx.doi.org/10.1111/j.1365-3121.2009.00891.x>.
- Compagnoni, R., Morlotti, E., Torelli, L., 1989. Crystalline and sedimentary rocks from the scarps of the Sicily–Sardinia trough and Cornaglia Terrace (Southwestern Tyrrhenian Sea): paleogeographic and geodynamic implications. *Chem. Geol.* 77, 375–398.
- Corti, G., Bonini, M., Conticelli, S., Innocenti, F., Manetti, P., Sokoutis, D., 2003. Analogue modelling of continental extension: a review focused on the relations between the patterns of deformation and the presence of magma. *Earth Sci. Rev.* 63 (3), 169–247.
- Continental extensional tectonics. In: Coward, M.P., Dewey, J.F., Hancock, P.L. (Eds.), *Geological Society Special Publication*. 28 Blackwell Science, Incorporated.
- Cultrera, F., Barreca, G., Burrato, P., Ferranti, L., Monaco, C., Passaro, S., Pepe, F., Scarfi, L., 2016. Active faulting and continental slope instability in the Gulf of Patti (Tyrrhenian side of NE Sicily, Italy): a field, marine and seismological joint analysis. *Nat. Hazards* 1–20.
- Dewey, J.F., Helman, M.L., Turco, E., Hutton, D.H.W., Knott, S.D., 1989. Kinematics of the western Mediterranean. In: Coward, M.P., Dietrich, D., Park, R.G. (Eds.), *Alpine Tectonics*. *Geol. Soc. Lond. Spec. Pub.* 45(1), pp. 265–283.
- Fabbri, A., Gallignani, P., Zitellini, N., 1981. Geologic evolution of the peri-Tyrrhenian sedimentary basins. In: Wezel, F.C. (Ed.), *Sedimentary Basins of Mediterranean Margins*. Proceedings/C.N.R. International Conference Held at Urbino University, pp. 101–126.
- Faccenna, C., Davy, P., Brun, J.P., Funicello, R., Giardin, D., Mattei, M., Nalpas, T., 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., Jolivet, L., Piromallo, C., Morelli, A., 2003. Subduction at depth of convection in the Mediterranean mantle. *J. Geophys. Res. Solid Earth* 108 (B2). <http://dx.doi.org/10.1029/2001JB001690>.
- Faccenna, C., Piromallo, C., Crespo-Blanc, A., Jolivet, L., Rossetti, F., 2004. Lateral slab deformation and the origin of the western Mediterranean arcs. *Tectonics* 23, TC1012. <http://dx.doi.org/10.1029/2002TC001488>.
- Faccenna, C., Funicello, F., Givetta, L., D'Antonio, M., Moroni, M., Piromallo, C., 2007. Slab disruption, mantle circulation, and the opening of the Tyrrhenian basins. *Geol. Soc. Am. Spec. Pap.* 418, 153–169.
- Finetti, I., Lentini, F., Carbone, S., Catalano, S., Del Ben, A., 1996. Il sistema Appennino Meridionale-Arco Calabro-Sicilia nel Mediterraneo Centrale: studio geologico-geofisico. *Mem. Soc. Geol. Ital.* 115, 529–559.
- Florio, G., Fedi, M., Cella, F., 2011. Insights on the spreading of the Tyrrhenian Sea from the magnetic anomaly pattern. *Terra Nova* 23, 127–133. <http://dx.doi.org/10.1111/j.1365-3121.2011.00992.x>.
- Funck, T., Hopper, J.R., Larsen, H.C., Loudon, K.E., Tucholke, B.E., Holbrook, W.S., 2003. Crustal structure of the ocean-continent transition at Flemish Cap: seismic refraction results. *J. Geophys. Res.* 108, 2531. <http://dx.doi.org/10.1029/2003JB002434>.
- Gamberi, F., Marani, M.P., 2004. Deep-sea depositional systems of the Tyrrhenian basin. In: *Mem. Descr. Carta Geol. Ital.* LXIV, pp. 127–146 (Rome).
- Gawthorpe, R.L., Leeder, M.R., 2000. Tectono-sedimentary evolution of active extensional basins. *Basin Res.* 12 (3–4), 195–218.
- Giunta, G., Nigro, F., Renda, P., Giorgianni, A., 2000. The Sicilian–Maghrebesides Tyrrhenian margin: a neotectonic evolutionary model. *Boll. Soc. Geol. Ital.* 119, 553–565.
