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Neogene-Quaternary evolution of the offshore sector of the southern Apennines accretionary wedge, Gulf of Taranto, Italy

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ABSTRACT

Southern Apennines represent a collisional orogenic belt whose compressional regime is commonly assumed to have ceased during Middle Quaternary. On the other hand, to the south the Calabria Arc is still characterized by subduction and the principal aim of the present research is to shed some light on the space and time transition from the ceased collision to the active subduction. Accordingly, we investigated the offshore sector of the Southern Apennines accretionary wedge, corresponding to the Taranto Gulf. To gain insights into the offshore accretionary wedge, we reconstructed a 3D geological and tectonic model by interpreting a grid of 40 seismic reflection lines (1100 km, 80 intersections), within an area of *ca.* 10^4 km^2, calibrated with 17 wells. The geometric and chronological constraints allow documenting a systematic Messinian-Quaternary thrust migration from internal towards external sectors of the wedge. The migrating deformational process was essentially associated with a leading-imbricate thrust system with a general NE-younging direction, where we could recognize and distinguish some major advancing phases characterized by alternating fast thrust propagation events and strain accumulation periods within the wedge. This process is well emphasized by the jump of the foredeep and piggy-back basins. The NE-wards wedge migration was also associated with a lithospheric-scale flexural folding that generated a set of normal faults striking parallel to the coeval thrusts, likely reactivating optimally oriented structures inherited from Mesozoic events. Finally, a persisting thrust activity up to the latest Quaternary and possibly up to Present in correspondence of the externalmost sector of the accretionary wedge has been documented and explained in terms of strain partitioning in the frame of a recent oblique convergence. The results of this research have possible implications for the seismic hazard assessment of the broader region which is possibly greater than previously assumed.

1. Introduction

The problem of better understanding the late Neogene and especially the Quaternary evolution of the offshore sector of the Southern Apennines, Italy (Fig. 1), corresponding to the Gulf of Taranto, is posed in this paper and the potential interest of improving our geological and seismotectonic knowledge on this specific area of the central Mediterranean is emphasized. Moreover, the general results here obtained could be also applied to other accretionary wedges in the world and therefore they could be of broader interest well beyond the investigated area.

The Italian peninsula is mainly shaped by the Apennines fold-and-thrust belt whose frontal sector is oriented (N)NW-(S)SE. Towards the south, the continental mountain belt merges offshore with the Calabrian Arc, which is conversely characterized by a progressive curvature towards SW and then W (*e.g.*, Finetti and Morelli, 1972; Polonia et al., 2011; Fig. 1). The distinction between Southern Apennines and the Calabrian Arc is not simply a matter of terminology, mean orientation or bathymetry/altimetry, but it is of great importance for the geodynamics of the Central Mediterranean because the Southern Apennines correspond to a purely collisional setting, while the Calabrian Arc represents an accretionary wedge associated with the persisting subduction of an Tethyan oceanic remnant (Malinverno and Ryan, 1986;

