The architecture and Neogene to Recent evolution of the W Calabrian continental margin: an upper plate perspective to the Ionian subduction system (Central Mediterranean)

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Abstract

The W Calabria continental margin forms the transition between the Pliocene to Recent Marsili spreading centre and continental Calabria, all parts of the upper plate of the Ionian subduction zone. Integrating high-resolution and crustal seismic images constrained by gravity modeling we provide a detailed reconstruction of the architecture of the margin and develop a new scheme for its Miocene to Present evolution. This time span encompasses the continent-continent collision between Africa and Eurasia, subsequent orogenic collapse and rifting apart between the two continental masses and the Pliocene to Recent emplacement of oceanic crust in the Vavilov and Marsili basins. The crust of the margin thins from the Calabria coast (~25 km) to the Marsili continent-ocean transition (~12 km). On the whole, upper and lower crust thin proportionally with pure shear geometry. The continental margin is covered by an Oligocene (?) to Present sedimentary succession reaching a maximum thickness of ~ 6.0 km in the Paola Basin. During the Miocene the continental margin experienced regional shortening accommodated by a large number of mainly W-vergent thrusts possibly associated with the late stages of the Kabilo-Calabrian chain. Shortening continued through Pliocene to Recent, but was accommodated by a limited number of W-vergent thrust faults located in the western part of the margin and by a few tens of kms wide syncline located in the eastern part of the profile. The accommodation space created in the syncline core hosted a ~4.5 km thick, Plio-Quaternary sedimentary succession, the Paola Basin. No significant extensional fault is observed along the profile. Miocene to Recent subsidence was controlled by i) a short wave length component related to shortening and responsible for the formation of the Paola Basin syncline and, possibly, contributing to the uplift of onshore Calabria, and ii) a long wavelength component responsible for the regional subsidence and ocean-ward tilting of the Calabria margin. Short wavelength subsidence ended in the late Pliocene but long wavelength downward movements persisted and even accelerated during late Pliocene (?) to Quaternary times when the present day bathymetry was achieved. Both horizontal deformations and vertical movements are difficult to explain in the context of a normal back-arc basin without taking into consideration patterns of secondary mantle flow generated by the retreat of the subducting slab.

1. Introduction

1.1. Background and goal of the paper

The Tyrrhenian Sea is one of the Tertiary to Recent back-arc basins developed within the frame of Europe-Africa convergence and, together with the shortening in the Apennines-Maghrebid orogen was mainly controlled by the NW-ward subduction of the Adriatic-Ionian plate. Following oceanic subduction and continental collision between Africa and Eurasia, the slab began to steepen and retreat towards the SE in the Early Miocene causing the opening of the
Ligurian-Provençal ocean first and then of the Tyrrhenian Sea [Malinverno and Ryan, 1986; Gueguen et al., 1998; Faccenna et al., 2007]. Oceanic accretion in the Tyrrhenian Sea was associated with the formation of two spreading centers, the Pliocene Vavilov Basin (4-2.5 Ma) and the younger Marsili Basin which is active since ~1.8 Ma [Kastens et al., 1988; Nicolosi et al., 2006; Sartori, 2001; Spadini and Podladchikov, 1996] (Figure 1).

The Tyrrhenian Sea is surrounded by the continental masses of Corsica-Sardinia in the W, Sicily to the S and peninsular Italy (inclusive of Calabria) in the E. The transition from the oceanic basin to the surrounding continents occurs by means of a system of continental margins thinning towards the ocean. The architectures of the E Sardinia and the N Sicily margins are relatively well-known [e.g. Mauffret and Contrucci, 1999; Pepe et al., 2000; Sartori et al., 2004; Trincardi and Zitellini, 1987] and numerical studies have addressed quantitative relations between thinning and subsidence [Spadini et al., 1995a, b and Pepe et al. 2004 for the Sardinia and Sicily margins respectively]. In contrast, very little is known on the continental margins of peninsular Italy and no tectonic work has been done to address their evolution during the Miocene.

The Tyrrhenian Sea and the continental domain adjacent to its SE part, the Calabrian Arc, have become areas of great interest to study the formation of back-arc basins and their relations with slab roll-back and steepening in a regime of overall convergence [e.g. Faccenna et al., 2007; Chiarabba et al., 2008]. The kinematics of Tyrrhenian ocean spreading is fairly well-known [Kastens et al., 1988; Patacca et al., 1990; Guegen et al., 1998; Sartori et al., 2004] and the kinematics of Alpine-Apennine deformations in Calabria and adjacent regions to the N (Campania) and to the W (Sicily) are well-constrained from the geological time span [Amodio Morelli et al., 1976; Bonardi et al., 2001; Grasso, 2001] to the GPS domain [D’Agostino and Selvaggi, 2004]. In addition, the present geometry of the Ionian-Tyrrhenian subduction zone is well-imaged by tomographic and seismological studies [e.g. Wortel and Spakman, 2000; Chiarabba et al., 2008].

In our contribution we focus on a poorly known but crucial part of the system, namely the west Calabria continental margin that connects the oceanic basin with the emerged Calabrian region. We do this by analyzing a WSW-ENE trending, ~120 km long transect from the oceanic crust of the Marsili Basin in the W, to the western shores of Calabria in the E. The transect crosses the Paola Basin, a major accumulation of Miocene to Recent sediments and valuable archive of information on the evolution of the region. The transect results mainly from the unpublished SISTER-11 seismic line, which provides a detailed image of the uppermost few kilometers of the crust inclusive of the Oligocene (?) to Messinian and Plio-Quaternary sediments, and is integrated with the high-penetration CROP-M27 line to constrain the thickness and architecture of the crust. The seismic profiles were interpreted, depth-converted, gravity-modeled and translated in a geological section through the margin. The section is then used to reconstruct horizontal and, more importantly, vertical movements experienced by the W Calabria continental margin from the
Miocene to Present. Integrating our conclusion with regional knowledge, we investigate the implications of our work for the evolution of the Tyrrhenian Sea and of the Ionian subduction zone.

1.2. The SE Tyrrhenian and the adjacent regions

1.2.1. First order features

The area of interest (Figure 2) includes the oceanic domains of the SE Tyrrhenian Sea (Marsili Basin), the adjacent continental masses of Calabria and Sicily with the Apennine-Maghrebian fold-and-thrust belt, and further to the E and S, a foreland composed of the Apulian platform, the Ionian ocean and the Iblean-Pelagian domain (Figure 1). In the Ionian abyssal plain, continental Calabria passes to a few hundred-km-long, SE-vergent, accretionary prism resulting from the offscraping and piling up of crystalline and sedimentary rock bodies named “External Calabrian Arc” [Finetti, 2005; Catalano and Sulli, 2006 with references].

The continental margins and the orogenic belts have an overall arched shape that was acquired during Neogene and Early Pleistocene times by anticlockwise and clockwise vertical axis rotations respectively of the Southern Apennines and of Sicily with the interposition of Calabria between the two domains [e.g. Mattei et al., 2007]. These rotations are not clearly seen in the GPS domain and seem to have terminated in the Quaternary together with Tyrrhenian spreading and foredeep migration [Mattei et al., 2007]. According to some authors, the Calabrian Arc is segmented by NW-SE trending transpressional shear zones interpreted on land [e.g. van Dijk et al., 2000; Tansi et al., 2007] and possibly continuing westwards in the southern Tyrrhenian [e.g. Finetti, 2005].

1.2.2. The continental margins

The oceanic crust of the SE Tyrrhenian passes to the surrounding continental masses through continental margins characterized by thinned crust with significant along-strike differences. In the Sicily margin, extension began in the late Miocene, ended in the late Pliocene and was associated with E to NE trending normal faults some of which bound important sedimentary basins (e.g. Cefalù Basin) [Fabbri et al., 1981; Pepe et al., 2000]. A short-lived episode of contraction occurred in the Early Pliocene [e.g. Pepe et al., 2005] possibly related to dextral transpression [Oldow et al., 1990].

The structure of the margin offshore W Calabria is not well known and characterized by the presence of sedimentary basins such as the Gioia Basin and, more importantly, the Paola Basin which is a roughly NNW-SSE trending depression hosting more than 4.5 km of Plio-Quaternary sediments [Bigi et al., 1989]. An extensional origin is attributed to the formation of the margin but rarely documented especially in the offshore domain.

Further to the N, very little is known on the segment of the margin connecting the Tyrrhenian oceanic crust (Marsili Basin) to the continental domains of southern Italy. Normal
faults are generally assumed but they are poorly documented and their kinematics is basically unknown.

1.2.3. The exposed fold-and-thrust belt

The Tyrrhenian Sea and its passive continental margins are surrounded to the E, SE and S by the Apennine-Maghrebid fold-and-thrust belt (Figures 1 and 2). From northern Calabria to Sicily, the orogenic belt is traditionally subdivided in three parts, the Southern Apennines, the Alpine Calabria Arc and the Sicilian-Maghrebides fold-and-thrust belt [Malinverno and Ryan, 1986; Bonardi et al., 2001; Grasso, 2001].