- Giunta, G., Luzio, D., Agosta, F., Calò, M., Di Trapani, F., Giorgianni, A., Oliveri, E., Orioli, S., Perniciaro, M., Vitale, M., Chiodi, M., Adelfio, G., 2009. An integrated approach to investigate the seismotectonics of northern Sicily and southern Tyrrhenian. *Tectonophysics* 476, 13–21.
- Goes, S., Giardini, D., Jenny, S., Hollenstein, C., Kahle, H.G., Geiger, A., 2004. A recent tectonic reorganization in the south-central Mediterranean. *Earth Planet. Sci. Lett.* 226 (3), 335–345.
- Guarnieri, P., 2006. Plio-Quaternary segmentation of the south Tyrrhenian forearc basin. *Int. J. Earth Sci.* 95 (1), 107–118.
- Gueguen, E., Tavarnelli, E., Renda, P., Tramutoli, M., 2010. The southern Tyrrhenian Sea margin: an example of lithospheric scale strike-slip duplex. *Ital. J. Geosci.* 129 (3), 496–505.
- Gvirtzman, Z., Nur, A., 1999. The formation of Mount Etna as a consequence of slab

- rollback. *Nature* 401, 782–785.
- Handy, M.R., Schmid, S.M., Bousquet, R., Kissling, E., Bernoulli, D., 2010. Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological–geophysical record of spreading and subduction in the Alps. *Earth Sci. Rev.* 102, 121–158. <http://dx.doi.org/10.1016/j.earscirev.2010.06.002>.
- Kastens, K., Mascle, J., 1990. The geological evolution of the Tyrrhenian Sea: An introduction to the scientific results of ODP leg 107. In: Kastens, K.A., Mascle, J. (Eds.), *Proc. ODP, Sci. Results 107. Ocean Drilling Program, College Station, TX*, pp. 3–26.
- Kastens, K.A., Mascle, J., et al., 1988. ODP leg 107 in the Tyrrhenian Sea: insights into passive margin and back-arc basin evolution. *Geol. Soc. Am. Bull.* 100 (7), 1140–1156.
- Keen, C.E., 1987. Dynamical extension of the lithosphere during rifting: some numerical model results. In: Fuchs, K., Froidevaux, C. (Eds.), *Composition, Structure and Dynamics of the Lithosphere–Asthénosphere System. Geodynamics Series 16*. Am. Geophys. Union, Geol. Soc. Am, pp. 189–203.
- Lavier, L.L., Manatschal, G., 2006. A mechanism to thin the continental lithosphere at magma-poor margins. *Nature* 440 (7082), 324–328.
- Malinverno, A., Ryan, W.B.F., 1986. Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the lithosphere. *Tectonics* 5, 227–245.
- Marani, M., Gamberi, G., Bortoluzzi, G., Carrara, G., Ligi, M., Penitenti, D., 2004. Seafloor morphology of the Tyrrhenian Sea. Scale 1:1,000,000. In: *Included to: Mem. Descr. Carta Geol. Ital. LXIV*. Rome.
- Martin, A.K., 1984. Propagating rifts: crustal extension during continental rifting. *Tectonics* 3, 611–617.
- Martin, A.K., 2006. Oppositely directed pairs of propagating rifts in backarc basins: double saloon door seafloor spreading during subduction rollback. *Tectonics* 25, TC3008. <http://dx.doi.org/10.1029/2005TC001885>.
- Milia, A., 1999. Aggrading and prograding infill of a peri-Tyrrhenian basin (Naples Bay, Italy). *Geo-Mar. Lett.* 19, 237–244.
- Milia, A., Torrente, M.M., 2014. Early-stage rifting of the Southern Tyrrhenian region: the Calabria–Sardinia breakup. *J. Geodyn.* 81, 17–29. <http://dx.doi.org/10.1016/j.jog.2014.06.001>.
- Milia, A., Torrente, M.M., 2015. Tectono-stratigraphic signature of a rapid multistage subsiding rift basin in the Tyrrhenian–Apennine hinge zone (Italy): a possible interaction of upper plate with subducting slab. *J. Geodyn.* 86, 42–60. <http://dx.doi.org/10.1016/j.jog.2015.02.005>.
- Milia, A., Turco, E., Pierantoni, P.P., Schettino, A., 2009. Four-dimensional tectono-stratigraphic evolution of the Southeastern peri-Tyrrhenian basins (Margin of Calabria, Italy). *Tectonophysics* 476, 41–56.
- Milia, A., Torrente, M.M., Massa, B., Iannace, P., 2013. Progressive changes in rifting directions in the Campania margin (Italy): new constraints for the Tyrrhenian Sea opening. *Glob. Planet. Chang.* 109, 3–17. <http://dx.doi.org/10.1016/j.gloplacha.2013.07.003>.