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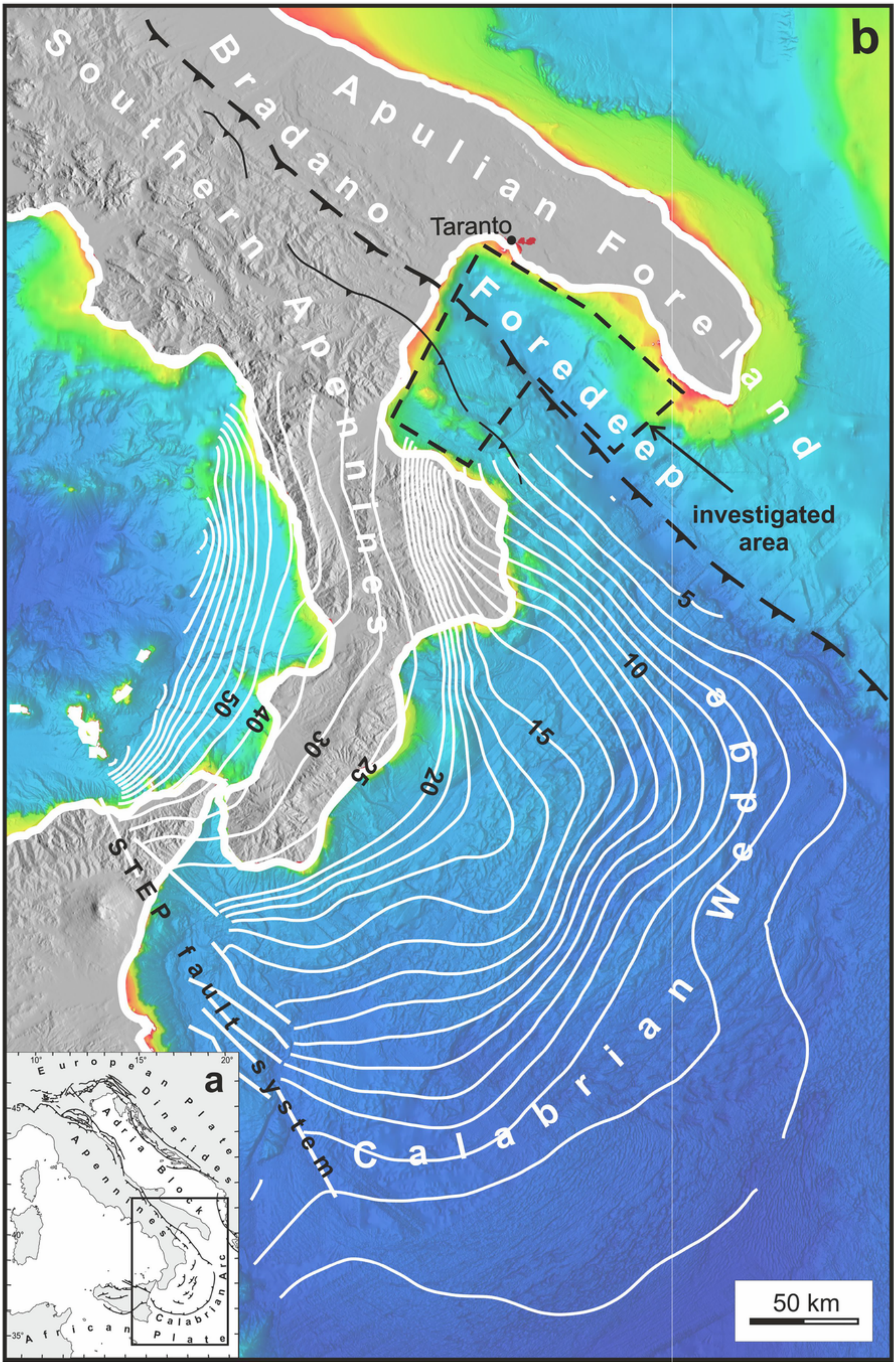


Fig. 1. a) Sketch map of the central Mediterranean showing the major geodynamic 'players', like Adria Block, Apennines and Calabrian Arc. b) Location of the investigated area within the Gulf of Taranto (dashed black polygon) in between the Apulian Foreland, on one side, and the Southern Apennines collisional belt and Calabrian Arc accretionary wedge system, on the other side. The black dashed line separates the fold-and-thrust belt (upper plate) from the lower subducting plate, while the black contour lines represent the isobaths of the basal de-

tachment (values in km) as reconstructed by Maesano et al. (2017). The investigated area also marks the transition between a pure collisional setting, well documented onland, and the persisting subduction along the Calabrian Arc.

Catalano et al., 2001). Additionally, and more important, the orogenic compressional regime of the former is commonly assumed to have completely ceased (*e.g.*, Meletti et al., 2000; Patacca and Scandone, 2001b), while the latter is still characterized by a well-defined Benioff zone (Fig. 1; Caputo et al., 1970; Selvaggi and Chiarabba, 1995; Solarino and Cassinis, 2007: Maesano et al., 2017).

The lateral change between the two distinct geodynamic environments occurs underneath the Ionian Sea in correspondence of the Taranto Gulf. However, no major tectonic structure(s) has been so far identified to represent a clear and sharp boundary separating the two crustal-lithospheric volumes characterized by such a different behaviour and geodynamic setting. Moreover, not only the location of such boundary has been not recognized yet with confidence, but it is also unknown whether the position of the collision-to-subduction shift was persistent in time, say at least during the whole Quaternary, or it has laterally moved through time, even recently. A key question is thus represented by how exactly the diachronical fading of the contractional tectonic regime occurred along strike within the Southern Apennines fold-and-thrust belt. In other terms it would be essential to reconstruct the space-time geodynamic evolution between the northern Bradano Foredeep area, where at present thrusting activity has almost ceased and a transcurrent tectonic regime now affects the region (*e.g.* Del Gaudio et al., 2007; Ridente et al., 2008; Di Bucci et al., 2010), and the arcuate sector of the submarine Calabrian Arc where plate convergence and thrusting (*e.g.* Doglioni et al., 1999; Del Ben et al., 2008; Polonia et al., 2011; Volpi et al., 2017) as well as subduction of the Ionian lithosphere is clearly still active (*e.g.* Caputo et al., 1970; Selvaggi and Chiarabba, 1995; Van Dijk et al., 2000; Solarino and Cassinis, 2007; Faccenna et al., 2011; Maesano et al., 2017).