The Southern Apennines developed from Early Miocene to Early Pleistocene and consist of detached sedimentary nappes involving Triassic-Paleogene shallow water and pelagic, mostly carbonate rocks and Oligocene-Miocene turbidites, deposited in an eastward migrating foreland basin [Cavazza and Wezel, 2003; Elter et al. 2003 and references therein]. Towards the E, the Southern Apennines orogenic wedge is thrust on the Apulian foreland.

The core of the Calabrian Arc is formed by the Calabria-Peloritani Domain, which during early Miocene times was located adjacent to Corsica-Sardinia and drifted SE-wards reaching its present position juxtaposed with the Southern Apennine-Maghrebide orogenic system in the late Miocene [Bonardi et al., 2001; Mattei et al., 2002]. Schematically, the Calabria-Peloritani Domain consists of a Hercynian basement, Alpine poly-metamorphic rock successions related to the deformation of the Southern Tethyan margin and Mesozoic sedimentary units with Tertiary syn-orogenic sedimentary sequences [Bonardi et al., 2001]. Rocks of the orogenic basement in central Calabria were deformed in pre-Neogene times and exhumed through the \(^{39}\text{Ar}/^{40}\text{Ar}\) and apatite fission track closure temperatures before the middle Miocene possibly in an overall extensional regime (orogenic collapse) [Rossetti et al., 2004; Thomson, 1994].

In various localities, the nappe pile is covered by neo-autocthonous Upper Miocene (?) to Pleistocene sedimentary successions [Martini et al., 2001; Tortorici et al. 1995; Mattei et al., 2002]. Basins located in the internal part of the Calabrian Arc, such as the Amantea, Crati and Gioia Tauro basins (Figure 2), are often considered of extensional origin. Forearc basins developed in eastern Calabria in Neogene to Quaternary times [Bonardi et al., 2001; Cavazza and De Celles, 1997].

1.3. A transect from the Marsili Basin to the Ionian foreland

The deep subsurface of the region is characterized by the NW-ward plunging Ionian slab. Detailed tomographic images depict a nearly continuous plate reaching depths of > 500 km with dips up to ~70-80° compatible with the distribution of earthquake foci [Wortel and Spakman, 2000; Chiarabba et al., 2008; Neri et al., 2009] (Figure 3). The lithosphere underneath the Marsili basin is characterized by a thin mantle with very low Vs values probably associated with extensive melting.
Moving towards the SE, the mantle becomes thicker and acquires higher Vs values [e.g. Panza et al., 2007a]. Such trend is compatible with heat flow values decreasing from the Marsili basin (> 200 mW/m²) to the W Calabria coast (~60 mW/m²) [Della Vedova et al., 1995; Zito et al., 2003] and seismic tomography data [Piromallo and Morelli, 2003, Faccenna et al., 2004]. Some authors envisage a different scenario characterized by a thin to very thin lithospheric mantle underneath the entire W Calabria continental margin [Gvirtzman and Nur, 2001]. The lithosphere of the Ionian plate is ~130 km thick [Pontevedro and Panza, 2006].

Crustal thicknesses along the profile are better defined. The Moho is ~10 km deep under the Marsili Basin; ~15 km at the transition with the continental crust and reaches ~25 km under the west Calabria coast [Scarascia et al., 1994; Cassinis et al., 2005; Nicolich and Dal Piaz, 1991]. Further to the SE, the base of Ionian crust is ~35 km deep close to the Calabria coastline and gradually shallows to ~20 km (Figure 3) [Scarascia et al., 1994; Cassinis et al., 2005; Nicolich and Dal Piaz, 1991].

The Calabrian upper crust along the transect of Figures 2 and 3 is composed of an orogenic substratum [e.g. Bonardi et al., 2001; Rossetti et al., 2004; Cello et al., 1996] partly covered by a mainly post-orogenic sedimentary succession of Late Neogene to Pleistocene-Recent age [Bacini, 2003; Sedimentari, 1980; Bigi et al., 1989; Finetti, 2005]. The sedimentary cover is thin in the western part of the continental margin but is ~4.5 km thick in correspondence with the Paola Basin, by far the thickest accumulation of sediments of the region. The importance of strike-slip versus contractional or extensional deformations in controlling the evolution of the Paola basin and other Tyrrenian basins is debated [e.g. Argnani and Trincardi, 1988; Finetti, 2005; Guarnieri, 2006].

The onshore part of the profile is composed of an orogenic backbone exposed in the Catena Costiera and in the Sila Massif partly covered by Neogene post-orogenic basins in the west (e.g. Amantea and Crati basins) [Cifelli et al., 2007; Martini et al., 2001] and in the east (Crotone basin) [Amadio Morelli et al., 1976; Cavazza and De Celles, 1998; Zecchin et al., 2004]. Sediments of the Amantea basin are exposed along the western coast of Calabria a few kms to the S of our transect. They dip gently to the W and could represent, therefore, the eastern, onshore continuation of the eastern part of the Paola Basin. The Crati basin, lies further to the E and is separated from the Amantea basin by the outcropping basement of the Catena Costiera. According to most, but not all authors [e.g. Argentieri et al., 1998; Cifelli et al., 2007; Cesarano and Turco, 2002] the Neogene basins in the internal part of the Calabrian arc are controlled by extensional tectonics. In the eastern reaches of the Sila Massif, post-orogenic, middle-upper Miocene marine deposits rest on top of the crystalline complex and sedimentary nappes of the Calabria-Peloritani Arc. The succession is locally named Crotone basin and is continuous with less known offshore Crotone-Spartivento basin.
forming a Tortonian to Quaternary forearc basin developed on top of the Ionian accretionary wedge [Rossi and Sartori, 1981].

In the E Calabria offshore, the accretionary wedge is composed of a poorly resolved pile of mainly SE-vergent thrust sheets partly covered by Mio-Pleistocene deposits, filling basins sealing the main structures [e.g. Catalano and Sulli 2006].

2. The seismic lines

Our study is mainly based on the unpublished multi-channel SISTER-11 seismic line [Bertotti et al., 1999] which images in great detail upper crustal features such as the Oligocene (?) to Present sediments across the margin and provides information on the geometry of the Paola Basin and of the underlying Kabilian-Calabrian units (Figure 2). To constrain the first order features of the continental crust we make use of the high-penetration CROP-M27 seismic line [Scrocca et al., 2003; Finetti, 2005]. The profiles were interpreted, time-to-depth converted and combined to produce a geological profile across the margin that was further defined using refraction and wide-angle seismic data, and tested by gravity modeling. Because of the absence of a detailed velocity model for the middle to lower crust (the target of this part of our study), the CROP-M27 seismic line was not migrated. This bears no significant consequences for the first-order information which we extract from the CROP-M27 line, namely crustal thickness values and, more specifically, their lateral changes.

2.1. The SISTER-11 line

2.1.1 Data acquisition and processing

The SISTER-11 line was recorded in June 1999 by a joint project between the Istituto Geomare Sud of Napoli (CNR) (presently Istituto per la Geologia Marina e dell’Ambiente Costiero, IMAC), the Faculty of Earth Sciences of the VU University of Amsterdam and the Dipartimento di Geologia e Geodesia of Palermo University. The line is ~95 km long and runs in a WSW-ENE direction, from the Marsili basin to the W Calabria coast (see Figure 2 for location).

The acoustic source used during seismic prospecting was a 75 cubic inch air gun fired at 25 m interval. Data were recorded with a 12-channel streamer, with 25 m inter-channel distance, for 7.0 s two way time (TWT) at 1000 Hz (1 ms) sampling rate. Both positioning and shot interval (12.5 m) were controlled by Differential Global Positioning System. Pre-stack data processing was performed using the following mathematical operators: sorting of the Common Depth Point (CDP), velocity analysis on every 50 CDP, normal move-out, stack of the CDP. The following algorithms were applied after stack: time-migration, “Surface-Related Multiple Attenuation” (algorithm for multiple attenuation), traces mixing, time variant filters, automatic gain control, time variant gain and spherical divergence correction.
258.1.2 Seismo-stratigraphic analysis

In seismic line SISTER-11 we have defined five seismic stratigraphic units characterized by distinctive changes in seismic properties and limited by marker reflections. Units A-D (from bottom to top) are found on continental crust while unit E is at the continent-ocean transition (Figure 4).

Unit A is the lowest seismic unit and is characterized by discontinuous reflections with variable amplitude and frequency (box a in Figure 4) underlying a high-amplitude reflection of variable lateral continuity (tA in box a of Figure 4). We associate seismic unit A with the upper part of Kabilian-Calabrian units that includes imbricate sheets of Hercynian basement, Alpine poly-metamorphic rock successions and Mesozoic sedimentary units.