- Milia, A., Torrente, M.M., Tesauero, M., 2017a. From stretching to mantle exhumation in a triangular backarc basin (Vavilov basin, Tyrrhenian Sea, Western Mediterranean). *Tectonophysics* 710–711, 108–126. <http://dx.doi.org/10.1016/j.tecto.2016.10.017>.
- Milia, A., Valente, A., Cavuoto, G., Torrente, M.M., 2017b. Miocene progressive forearc extension in the Central Mediterranean. *Tectonophysics* 710–711, 232–248. <http://dx.doi.org/10.1016/j.tecto.2016.10.002>.
- Milia, A., Iannace, P., Tesauero, M., Torrente, M.M., 2017c. Upper plate deformation as marker for the Northern STEP fault of the Ionian slab (Tyrrhenian Sea, central Mediterranean). *Tectonophysics* 710–711, 127–148. <http://dx.doi.org/10.1016/j.tecto.2016.08.017>.
- Mitchum, R.M., Vail, P.R., Sangree, J.B., 1977. Seismic stratigraphy and global changes of sea level, Part 6: stratigraphic interpretation of seismic reflection patterns in depositional sequences. In: Payton, C.E. (Ed.), *Seismic Stratigraphy—Application to Hydrocarbon Exploration*. Am. Ass. Petr. Geol. Mem. 26, pp. 117–133.
- Mohn, G., Manatschal, G., Beltrando, M., Masini, E., Kuszniir, N., 2012. Necking of continental crust in magma-poor rifted margins: evidence from the fossil Alpine Tethys margins. *Tectonics* 31 (1).
- Monaco, C., Tortorici, L., Paltrinieri, W., 1998. Structural evolution of the Lucanian Apennines, southern Italy. *J. Struct. Geol.* 20 (5), 617–638.
- Neumann, E.R., Ramberg, I.B. (Eds.), 1978. *Petrology and Geochemistry of Continental Rifts*. Reidel, Dordrecht (296 pp).
- Nicolich, R., 1981. Crustal structures in the Italian Peninsula and surrounding seas: A review of DDS data. In: Wezel, F.C. (Ed.), *Sedimentary Basins of the Mediterranean Margins*. C.N.R. Italian Project of Oceanography. Tectoprint, Bologna, pp. 489–501.
- Nicolosi, I., Speranza, F., Chiappini, M., 2006. Ultrafast oceanic spreading of the Marsili Basin, southern Tyrrhenian Sea: evidence from magnetic anomaly analysis. *Geology* 34, 717–720.
- Nigro, F., Renda, P., Arisco, G., 2000. Tettonica recente nella Sicilia nord-occidentale e nelle Isole Egadi. *Boll. Soc. Geol. Ital.* 119, 307–319.
- Palano, M., Piromallo, C., Chiarabba, C., 2017. Surface imprint of toroidal flow at retreating slab edges: the first geodetic evidence in the Calabrian subduction system. *Geophys. Res. Lett.* 44 (2), 845–853.
- Patacca, E., Sartori, R., Scandone, P., 1990. Tyrrhenian basin and Apenninic arcs: kinematic relations since late Tortonian times. *Mem. Soc. Geol. Ital.* 45, 425–451.
- Pepe, F., Bertotti, G., Cloetingh, S., 2004. Tectono-stratigraphic modelling of the north Sicily continental margin (southern Tyrrhenian Sea). *Tectonophysics* 384 (1–4), 257–273.
- Pontevevo, A., Panza, G.F., 2006. The lithosphere–asthenosphere system in the Calabrian Arc and surrounding seas — Southern Italy. *Pure. Appl. Geophys.* 163, 1617–1659.
- Posamentier, H.W., Vail, P.R., 1988. Eustatic control on clastic deposition. II. Sequence and system tract models. In: Wilgus, C.K., Hastings, B.S., Posamentier, H., Van Wagoner, J., Ross, C.A., Kendall, C.G.C. (Eds.), *Sea Level Changes - An Integrated Approach*. Society Economic Paleontology Mineralogy Special Publication. 42, pp. 125–154.
- Renda, P., Tavarnelli, E., Tramutoli, M., Gueguen, E., 2000. Neogene deformations of Northern Sicily, and their implications for the geodynamics of the Southern Tyrrhenian Sea margin. *Mem. Soc. Geol. Ital.* 55, 53–59.
- Reston, T.J., Pérez-Gussinyé, M., 2007. Lithospheric extension from rifting to continental breakup at magma-poor margins: rheology, serpentinisation and symmetry. *Int. J. Earth Sci.* 96 (6), 1033–1046.