Accordingly, the identification, location and characterisation of such important behavioural boundary have crucial implications for the seismotectonics of the broader area. Indeed, this boundary should in principle separate seismogenic from non-seismogenic volumes, while the seismological characteristics of the potentially active faults could also vary from northwest to southeast in terms of dimensions, kinematics and hence maximum expected magnitude. Therefore, the seismic hazard assessment of the broader region likely depends on the answer to the posed questions.

With this investigation we wanted to shed some light on the above critical problem, and the aims of the research are manifold. The first purpose is to investigate the offshore sector of the Taranto Gulf (Fig. 1) exploiting a relatively dense grid of seismic profiles from the Italian Videpi Project (Ministero dello Sviluppo Economico et al., 2009) for reconstructing the 3D geometry of the offshore Southern Apennines accretionary wedge and its Late Miocene to Quaternary evolution.

Secondly, we focus on the most external tectonic structures of the wedge for constraining their most recent activity, to verify the possibility they are still accommodating some amount of contractional deformation and the possible seismic hazard.

Thirdly, we analyse the Pliocene-Quaternary evolution of the western Apulian margin mainly affected by several normal faults associated with the flexural deformation of the underthrusting plate. Also this extensional deformation was likely shifting in space through time and its better understanding could contribute to the same major final goal of improving the seismic hazard assessment of the broader region.

2. Regional setting

In the last decades, the Southern Appennines have been investigated by numerous researchers and a large literature exists on both stratigraphic and tectonic aspects of this fold-and-thrust mountain belt (*e.g.* Mostardini and Merlini, 1986; Casero et al., 1988; Roure et al., 1991; Lentini et al., 1996; Monaco et al., 1998; Doglioni et al., 1999; Mazzoli et al., 2000; Mazzotti et al., 2000; Menardi Noguera and Rea, 2000; Patacca and Scandone, 2001a, 2001b; among many others). From a geodynamic point of view, the investigated area belongs to the Central Mediterranean realm whose evolution is strictly related, since the Mesozoic, to the northward motion of the Nubia plate (*e.g.* Mazzoli and Helman, 1994) and its relative progressive convergence with Europe (Lort, 1971). The articulated shape of the two plates and the interposed oceanic basins caused complex orogenic processes acting diachronically in the different sectors. In this composite tectonic framework, rock volumes at different scales were affected by a polyphased tectonics with multiple, sometimes variably oriented, compressional phases often followed by transcurrent and extensional regimes (*e.g.* Hippolyte et al., 1995). For example, along the axial sector of the Apennines chain, but mainly west of the present-day water divide (*i.e.* in a more internal sector of the recently generated orogenic belt), several normal faults have been forming since (Middle-)Late Pleistocene and are still active nowadays (*e.g.* DISS WG, 2015). This is well documented by both historical and instrumental seismicity which affects the upper crustal levels (Castello et al., 2005; Chiarabba et al., 2005; Di Bucci et al., 2006; Guidoboni et al., 2007) and suggested by break-out data from boreholes (Montone and Mariucci, 1999; Montone et al., 2012). Likewise the Hellenides facing the northeastern side of the Apulian block have been affected by a similar polyphased tectonic evolution characterized by several more or less coaxial compressional events followed by an extensional regime due to the orogenic collapse (*e.g.* Mercier, 1981; Mercier et al., 1987; Caputo and Pavlides, 1993; Chatzaras et al., 2013: Kaplanis et al., 2013).

As it is well documented by numerous geological investigations, the accretionary prism migrated from west to east since the Early Miocene, producing the diachronic onset of the foredeep sedimentation (progressively younger towards the Adriatic Foreland) with the development of a series of eastward younging depocenters and the occurrence of several piggy-back basins on top of the advancing allochtonous units (Patacca and Scandone, 1989, 2001b).

The progressive migration of the accretionary prism and the associated foredeep and satellite basins are related to the flexure-hinge retreat of the westward subducting Apulian lithosphere (Malinverno and Ryan, 1986; Patacca et al., 1990; Doglioni, 1991; Scrocca et al., 2005). Oceanic crust and thinned continental crust was initially subducted till the arrival at the convergent system of the Adria continental block that caused the beginning of the collisional phase. Also the onset of the collision was diachronic along strike, that is to say it started during Pliocene in the northern sectors of the Southern Apennines, but it has not occurred yet southwards along the Calabrian Arc (Fig. 1).