Unit B is the first sedimentary cover unit and is characterized by medium amplitude, discontinuous reflections (box a in Figure 4). Unit B has a lower part where reflections are parallel to the top of unit A and an upper one in which reflections are sub-horizontal and onlap horizons of the lower sub-unit (Figure 4, box a). On the whole, unit B fossilizes pre-existing topography and is, therefore, the thickest between (fault-controlled) highs of the Kabilian-Calabrian units. Because of its stratigraphic position and seismic signature we correlate unit B with the Oligocene (?) to lower Messinian clastic to terrigenous deposits widespread in the southern Tyrrhenian Sea [Bacini Sedimentari, 1980] and unconformably overlying the Kabilian-Calabrian units in Calabrian Arc (Figure 5) [Bonardi et al., 2001, Elter et al., 2003].

Unit C is bounded at the top by reflector “M” (boxes b and c in Figure 4), a horizon of regional importance associated with the top of evaporites deposited during the late Messinian salinity crisis or to an erosional unconformity formed during the late Messinian sea level fall [Malinverno et al., 1981 and references therein]. Two distinct seismic signatures are observed in unit C corresponding to shallow- and deep-water (redeposited) evaporites. Shallow-water evaporites (Figure 4, box b) are characterized by parallel and relatively continuous reflections. Evaporites resedimented in deep water (Figure 4, box c) produce discontinuous but sub-parallel reflections of moderate amplitude bounded upward and downwards by continuous reflections of moderate amplitude. Most of the evaporites found along SISTER-11 are of shallow water environment and redeposited evaporites are found only in the deeper parts of the Paola basin.

Unit D overlies the “M” horizon and is generally defined by continuous and moderate to high-amplitude reflections (box d in Figure 4). It can be correlated with the Plio-Quaternary sedimentary succession widespread in the Tyrrenian [Bacini Sedimentari, 1980; Kastens et al., 1988] (Figure 5). We have subdivided unit D in four sub-units named D1-4 from bottom to top. Sub-unit D1 has discontinuous, moderate-amplitude reflections and is marked at the top by a high-amplitude and well-defined laterally continuous event. Reflections inside D1 are generally parallel to the M horizon but, locally, they can onlap it. In some regions, reflections become divergent or...
acquire clinoform patterns. The time-thickness of D1 varies due to the irregular morphology of the underlying top of Messinian and the internal geometry of clinoforms and reaches its maximum values west of the depocenter of the Paola Basin (see section 4.2.2).

Sub-unit D2 has typically parallel, discontinuous and moderate- to low amplitude reflections which become continuous and with higher amplitude in the upper part of the sub-unit. In the Paola basin, reflections diverge slightly towards the depocenter and display a clinoform geometry moving westward. In the area between CDP 2750-3000, a number of normal faults, with limited apparent slip, offset strata of sub-unit D2 defining a region of intense deformation. Where visible, the D2 upper limit is a strong and continuous reflector. Sub-unit D2 becomes thinner to the W of CDP 3032500 and eventually loses its continuity approaching the Marsili basin. Consequently, outside the Paola Basin sub-units D1 and D2 are mapped together (D1-2) in the sections of Figure 4 and Plate 3051 (see next section).

Sub-unit D3 shows high-frequency, well defined reflections with good laterally continuity. In the Paola Basin, D3 reflections onlap the underlying D2 unit towards the E, but become parallel to it westwards. The D3 upper limit is a strong and continuous reflection that becomes an erosional surface towards the ridge west of the Paola basin (CDP 2800-3000).

Sub-unit D4 has well organized and continuous reflections over most of the profile with the exception of the area of the continental slope where they are chaotic. Reflections of sub-unit D4 are basically sub-horizontal and fossilize pre-existing morphologies.

Unit E is found at the continent-ocean transition and corresponds to a zone of disturbed reflections, limited upward by high-amplitude, locally continuous reflectors partly covered by a thin layer of sediment-derived horizons (box e in Figure 4). We associate Unit E with magmatic intrusions.

2.1.3. Depth conversion

Following the seismic facies analysis, the SISTER-11 line was depth-converted. As no information is available on the velocities of recognized seismic units in the west Calabria continental margin, we have adopted average velocities (Figure 5) from litho-stratigraphy and sonic log data available for coeval deposits in 7 wells drilled offshore southern and western Sicily (Table 3231). We did not consider seismic velocities of the Plio-Pleistocene interval measured at ODP site 324654 as they are obtained from a succession much thinner (0.250 km vs 4.5 km) than the one observed in the investigated continental margin. The values we have used are 2100, 3300 and 2800 m/s for the Plio-Pleistocene, Messinian evaporites and pre-Messinian sedimentary rocks respectively. A value of 5500m/s was used for the crystalline rocks forming Kabilian-Calabrian units as well as for the magmatic intrusions (unit E). The uncertainties implicit in our approach bear no significant consequences for the tectonic reconstructions we present.
The obtained depth-converted section is displayed without vertical exaggeration (Plate 1) to highlight the structural setting of the Kabilian-Calabrian chain and with V.E. = 2:1 to better display the architecture of its Plio-Quaternary sedimentary cover (see next paragraphs).

2.2 The CROP-M27 line

2.2.1 Acquisition and depth conversion

The CROP-M27 profile was shot in 1991 by the Osservatorio Geofisico Sperimentale of Trieste. An air-gun array of 4906 cubic inches and a ninety-channel streamer, with 25m inter-channel distance, were the hardware components used during seismic prospecting. Shot interval was 100m, resulting in 23-fold coverage. Seismic signals were recorded for 30.0s/TWT at 4 ms sample rate. The processing sequence applied to the seismic data included the following mathematical operators: geometry definition, sum of two adjacent traces, amplitude recovery, predictive deconvolution, multiple attenuation, velocity analysis, normal move out and stack of the CDP, F-K filter, and time variant filters.

2.2.2 Seismo-stratigraphic interpretation and depth conversion

Seismo-stratigraphic analysis of line CROP-M27 was applied only to the domain underneath units B and C which are much better imaged in the SISTER-11 line and which were defined in section 2.1.2. The analysis of CROP-M27 was performed using seismic attributes (amplitude, frequency and lateral continuity) and internal and external geometries of seismic bodies. The highest unit identified in profile CROP-M27 (unit A in Figure 6) is characterized by low-frequency, discontinuous and somewhat chaotic reflections and stretches basically over the entire profile. Unit A has a fairly constant thickness of ~3.5s/TWT underneath the Paola Basin (CDP 1500-1200), thickens to ~4.5s between the Paola Basin and Alcione Volcano, again thins westward to 2s towards the Marsili basin and eventually disappears approaching the western end of the continental crust. In the lower part of unit A, often underneath a wavy, high-amplitude and discontinuous horizon, reflections become more regular. On the whole, we interpret Unit A as associated with the Kabilian-Calabrian units. The upper interval of Unit A corresponds to the more deformed portion of the tectonic edifice.

The lower crustal unit (LC) is a layer between unit A and the band of reflections associated with the Moho (Figure 6). The upper part of unit LC displays high frequency and high amplitude reflections while its lower interval is nearly transparent. Thickness of unit LC is ~3s/TWT underneath the Paola Basin that thins towards the Marsili basin to ~1.5 s/TWT.

The Moho is imaged as a band of reflections at the bottom of unit LC, roughly between 8.5 and 12s/ TWT reaching its largest depths underneath the depocenter of the Paola Basin. A few, low amplitude, discontinuous and low frequency reflections are visible underneath the Moho and bright spots can be recognized, for instance, underneath the Paola Basin and Alcione Volcano.
At the western termination of the CROP-M27 line we have defined an oceanic crust unit (OC) which is characterized, from top to bottom, by high-frequency, well defined reflections with good laterally continuity (L3), low-frequency discontinuous reflections (L2) and high-amplitude, high-frequency events (L1). Reflections of Unit OC can be laterally tied to ODP Site 650 well data [Shipboard Scientific Party, 1987] where units L1 and L2 correspond to layers 1 and 2 of the oceanic crust. Layer 2 is overlain by ~600 m of unconsolidated volcanoclastic and pelagic sediments the base of which has been dated at ~1.8 Ma thereby providing a lower boundary for the onset of ocean spreading [Shipboard Scientific Party, 1987].

The line-drawing interpretation was depth-converted using velocities derived from the Aeolian Islands-Calabria wide-angle profile [Scarascia et al., 1994] and gravity tested (see next section). The adopted seismic velocities are shown in Figure 6 and specified in Table 2 (Unit D1-4, 3782100 ms\(^{-1}\), C, 3300 ms\(^{-1}\), B, 3000 ms\(^{-1}\), A 5500-6000 ms\(^{-1}\), LC, 6500-7500 ms\(^{-1}\)).

2.2.3 Gravity modeling

To cross check the crustal structure derived from the depth-converted CROP-M27 and SISTER-11 lines (I-II in Figure 7) we have Bouger gravity-modeled a 240 km long profile from the Tyrrenian to central Calabria (A-A’ in Figure 7). To reach and include in our analysis the lithospheric mantle and the underlying asthenosphere, we have adopted a 640km long transect, substantially longer than the CROP-M27 line (Figure 7).