- Ridente, D., Petrungaro, R., Falese, F., Chiocci, F.L., 2012. Middle–Upper Pleistocene record of 100-ka depositional cycles on the Southern Tuscany continental margin (Tyrrhenian Sea, Italy): sequence architecture and margin growth pattern. *Mar. Geol.* 326, 1–13.
- Rosenbaum, G., Lister, G.S., 2004. Neogene and Quaternary rollback evolution of the Tyrrhenian Sea, the Apennines, and the Sicilian Maghrebides. *Tectonics* 23, TC1013. <http://dx.doi.org/10.1029/2003TC001518>.
- Ruppel, C., 1995. Extensional processes in continental lithosphere. *J. Geophys. Res.* 100, 24187–24215.
- Russell, S.M., Whitmarsh, R.B., 2003. Magmatism at the west Iberia non-volcanic rifted continental margin: evidence from analyses of magnetic anomalies. *Geophys. J. Int.* 154, 706–730.
- Sartori, R., 1989. Drillings of ODP Leg 107 in the Tyrrhenian Sea: tentative basin evolution compared to deformations in the surroundings chain. In: Boriani, A., Bonafede, M., Piccardo, G.B., Vai, G.B. (Eds.), *The Lithosphere in Italy*. Vol. 80. Accademia Nazionale Lincei, pp. 139–156.
- Sartori, R., 1990. The main results of ODP Leg 107 in the frame of neogene to recent geology of Perityrrhenian areas. In: Kastens, K.A., Mascle, J. (Eds.), *Proceedings of the Ocean Drilling Program, Scientific Results 107. Ocean Drilling Program, College Station, TX*, pp. 715–730.
- Sartori, R., 2005. Bedrock geology of the Tyrrhenian Sea insight on Alpine paleogeography and magmatic evolution of the basin. In: Finetti, I.R. (Ed.), *CROP Project: Deep Seismic Exploration of the Central Mediterranean and Italy*. Elsevier, Amsterdam, pp. 69–80.
- Schellart, W.P., Jessell, M.W., Lister, G.S., 2003. Asymmetric deformation in the backarc region of the Kuril arc, northwest Pacific: new insights from analogue modeling. *Tectonics* 22 (1047). <http://dx.doi.org/10.1029/2002TC001473>.
- Serri, G., 1990. Neogene–Quaternary magmatism of the Tyrrhenian region: characterization of the magma sources and geodynamic implication. *Mem. Soc. Geol. Ital.* 41, 219–242.
- Servizio Geologico d'Italia, 2013. Foglio 595 Palermo della Carta Geologica d'Italia alla scala 1:50.000. Coordinatore Catalano, R., Note illustrative a cura di Catalano, R., Avellone, G., Basilone, L., Contino, A., Agate, M. (218 pp).
- Tavarnelli, E., Renda, P., Pasqui, V., Tramutoli, M., 2003. The effects of post-orogenic extension on different scales: an example from the Apennine–Maghrebide fold-and-thrust belt, SW Sicily. *Terra Nova* 15, 1–7.
- Tesauero, M., Kaban, M.K., Cloetingh, S.A.P.L., 2008. EuCRUST-07: a new reference model for the European crust. *Geophys. Res. Lett.* 35, L05313. <http://dx.doi.org/10.1029/2007GL032244>.
- Trua, T., Serri, G., Rossi, P.L., 2004. Coexistence of IAB-type and OIB-type magmas in the southern Tyrrhenian backarc basin: evidence from recent seafloor sampling and geodynamic implications. In: *Mem. Descr. Carta Geol. Ital. LXIV*, pp. 83–96 (Rome).
- Weimer, P., Link, M.H., 1991. Global petroleum occurrences in submarine fans and turbidite systems. In: Weimer, P., Link, M.H. (Eds.), *Seismic Facies and Sedimentary Processes of Submarine Fans and Turbidite Systems*. Springer-Verlag, New York and Berlin, pp. 9–67.
- Whitmarsh, R.B., Miles, P.R., 1995. Models of the development of the West Iberia rifted continental margin at 40°30'N deduced from surface and deep-tow magnetic anomalies. *J. Geophys. Res.* 100, 3789–3806. <http://dx.doi.org/10.1029/94JB02877>.
- Zito, G., Mongelli, F., De Lorenzo, S., Doglioni, C., 2003. Heat flow and geodynamics in the Tyrrhenian Sea. *Terra Nova* 15, 425–432. <http://dx.doi.org/10.1046/j.1365-3121.2003.00507.x>.