Gravity modeling in the region is hampered by two major uncertainties. The first one is the insufficient knowledge of how much of the present topography is dynamically sustained. Dynamic topography is known to be important in back-arc basins [e.g. Husson, 2006] and is probably important in the SE Tyrrenian basin which does not seem to be in isostatic equilibrium [Caratori Tontini et al., 2007]. In addition, dynamic processes are probably responsible for the too-deep position of the Marsili basin deeper than what predicted by thermal subsidence models [Kastens et al., 1988; Spadini et al., 1995]. In the absence of quantitative estimates and similarly to what done by Gvirtzman and Nur (2001) we will neglect the role of dynamic topography. This approach does not have significant consequences on estimates of crustal thicknesses of the W Calabria margin which is the object of interest to this study.

The second source of uncertainty is the poorly resolved (lithospheric or asthenospheric) nature of the wedge between the Calabria continental crust and the subducting Ionian lithosphere (see section 1.3.1). To honor these uncertainties, we examined two end member gravity models and present the one which gives the best fit. Similarly to what previously mentioned, the consequences for the goal of this study, namely, estimating correctly crustal thicknesses, are minor.

Gravity anomaly data has been extracted from the Bouguer gravity maps of Italy and of the Tyrrenian Sea [Carrozzi et al., 1986 and Morelli, 1970 respectively]. The Bouguer gravity field of the Tyrrenian region is dominated by a long wavelength, high-amplitude, positive anomaly (+250...
mGal) coincident with the site of maximum lithospheric thinning beneath the Tyrrhenian bathial
plain. The SE margin of the Tyrrhenian anomaly is marked by local gravity lows positioned along
the W Calabria offshore from the Gulf of Polistena to the Gulf of S. Eufemia. The most important
of these negative anomalies coincides with the Paola Basin (Figures 2 and 7).

The gravity profile (Figure 8) was digitized with steps of ~1.6 km and interpreted using a
2.5D technique allowing the data inversion for density and thickness of any layer [Fedi, 1989]. The
lateral widths (strikes) of all layers across the section were assigned taking into account the
presumed geological setting of the structures on the opposite sides of the profile.

Gravity modeling was extended to 90km depth. This is justified by the fact that deeper
causative sources are either not relevant or accounted for in a different manner. The first source, the
upwelling mantle underneath the Tyrrhenian Basin is only important above 90-100km, the depth at
which partial melting starts being important [Cella et al., 2006]. The effect of the second source,
the subducted slab is accounted for with the backstripping procedure described below. We have
estimated the effect of the third, causative source, the rise of the boundary between upper and lower
asthenosphere from ~300 to ~250 km depth beneath the Southern Apennine-Calabrian Arc [Panza
et al, 2007b] was computed performing Vs-density conversion following the Nafe and Drake
[1963] rule. The resulting anomaly amplitude is small (~20 mGal) and explained by the small
density contrast (~0.1 g/cm³), the great depth to the source and the long wavelength anomaly.

We have removed from the measured gravity profile the broad positive anomaly associated
with the slab subducted beneath the Tyrhenian Sea as obtained from a 2.5D finite element density
model accounting for three main variables: (i) heating by conduction from the hotter
asthenosphere; (ii) advection of heat in the moving slab; (iii) heating by compression of the
asthenosphere [Cella et al., 2006]. The oceanic crust of the Ionian slab was not modeled at depths
>40 km, where the basalt-eclogite transition occurs, because its density should reach values
comparable with those of the mantle lithosphere. The backstripping technique was chosen since the
gravity effect of the modeled structures can hardly be split into meaningful components by
numerical filtering.

Densities assigned to the elevated mantle are consistent with the petro-physical changes it
experienced during partial melting due to adiabatic decompression and computed using the
geothermal scheme of the Tyrhenian Basin [Zito et al., 2003] and the partial melting model by
McKenzie and Bickle [1988] [Cella and Rapolla, 1997]. The model assumes only pressure and
temperature variations within the mantle, whereas also compositional differences should be taken
into account [Panza et al., 2007a]. However the procedure provides reliable density estimates for
our purposes, using (i) the potential temperature of the mantle (T_p = 1330° C), (ii) the degree of
lithospheric thinning (β=6-7) and (iii) the lithospheric thickness before stretching (115-130 km)
[Hutchison et al., 1985; Pasquale et al., 2003; Zito et al., 2003] to predict the amount and
composition of the melt fraction and the modal norm and density of the solid rock after melt segregation.

The depth of the Moho beneath the Tyrrhenian basin was derived from previous geophysical studies [Nicolich, 1989; Scarascia et al., 1994 and references therein]. Our modeling took advantage of recent geophysical studies based on nonlinear inversion of Rayleigh surface-wave dispersion data [Suhadolc and Panza, 1989; Pontevivo and Panza, 2006; Panza et al., 2007a; Panza and Raykova, 2008]. They updated information about the deep structure of the Italian region by averaging the mechanical properties with a resolution (cells sized 1·1º) able to provide references at regional scale to constrain the location of Moho and LAB.

Densities of the different units (Table 2) have been checked converting their seismic velocities using the Gardner rule as a general guide [Gardner et al., 1974, Potter and Stewart, 1998]. Values assigned to Layers 2 and 3 (“ocean-like” crust) were cross-checked with experimental data [Carlson et al., 1988].

The best fit model we obtain (Figure 8) shows a quasi optimal agreement with the crustal section constrained by seismic reflection and surface-wave dispersion data [Panza and Raykova, 2008] with some deviations associated with the Moho depth in the central segment of the section. The top of asthenosphere beneath the central sector of the Marsili Basin was detected at ~20 km depth, consistent with recent evidences [see cell B4 in: Pontevivo e Panza, 2006; Panza and Raykova, 2008]. Moving eastward, the mantle lithosphere rapidly thickens up to 80-90 km beneath the W Calabria continental margin and the Calabrian crustal wedge which overlies the Ionian slab.

3. A section across the W Calabria continental margin

3.1. The crustal picture

The overall crustal configuration of the west Calabria continental margin as derived from integrated analysis of the CROP-M27 and SISTER-11 lines and gravity modeling is shown in the upper panel of Figure 9. The Moho lies at a depth of ~35 km beneath the Calabria Arc (Sila Massif) and rapidly shallows up to ~25 km in correspondence with the Calabria coastline. Westward, the Moho slightly deepens again to a depth of ~27 km in correspondence with the depocenter of the Paola Basin and then climbs gently and regularly reaching a depth of ~15 km at the end of the profile corresponding to the continent-ocean transition. Farther west, the ~10 km thick oceanic crust of the Marsili basin is recognized. These results are consistent with estimates from inversion of surface-wave dispersion data (cells B4, B5 and B6 of Panza and Raykova [2008]).

To track changes in crustal thickness and, thereby, the obvious thinning experienced by the west Calabria continental margin we plot thinning factors (defined as $\delta = (\text{initial thickness})/(\text{final thickness})$) along the transect assuming an initial crustal thickness of 35 km corresponding to the present-day Moho depth underneath the Calabria Arc (Figure 9). As no extension is documented in
the geological record and in seismic lines from Pliocene to Quaternary times, we assume that 476
crustal thinning occurred before the Pliocene and, therefore, disregard Pliocene to Quaternary 477
sediments in computing final crustal thickness values. Five kilometers wide boxes have been used 478
for calculations.

Crustal thinning starts becoming important in correspondence with the W coast of Calabria 479
and, on the whole, shows then a fairly gradual increase from the E to the W leading to a thinning 480
factor of ~3.2 at the continent-ocean transition (Figure 9). With respect to a best-fit straight line, 481
only minor deviations are observed in the central sector and in the continent-ocean transition zone 482
which we do not consider as significant. A different picture is provided by thickness changes of the 483
upper crust inclusive of the unit A (Kabilian-Calabrian units) and the overlaying pre-Pliocene 484
sedimentary succession. Thinning factors are obtained adopting the thickness of the upper crust 485
underneath continental Calabria (~27 km) as the initial value. The overall trend (straight line in 486
Figure 9) is essentially similar to that of the entire crust suggesting that regional thinning affected 487
equal amounts the upper and lower crust. Two local deviations are observed underneath the 488
Paola Basin and towards the zone of the continent-ocean transition where upper crustal thinning is 489
larger than the crustal one.

3.2. The sedimentary cover

3.2.1. The pre-Pliocene succession

Oligocene (?) to Messinian deposits (units B and C) are interpreted all along the profile, but 496
they are grouped together in a single unit in the distal part of the margin because of insufficient 497
resolution of the data (Plate 1). On the whole, they tend to fossilize pre-existing topography and 498
reach, therefore, the largest thicknesses between (fault-controlled) basement highs (e.g. CDPs 600- 499
99900 and E of CDP 2400). Thicknesses in the Paola Basin area are around 1200 m and not 500
significantly different from the surrounding regions. In more detail, Oligocene (?) to lower 501
Messinian sediments display a lower sub-unit (see section chapter 2.1.2) with fairly constant 502
thickness of ~200 m conformably covering basement and an upper one which onlaps the gently 503
folded and faulted lower one.

Messinian evaporites and associated deposits (unit C) are widespread along most of the W 504
Calabria continental margin typically with a thickness of ~400 m. In the central sector they 505
unconformably overlie the Oligocene (?) - lower Messinian sediments. In the Paola Basin, on the 506
contrary, internal reflections generated by both shallow- and resedimented evaporites are sub- 507
parallel to those of the underlying unit B. Deep water resedimented evaporites reach their 508
maximum thickness of ~1000 m in the Paola Basin.
Plio-Quaternary deposits (unit D) are found over the entire transect and display substantial variations in thickness and tectonic style (Plate 1). They are ~1.0 km thick at the E termination of the line, thicken up to 4.5 km in the depocenter of the Paola Basin and decrease first rapidly to ~1.5 km at CDPs 2200-2300 and then, more gently to <800 m at the end of the line.

Sub-unit D1 (see chapter 2.1.2) appears ~5 km from the eastern termination of the line (Plate 1) and within a few kilometers reaches a thickness of ~1.5 km close to the depocenter of the Paola Basin. The westward thickening of D1 is controlled by a set of W-vergent thrust faults (see below). Thickness of unit D1 remains fairly constant until CDP 2900 and then decreases to <1000 m around CDP 2600. Thinning of unit D1 is associated with W-ward dipping clinoforms.

Sub-unit D2 (Plate 1) starts at the eastern end of the line, and has a thickness of ~800 m which increases gradually to ~2000 m in the Paola basin. It then thins to ~900 m in the proximity of CDP 2950 and reaches a thickness of ~500 m at CDP 2600. Thinning between the Paola Basin depocenter and CDP 3000 goes together with W-ward convergence of reflections. Thinning between CDPs 2800 and 2600 is associated with west-ward dipping clinoforms downlapping on the top of subunit D1.

From CDP 2400 to the western termination of the line, sub-units D1 and D2 could not be differentiated and have been grouped in subunit D1 + D2. This overlies and is conformable with strata of unit C (Plate 1). Thicknesses are ~1000 m at CDP 2400, very gently decrease to ~600 m at CDP 1500 - 1600 and remain constant further to the W.

Sub-unit D3 is detectable over most of the margin. It displays important variations in thickness varying from ~600 m in the area close the depocenter of the Paola Basin to less than 100 m in the central and distal sector of the margin. Reflections in sub-unit D3 are basically horizontal east of the depocenter of the Paola Basin, and west of CDP 1400. In both areas they onlap underlying tilted units. In the intervening region, D3 reflections drape the underlying units.

Between CDPs 2800 and 3000, the top of sub-unit D3 is slightly erosive.

Sub-unit D4 is characterized by well-defined and laterally continuous events except in the area close to the continental slope where it exhibits chaotic and discontinuous reflections. Thickness of unit D4 varies from ~450 m in the area close to the continental slope to less than 80 m in the deformed area west of the depocenter of the Paola Basin (CDP 2750-3000, Plate 1) and farther to the west. As reflections in sub-unit D4 are basically horizontal (apparent dip < 1°), they onlap underlying units and display thickness changes related to older deformation and sedimentary geometries. The absence of deformation in this area and farther to the west demonstrates post-kinematic deposition.
A variety of faults is observed along the west Calabria continental margin transect (Plate 1). Although they rarely have displacements larger than a few hundreds of meters they document tectonic regimes active in the region through time.

Three fault systems associated with positive flower structures are observed at CDPs 2250-2550, 1350-1500 and 950-1200 (Plate 1). Faults are generally reverse, have small offsets and typically converge at depth into vertical faults. Some of the faults in the easternmost flower structure could be a reactivation of older E-vergent thrusts. Most faults are sealed by Messinian sediments but persistent activity is locally observed at CDP 2400. In the absence of 3D information, we cannot say much on the direction and length of the flower structures. If comparable to the roughly N-S trending structures recognized in the onshore, they could be secondary features associated with overstepping between NW-SE striking sinistral strike-slip faults [Tansi et al., 2007].

Thrust faults, predominantly dipping to the E, are quite common along the profile especially in the eastern side of the Paola basin where they affect pre-Pliocene rocks (present day dips between 18° and 28°). In contrast, shortening affecting Pliocene and younger layers is more localized and is basically concentrated in the western part of the section between CDPs 500 and 563 (Figures 10a and 10b).

Few normal faults, dipping 30-40° to the E and W, are observed between CDPs 2400 and 565. Faults generally have small displacements up to few hundreds of meters and end in sub-units D2 or D3 (Figure 10c). One normal fault dipping ~60° to the W, located around CDP 1400, has a larger offset of ~580m. 3D bathymetric data suggests a NNW-SSE trend for this fault.

3.3. The continent-ocean transition

At the western end of the SISTER-11, at the transition between continental and oceanic crust (CDPs 100 and 300), a domain with chaotic reflections has been defined (unit E in section 2.1.2) which we have interpreted as associated with magmatic intrusions interrupting the continuity of the Kabilian-Calabrian crust (Plate 1 and Figure 11a). The dispersion of volcanoclastic sediments could be responsible for the loss of seismic signal to the E of the magmatic zone between CDPs 50 and 500 (Plate 1).

The bathymetric map reveals that the area of magmatic bodies is located at the base of a seamount ~20 km long, ~12 km wide and elongated in NNE direction, parallel to the strike of the Marsili Seamount (Figure 11b). A bathymetric profile across the seamount (Figure 11c) documents a substantial difference between the sea floor depth to the E and to the W of the edifice (2.4 and 3.5 km respectively) possibly related to a W dipping normal fault.

4. The Paola basin
4.1. Architecture

4.1.1. The overall shape

The Paola basin is the largest accumulation of Pliocene to Present sediments in the SE Tyrrenian region. Pre-Pliocene deposits (units B and C in the previous sections) do not show significant thickness changes in the region of interest (Plate 1) and are, therefore, considered to precede the development of the Paola Basin.

On the whole, the Paola Basin has the shape of an asymmetric syncline (Figure 12). The basin floor (base of unit D) descends from a depth of ~1 km at the eastern termination of the line to 5 km in the depocenter of the basin (CDP 3200 located ~15 km to the W of the line end) resulting in a W dipping slope of ~17°. Such steepening is mainly a consequence of gently dipping, W-vergent thrusts. West of the depocenter, the basin floor gently shallows to depths of ~2.5 km (CDP 2550) with a slope decreasing from 11° to 8°. From CDP 2550 westward, the basin floor remains basically flat and we adopt CDPs 2500-2600 as the conventional western boundary of the Paola Basin.

4.1.2. The internal architecture

Sub-unit D1 has a thickness of ~2.3 km at the depocenter of the basin (CDP 3200). Towards the E, thicknesses decrease as the D1 reflections onlap the top of the basin substratum steepened by the W-vergent thrusts. The uppermost part of D1 passes the steepened margin and gently onlaps the undeformed M horizon pinching out at ~ CDP 3600, a few kilometers to the E of the last thrust. From the depocenter westwards, D1 has a remarkably constant thickness associated with parallel reflections until CDP 2900 where it thins to <1 km at the termination of the basin (CDP 2600). Thinning between CDPs 2900 and 2600 is associated with clinoforms in the upper part of D1 which are now sub-horizontal but acquire an W-ward dip once compensated for overall tilting of the western flank of Paola Basin (Figures 12 and 13).

Reflections of sub-unit D2 have a clear divergent pattern from the eastern termination of the line where D2 is <1 km thick, to the depocenter where its thickness is ~2.0 km. Thicknesses of D2 start decreasing again from CDP 3150 and are ~1 km from CDPs 2950 to 2700 diminishing to < 120.5 km at the termination of the basin. Thinning of D2 from the basin depocenter to the W is associated initially (CDPs 3150-2950) with a westward convergence of the reflections, especially in the upper part of the sub-unit. From CDPs 3000 to 2750, the top of D2 is formed by and erosional surface gently cutting down-section towards the W. The thinning observed between CDPs 2750 and 2600 is associated with the presence of W-ward dipping clinoforms downlapping onto sub-unit D1 (Figure 13).

Sub-unit D3 is ~0.5 km thick at the centre of the basin where its reflections are basically sub-horizontal. Towards the E, reflections remain sub-horizontal, onlap the gently W-ward dipping substratum but become chaotic in the last 4-5 km of the section. A different pattern is observed in
the western flank of the basin as reflections converge towards the W resulting in a thinning to values of few hundreds of meters. From CDP 3000 to the W, D3 remains constantly thin with reflections parallel to those of underlying sub-units.

Sub-unit D4 is characterized by the horizontal position of the reflections which seal the underlying topography. This is apparent both in the eastern and western sides of the basin where D4 reflections onlap the basin-ward tilted reflections of D3. As a consequence, the thickness of D4 is greatest around the depocenter of the basin (~0.8 km) decreasing both to the E and to the W. West of CDP 3000, D4 is merely a thin group of reflections parallel to their substratum.

4.2. Tectonics of the Paola Basin

4.2.1. Method

Based on the detailed reconstruction we have made of the architecture of the Paola Basin and on the stratigraphic and paleobathymetric interpretation inferred from the analysis of seismic facies we have constructed a model for the evolution of the basin from the Pliocene to Present (Figure 14). The evolution is summarized in four sections representing the Paola Basin at moments corresponding to the top of the four sub-units distinguished in previous sections, D1, D2, D3 and D4 (this corresponding to the Present situation). The stratigraphic or absolute ages of these horizons are unknown. To construct the sections we have i) removed the sediments younger than the time step, ii) predicted the paleobathymetry mainly using information from the seismic lines and relying in particular on the topsets-foresets geometries observed in different sub-units; iii) “hanged” to the bathymetric profile the underlying part of the section inclusive of thicknesses of sedimentary bodies and their internal geometry. Because of the lack of density and lithology data, sediments thicknesses have not been corrected for compaction. Respecting bed lengths, our reconstruction takes into account also the shortening experienced by the section during the evolution of the basin.

To better visualize vertical movements experienced by the different localities of the Paola basin we have constructed subsidence curves using thickness data and our paleobathimetry estimates from synthetic wells (1, 2, 3 and 4 in Figure 14). In the absence of constraints on the ages of the different sub-units, we have assumed that the duration of the corresponding time intervals is proportional to their relative thickness measured in the central parts of the basin.

4.2.2. The evolution of the Paola Basin

The early Pliocene topography and morphology of the west Calabria continental margin transect, at the beginning of the development of the Paola Basin are not well constrained. We assume a generally flat morphology as suggested by the fairly constant thickness of Messinian sediments (unit C) and the lack of major erosion and deformation features (Plate 1). We also
assume that a water column of few hundred meters was present which could host the prograding system developed during D1 (see below).

Immediately before or during the initial stages of the D1 time interval, the basin floor and underlying formations in the eastern part of the section steepened to 10-15º as a consequence of the activation of a set of W-vergent thrusts which might have led to the development of topography to the E of the section. The exposed region was probably the source area for D1 sediments which were shed into the Paola basin. Coeval with and following steepening, regional subsidence affected the Paola basin allowing for sediment aggradation and for the progressive onlap of the uppermost part of D1 on the gently E-ward tilted Messinian sediments in the E of the section. Sea floor morphology at the end of D1 (Figure 14a) is constrained by a topset-foreset transition (presently located at CDP 2900) separating a shallow depression in the E from a several hundred meters deep bathymetry to the W (Figures 12 and 13).

During the D2 time interval (Figure 14b), thrusting in the eastern part of the section ended but shortening continued leading to the incipient development of the Paola basin syncline as documented by D2 reflections diverging towards the basin center. Subsidence affected most of the section although with different magnitudes (Figure 15). The strongest subsidence is recorded in the central part of the basin, corresponding at present to CDPs 3200-3300. Here, sediment input did not keep pace with subsidence and a paleo-bathymetry of a few hundred meters developed which will be filled during D3 (see below). The amount of subsidence gradually decreased from the depocenter towards the E as shown by the W-ward diverging reflections. Here, subsidence affected also previously exposed areas and D2 sediments reached the eastern end of the section. The amount of subsidence decreased also to the W of the basin depocenter where a number of W- and E-dipping normal faults offset reflections in the upper part of D2 over a width of several kms along the section. To the W of the deformed area, W-dipping foresets document the presence of a paleo-bathymetry and the arrival of sediments by-passing the emerged area (Figure 14b). No erosion is observed suggesting a position just below sea level.

Time interval D3 (Figure 14c) marks the beginning of the end of the evolution of the Paola Basin. Subsidence was still ongoing but reflections in the central and eastern parts of the section are sub-horizontal and onlap the W-ward tilted D2. At the eastern termination of the line, D3 reflections laterally pass to a more chaotic zone suggesting the presence of a slope with gravitational mass movements. The magnitude of subsidence was decreasing from the basin center to the W of the basin depocenter (Figure 15) where an erosional surface developed over an along-section width of several kms and which we interpret as resulting from sub-aerial exposure.

Reflections in sub-unit D4 (Figures 13 and 14) are sub-horizontal and onlap older subunits both in the E and the W filling and smoothing pre-existing morphology, thereby marking the end of shortening. Subsidence (Figure 15) was however, generalized and, not being compensated by sufficient sediment input, led to the development of the present day bathymetry.
4.2.3. The role of sediment loading

Obviously, part of the subsidence which created the Paola basin is due to the load exerted by the sediments deposited in the area. Using standard equations [Allen and Allen, 1990] and a local isostatic compensation approximation, we have estimated the relative importance of sedimentary and tectonic loading. Using parameters shown in Table 2 we have calculated the position of the base of the Paola Basin (corresponding to the horizon M) in the absence of sediments of unit D, which is, in a water-loaded setting. The plot of Figure 16a shows the importance of sediment loading but tectonic processes are still needed to cause differential vertical movements varying from ~0.3 km and ~0.8 km in eastern and western termination of the basin respectively, to > 2.0 km in the central parts of the basin.

The evolution through time of a synthetic well (3 in Figure 14) through the depocenter of the basin is described in Figure 16b documenting the variable importance of sediment- and tectonic-loading through time. Results combined with time-depth, sea-level and sediment-accumulation curves (Figure 16b) indicate that the total subsidence for the M-reflection is ~4.5 km, the load exerted by the sediments for sub-units D1-D4 are ~750, 900, 180 and 240 m respectively (total ~2100 m), and the rate of tectonic subsidence is higher during the D1-3 time interval.

5. The W Calabria continental margin and the SE Tyrrhenian-Ionian system

The combined analysis of high-resolution and deep crustal seismic imaging, constrained by gravity modeling and supported by published geophysical and petrological data (e.g. Frezzotti et al., 2009 and references therein) has provided new information on the structures and evolution of the W Calabria continental margin, a key area to understand the evolution of the Tyrrhenian back-arc basin. In the following, we investigate the implications of our data for the evolution of the Tyrrhenian system by analyzing horizontal deformations and vertical movements along a transect from the present Marsili Basin in the W to the Crotone Basin in the E (Figure 2). By doing this, we propose an “upper plate” perspective to the complex phenomena associated with the retreat of the subducting Ionian slab. Our reconstruction covers the last 10Ma, a time span of great interest encompassing orogenic collapse following continent-continent collision between Africa and Eurasia, subsequent orogenic collapse, rifting apart between the two and the successive emplacement of oceanic crust in the Vavilov and Marsili basins. We focus in particular to the last 5Ma, the time during which the Paola basin developed.

5.1 Horizontal deformations

By far, the most common structures observed in the sedimentary cover of the W Calabria continental margin are of contractional nature. With the partial exception of the feature located at CDPs 1300-1400, the few normal faults observed in the profile have a total offset of < 1 km, merge
at depth within the D unit and are, therefore, unlikely to have accommodated any significant crustal extension. Shortening structures in the pre-Pliocene succession are distributed over most of the section. They are nearly exclusively E-dipping thrusts, accommodating W-ward displacements in the order of tens to few hundred meters. The contractional style changed towards the late Messinian-early Pliocene, when thrusting was confined to the most distal parts of the margin and when the 30-40 km wide Paola Basin syncline developed. We see no quiescence interval separating the two stages.

Towards the E, the analyzed transect of the W Calabria continental margin passes to the metamorphic rocks of the Catena Costiera and then to Crati sedimentary basin (Figure 2). With few exceptions [e.g. Cesarano and Turco, 2002 and Figure 6 in van Dijk et al., 2000; Martini et al., 2001], it is generally assumed that the Crati basin developed in an extensional regime [e.g. Cifelli et al., 2007; Mattei et al., 2002]. Further to the E, the eastern side of the Sila Massif is onlapped by Serravallian to Pleistocene sediments of the Crotone basin. Here, the base of Miocene to Pliocene sediments unconformably covers a peneplained basement and is not cut by significant syn-sedimentary faults [sheet 237 of the Geological Map of Italy, scale 1:100.000; Massari et al., 2002]. Spectacular growth faults have been identified in the Pliocene succession, but they sole out in the basin fill and, therefore, do no document crustal extension [Zecchin et al. 2004]. Folds have been documented in the Crotone basin fill but it is debated if they represent a late Miocene contractional episode [e.g. Amodio-Morelli et al., 1976] or if they are associated with the isostatic rebound of Calabria following the Messinian base level drop [Cavazza and De Celles, 1998].

Plotting information on the Pliocene to Quaternary tectonics on a transect across the upper plate of the Ionian subduction zone, from the Marsili oceanic crust to E Calabria (Figure 17) it is obvious how most of the transect has either been shortened or remained undeformed and that the area potentially experiencing extension (if at all present) is narrow.

5.2. Vertical movements

5.2.1. Miocene to Quaternary record

Towards the end of the Messinian, roughly corresponding to the birth of the Paola basin, the area along the regional transect was generally close to sea level. Upper Messinian marine to transitional sediments are indeed present along the entire SISTER-11 line, in the Amantea and Crati basins [Mattei et al., 2002] and, further to the E, also in the Crotone basin. A post-Messinian age for formation of the basement highs between the sedimentary basins (Catena Costiera and Sila Massif) is suggested by the fact that Pliocene sedimentary strata dip away from the highs. The presence of a relatively thick succession of Messinian and older sediments suggests that most of the section was experiencing subsidence at the Messinian-Pliocene transition, when the Paola basin began to develop.
Pliocene to Quaternary vertical movements along the regional transect can be inferred for the area of the Marsili Basin (since 1.8-1.5Ma), the Paola basin and for onshore Calabria. In the Marsili basin, the vesicular character of the basalts traversed by ODP 650 and the benthic foraminifera in the immediately overlying sediments suggest water depths of 1-2 km at ~1.8 Ma, that is, shortly after the emplacement of oceanic crust [Kastens et al., 1988; Wang et al., 1991]. Compared with the present day water depth of > 4 km, this implies that the Marsili basin and the adjacent distal part of the W Calabria continental margin experienced a subsidence of 2-3 km during < 1.8 Ma. The onset of subsidence is not dated but it is likely to have started a few Ma earlier, during continental rifting.

The sign and magnitude of Miocene to Quaternary vertical movements in the area of the Paola Basin are well constrained by the SISTER-11 data set (Figures 13 and 15). The general pattern is characterized by a central area experiencing strong subsidence flanked by two domains where subsidence was less important. This pattern is clearly associated with the development of the Paola Basin syncline. Towards the W, the syncline passes to an anticline which is presently at ~1km water depth and experienced subsidence during Pliocene to Quaternary times (Figure 14). Noteworthy is that subsidence continued also during the D4 time interval, that is, following the end of shortening in the Paola Basin syncline. The eastern continuation of the Paola basin syncline is not imaged in the SISTER-11 line which ends on its eastern, W-dipping flank. The similarly dipping sediments of (the northern prolongation of) the Amantea basin probably represent the eastern, onshore, continuation of the Paola basin syncline. In this case, the basement rocks outcropping in the Catena Costiera could correspond to the anticline lying to the E of the Paola basin syncline. The half wave length of such folding can be estimated at ~18km on the basis of the distance between the western anticlinal high and the Paola basin depocenter (Figure 18).

Vertical movements in onshore Calabria are poorly documented for the 5-1Ma time interval as basement rocks of the Catena Costiera and the Sila Massif were already above the Apatite Partial Annealing Zone [Thomson, 1994] and, probably also above the He Partial Retention Zone [Faccenna, personal communication, 2009]. Generalized uplift is suggested by the position above sea level of Pliocene marine sediments in the Crati and Crotone basins. Superimposed on this large wavelength pattern, stronger localized uplift led to the development of the Catena Costiera and Sila Massif basement highs. Continuous upward movement during the last 0.7My is documented by uplifted flights of marine terraces [Westaway, 1993; Bordoni and Valensise, 1998; Antonioli et al., 1998].

The wavelengths of vertical movements

To discuss processes controlling vertical movements in the area we have plotted the vertical position of the distal segment of the margin, of the Paola Basin and of onshore Calabria at ~1.5Ma (corresponding to a horizon slightly below the base of sub-unit D3) and at present (Figure 18).
The plot at 1.5Ma (dashed lines in Figure 18) shows the vertical position of the Marsili oceanic crust and of the adjacent segment of the distal margin as inferred from Kastens et al., [1988] and Wang et al. [1991]. The plot also displays Paola basin with the paleobathimetry and the basin fill thickness we have derived from the SISTER-11 seismic line. Further to the E, we have schematically plotted the Crati basin. From this profile we note the similarity between the width of the Paola basin and the distance between the depocenters of the Paola and Crati basins, both being ~37 km. This suggests that folding controlling the evolution of the Paola basin might have also contributed to the uplift of the Catena Costiera high and to subsidence of the Crati basin.

The solid lines in Figure 18 show the present vertical position of the Marsili oceanic crust (~4km) and of the Paola basin. Comparison between the situations at 1.5Ma and at present indicate a deepening of >2km in the Marsili basin and, interestingly, of ~1km of the high bounding to the W Paola Basin. We note that the this western high lies on a straight line connecting the Marsili basin and the present day coast line (Figure 18) and propose, therefore, that regional subsidence during the D4 time interval, that is, following the cessation of Paola basin folding, was controlled by large wave length subsidence of the Marsili basin causing a W-ward tilt of the entire margin, probably associated with sub-crustal processes. Extrapolating the analysis towards the E, in the onshore areas, our simple model predicts an uplift of few hundred meters for the eastern part of the Crati basin and of ~1.2 km for a locality 30-40 km from the coast line, roughly representative of the present day Sila massif. This is somewhat less than the 700 m recorded by the analysis of marine terraces [Westaway, 1993].

6. Conclusions

The interpretation of the high resolution SISTER-11 seismic line integrated with deeper seismic transects, with gravity data and with regional observations has provided new and unexpected results relevant for the understanding of the Tyrrhenian system at large. A first striking observation is the nearly complete lack of significant normal faults affecting Messinian to Quaternary sediments. In this respect, the W Calabria continental margin differs from other margins of the Tyrrhenian Ocean such as N Sicily and E Sardinia. The absence of normal faults is in apparent contrast with the crustal thinning documented along the margin and raises the fundamental and hitherto unanswered question of how and such thinning was achieved.

The second important conclusion from our study is that the W Calabria margin experienced continuous shortening from the Miocene to Recent (possibly with the exception of limited Messinian extension), that is, during Tyrrhenian rifting and drifting. Initially, that is during middle to Late Miocene times, deformation was accommodated by thrusting distributed over the entire margin. From the Early Pliocene, most thrusts were abandoned and deformation was localized in the region where the Paola Basin syncline developed. We also proposed that syncline development was associated with the formation of two anticlines, to the W and E of the Paola basin. The
anticline in the E can partly explain the elevated position of the Catena Costiera separating the
Paola basin from the Crati basin. We note again how horizontal deformations documented for the
Calabria margin are different from what observed in the N Sicily and E Sardinia margins. The lack
of significant young faults is in agreement with results of morphostructural zoning which point to
the absence of zones capable of producing earthquakes with magnitudes M>6 (e.g. Peresan et al.,
Peresan et al., 2002).

Simple models predict that associated continental margins associated with back-arc basins
should experience extension (and crustal thinning) before and during the emplacement of oceanic
crust. The W Calabria margin did not follow these rules and basically experienced continuous
shortening. Possible explanations lie in the regional eastward flow of the upper mantle detected by
Panza et al., [2007b with references] and/or in the secondary patterns of mantle flow originated
from the steepening and retreat of the (Ionian) subduction slab [e.g. Faccenna et al., 2005].

Numerical and analog models [Piromallo et al., 2006; Funiciello et al., 2006; Stegman et al. 2006]
underline the importance of poloidal and toroidal mantle flows associated with the retreat of the
subducting slab. Displacement vectors in most of these models predict upper plate extension but
more complex patterns characterized by upper plate shortening have also been envisaged (Figure
5d in Funiciello et al. [2006]).

The third relevant conclusion is that vertical movements in the region between the Marsili
basin and onshore Calabria operated at two different wavelengths. The first one is of ~37-40 km is
in essence associated with crustal folding. The most apparent structure developed was the Paola
Basin; vertical movements and topography in the adjacent Catena Costiera the Crati basin could be
(partly) associated the same process. A second group of processes operated at a much larger scale,
300-400 km and caused the deepening of the Marsili basin and of the adjacent margin. Part of
the elevation of onshore Calabria could also be caused by the similar phenomena. Because of their
long wavelength, these vertical movements are related to mantle processes, that is, thermal cooling
following rifting and secondary patterns of flow (dynamic topography) developed during the retreat
of the Ionian subducting plate. In the case of the W Calabria continental margin, the long
wavelength vertical movements became dominant during the D4 time interval (probably
corresponding to the last 1 Ma) and followed a time period when folding was the prevalent process.

Acknowledgements

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vision and perseverance of Ennio Marsella (Naples). We gratefully acknowledge his engagement
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warmly thanked for the constructive comments that helped to clarify several points. This research has been funded by partly supported by ISES (Netherlands Research Centre for integrated Solid Earth Science) in the VRF program.
Figure captions

Figure 1. Schematic tectonic map of the central-western Mediterranean (see text for references). ALKAPECA units, Alboran, Kabylies, Peloritan, and Calabria, [Bouillin, 1986]. The box around Calabria indicates the region of Figure 2.

Figure 2. Structural scheme of the southern Apennines and the adjacent offshore areas simplified from Bigi et al. [1989] and Catalano and Sulli [2006]. Shaded relief based on bathymetric data from NOAA, www.ngdc.noaa.gov. Abbreviations are as follows: MS, Marsili Seamount; AS, Alcione Seamount; LS, Lametini Seamount; AA; main volcanoes of the Aeolian Arc; CB, Crati basin; Cc; Catena Costiera; CTB; Catanzaro Basin; AB, Amantea Basin; CB, Crotone Basin; IP, Iblean-Pelagian Foreland; AD, Apulian Domain. I--IV; traces of Figures 3, 17 and 18, D-D' trace of DSS profile (see text for references).

Figure 3. Cross-section from the Marsili ocean crust (Southern Tyrrhenian) to the Ionian foreland displaying the lithospheric setting of the “Ionian Subduction zone” (See Figure 2 for location). No vertical exaggeration.

Figure 4. The W Calabria continental margin as imaged in the SISTER-11 profile and its seismic facies interpretation (see Figure 2 for location). Boxes a, b, c, d and e, display parts of the line. Unit A is the upper part of Kabilian-Calabrian units belt inclusive of deformed Hercynian basement, Alpine poly-metamorphic rock successions and Mesozoic sedimentary units; unit B is composed of Oligocene to lower Messinian clastic to terrigenous deposits unconformably overlaying the Kabilian-Calabrian; unit C is includes shallow- and deep-water (redeposited) Messinian evaporites (boxes b and c, respectively); units D1-4 correspond to the Plio-Quaternary sedimentary succession; unit E corresponds to magmatic intrusions; tA is the top of Kabilian-Calabrian units, M the top of Messinian evaporites. Limits of seismic units and unconformities are evidenced by thick dotted lines. Internal subdivision of unit B into lower and upper sub-units is evidenced by thin solid lines.

Figure 5. Seismo-stratigraphic scheme of SISTER-11. Correlation between seismic unit, stratigraphy and seismic velocities is based on seismic facies analysis, stratigraphic data available onshore close to the investigated margin (see text) and from litho-stratigraphy and sonic log data available from wells through for coeval deposits wells offshore southern and western Sicily.

Figure 6. (a) The unmigrated CROPM27 reflection profile, and (b) its line-drawing interpretation (see Figure 2 for location). Abbreviations are as follows: LC, lower and intermediate crust; COT, continent ocean transition, A, Kabilian-Calabrian units, BC, Oligo-Miocene
units; M, top of Messinian deposits; D1-4, Plio-Quaternary units; OC, oceanic crust; L1, L2, and L3, layer 1, 2, and 3 of the oceanic crust. SV, seismic velocities related at the internal layering of the crust and Moho as derived by wide-angle seismic profile (see text for references).

Figure 7. Bouguer gravity anomaly map of the SE Tyrrhenian Basin based on data from Morelli [1970] and Carrozzo et al. [1986]; Equidistance = 5 mGal; Step grid =1.5'; I-II Sister-11 track; The whole line (A-A') marks the interpreted gravity profile.

Figure 8. Model of densities of the lithospheric structure achieved by 2.5 D inversion of gravity data of the whole transect shown in Figure 7. Crustal data across the W Calabria continental margin are derived from time-to-depth conversion of the Crop-M27 line-drawing coupled with those derived by the SISTER-11 line. The black lines within the crust indicate boundaries between layers suggested by gravity interpretation, whereas the dashed lines indicate reflections. Velocity and density values used are given in Table 2.

Figure 9. (a) Crustal configuration of the W Calabria continental margin as derived from integrated analysis of seismic data and gravity modeling. (b) Cumulative crustal (solid line) and upper crustal (inclusive of Kabilian-Calabrian units and the overlying pre-Pliocene sedimentary succession) (dashed line) thinning factors across the margin.

Figure 10-A. Closely spaced, W-vergent reverse faults (dotted lines) affecting the post-Messinian deposits in the distal sector of the margin. Top of Sub-Units D1-2, 3 and 4 are marked by solid lines. M, top of Messinian evaporites. See Plate 1 for location. Note the twofold vertical exaggeration.

Figure 10-B. Reverse (dotted lines) and normal (thick solid line) faults observed in the distal sector of the margin. Top of Sub-Units D1-2, 3 and 4 are marked by thin solid lines. M, top of Messinian evaporites. (See Plate 1 for location). Note the twofold vertical exaggeration.

Figure 10-C. Closely spaced, E-dipping, normal faults (dotted lines) with small displacements affecting sub-units D1-2 and/or the lower part of D3. S, apparent slip; a, apparent dip. M, top of Messinian evaporites. See Plate 1 for location. Note the twofold vertical exaggeration.

Figure 11. (a) The continent-ocean transition as imaged by the SISTER-11 line. MI, magmatic bodies; arrows indicate the top of the magmatic bodies. (b) Shaded relief based on bathymetric data (illumination from NE) of the southern Tyrrhenian Sea (data from NOAA, www.ngdc.noaa.gov) showing the morphology of the seamount developed at the continent-ocean transition zone. Note the similar elongation (N-S) of the Marsili Seamount and of the seamount identified at the continent-oceanic transition. White solid line indicates the segment of the SISTER-11 line; AA, volcanoes of the Aeolian Arc; AS,
Figure 12. The Plio-Quaternary sedimentary succession of the Paola Basin and its internal subdivision in sub-units (D1-4) limited by unconformities (thick solid lines). Internal layering is evidenced by thin dotted lines. Reverse and transpressive faults are evidenced by thin solid and dashed lines respectively. Sbm, sea-bottom multiple; a, apparent dip. M, top of Messinian evaporites. (Note the twofold vertical exaggeration).

Figure 13. The western sector of the Paola Basin. Note the thinning of sub-units D1 and D2 associated with clinoforms. Top of sub-units are evidenced by thick solid lines. Internal layering of sub-units is evidenced by thick dotted lines. Normal faults are indicated with thin dotted lines. Sbm, sea-bottom multiple; M, top of Messinian evaporites.

Figure 14. Kinematic evolution of the Paola Basin during D1, D2, D3 and D4. 1, 2, 3 and 4 indicate the position of synthetic wells of Figure 15. Top of sub-units are evidenced by thick solid lines. Internal layering of sub-units is shown by thick dotted lines. Normal faults are evidenced by thin dotted lines. M, top of Messinian evaporites.

Figure 15. Subsidence curves for synthetic wells (1, 2, 3 and 4) in the Paola Basin. See Figure 14 for location of wells.

Figure 16. (a) Position of the base of the Paola Basin (corresponding to the horizon M) in the absence of Plio-Quaternary sediments (star), that is, in a water-loaded setting. (b) The evolution through time of a synthetic well (3 in Figure 14) which shows the variable importance of sediment- and tectonic-loading through D1-4 time interval.

Figure 17. The distribution of different tectonic regimes along a transect from the Marsili basin and the Ionian accretionary wedge.

Figure 18. Vertical position and movements of the W Calabria margin. Dashed lines indicate the bathymetry of the Marsili basin as constrained by the vesicular basalts and the paleontological assemblage [e.g. Kastens et al., 1988], the position of the top D2 and top D1 horizons in the Paola basin region (see text for discussion) and, further to the E, the schematic position of the Crati basin. The solid lines represent the position of the above mentioned horizons at Present. Note how the western, less subsiding, side of the Paola Basin lies on a straight line connecting the Marsili basin with the present day coast line. The eastward continuation of the same line, predicts an uplift of several hundred meters in the onshore region.

Plate 1. (a) Geological upper crustal section across the Calabria continental margin as derived from depth conversion of the SISTER-11 line (b). Box indicate the portion of the SISTER-11
line displayed at smaller scale in Figures 10-A, 10-B and 10-C. The section has no vertical exaggeration.

Table 1. Seismic velocities derived from sonic log data for coeval sedimentary units recognized in 7 wells drilled offshore southern and western Sicily.

Table 2. Density values adopted for gravity modeling.
References


Neri G., Orecchio B., Todaro C., Falcone G., Preti D., 2009. Subduction beneath Southern Italy close the ending: Results from seismic tomography. Seismological Research Letters, 80 (1), 63-70


Fig. 1 Pepe et al.
<table>
<thead>
<tr>
<th>Well (location)</th>
<th>Age</th>
<th>Lithology</th>
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<th>Vel. (m/s)</th>
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<td>Eva (36° 26' 47&quot;) (14° 40' 24&quot;)</td>
<td>PP Mess. Mio.</td>
<td>Calcarenites, marls, Gypsum, Limestones, marls, shales</td>
<td>499 187 723</td>
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<td>Giada (36° 54' 00&quot;) (14° 16' 00&quot;)</td>
<td>PP Mess. Mio.</td>
<td>Limestones, marls, Gypsum, Limestones, marls</td>
<td>784 51 474</td>
<td>1815 3400 2605^</td>
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<td>Aretusa (36° 28' 00&quot;) (14° 57' 00&quot;)</td>
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<td>154 137 583</td>
<td>2750 * 2635 2886</td>
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<td>Spada M. (36° 35' 00&quot;) (14° 49' 37&quot;)</td>
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<td>1728^ ----- 1949</td>
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Table 1 Pepe et al.
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<th>Causative source</th>
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<td>Plio-Pleistocene</td>
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<td>Oligo-Miocene</td>
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<td>2.92-2.84</td>
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<td>Ionian crust</td>
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<td>Layer 2</td>
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<td>Layer 3</td>
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Fig. 8 Pepe et al.
Fig. 10-C Pepe et al.
Fig 14 Pepe et al.
Figure 15 Pepe et al.
Figure 16 Pepe et al.
Figure 18 Pepe et al.