Diverging opinions stir up the debate on the present-day activity on the most external structures of the Appenines. Indeed, mainly based on the interpretation of seismic profiles, it was commonly assumed that compression, and especially contraction (*viz.* thrusting), has ceased at the beginning of the Middle Pleistocene in the Bradanic sector for the Southern Apennines (*e.g.* Hippolyte et al., 1995; Patacca and Scandone, 2004; Milia et al., 2017). At that time a major geodynamic rearrangement has been suggested to have occurred in the Central Mediterranean (*e.g.*, Cinque et al., 1993; Patacca and Scandone, 2004; Goes et al., 2004) geodynamically affecting the broader area.

On the other hand, other authors recognized compressional earthquakes along the Appenines foothills relating them to persisting thrust activity (Scrocca, 2006; Scrocca et al., 2007), while the inferred presence of contractional structures affecting the Bradano foredeep deposits (Pieri et al., 1997) suggest the occurrence of compressional activity throughout the whole Middle-Late Pleistocene.

In line with this, the coastal sector of the Taranto Gulf has been also investigated by analysing the superb staircase of marine terraces characterizing the region for >80 km and by calculating the long-term uplift rates affecting that area since Middle Quaternary (Caputo and Bianca, 2005; Caputo et al., 2010). The average (in time) long-term uplift-rate measured in several coast-perpendicular profiles varies from 1.7–1.8 to *ca.* 0.4 mm/a, from SW (Sinni River) to NE (Lato River), respectively. Based on the analysis of the differential uplift rates along a NE-SW transect crossing the chain-foredeep-foreland system, the above authors have also suggested that the accretionary wedge has been affected by underthrusting throughout the last 600 ka and that a compressional regime is still active in the coastal sector of the Gulf of Taranto.

2.1. Working procedure

In order to achieve the posed targets we followed a multi-step methodological approach. The first step of the research was the collection of all available data providing information on the investigated area (geological maps and sections, isochron maps, seismic reflection profiles, exploration well data, bathymetry, *etc.*). Whenever possible, all graphical information was preliminarly elaborated to create a consistent dataset. Undoubtedly, the bulk of the used data is represented by seismic reflection profiles and stratigraphic logs of wells carried out in the past decades for hydrocarbon exploration. Indeed, during the 1960s and 1970s the Southern Apennines have been explored by the Italian oil company Agip S.p.A. (nowadays ENI S.p.A.), which acquired onshore and offshore seismic profiles for thousands of kilometers and drilled numerous boreholes. Presently, part of this huge dataset has been made available to the public and it has been made accessible in the frame of a project promoted by the Geological Society of Italy (Ministero dello Sviluppo Economico et al., 2009). This national project is aimed at creating a georeferenced database, easily accessible *via* web (unmig.sviluppoeconomico.gov.it/videpi/) consisting of scanned seismic reflection profiles and well logs including expired mining permits and concessions issued in Italy.

For the aims of this paper, we analysed 40 seismic profiles, belonging to zones D and F as subdivided in the VIDEPI Project (Fig. 2). The average space between sections is about 10 km, while the total length of analysed profiles is *ca.* 1100 km. The studied seismic reflection profiles are time (seconds TWT) not-migrated stack sections presenting different kinds of seismic signal noise and anomalies (*e.g.* multiple reflections, diffraction curves, *etc.*) that were taken into account during the analysis and the subsequent interpretation.

We also analysed 17 wells (Fig. 2; Table 1) for reconstructing the lithostratigraphy of the area and calibrating the interpretation of the seismic profiles. Some of the considered wells are relatively old and the nomenclature of the sedimentary units is sometimes no more in use in the modern literature; for the sake of simplicity in this note we use the recent stratigraphic nomenclature.

In this research the Midland Valley's software Move™ has been used as a key tool for carrying out the interpretation of the selected seismic reflection profiles and to build a 3D geological-tectonic model of the investigated area following a classical workflow as illustrated below.

2.2. Seismostratigraphic model

We firstly defined the seismostratigraphic model for the study area by investigating the relationships between seismic reflection profiles and stratigraphy. Based on literature data and particularly on a detailed analysis of the selected wells logs, we were able to recognize and distinguish some major seismostratigraphic units (Fig. 3) characterized by fairly uniform petrophysical properties and hence homogeneous lithology.

Within the accretionary wedge, the deepest seismostratigraphic unit we consider is represented by an undifferentiated *Allochtonous Unit* (*ALL*) characterized by scarcely or locally continuous reflectors with

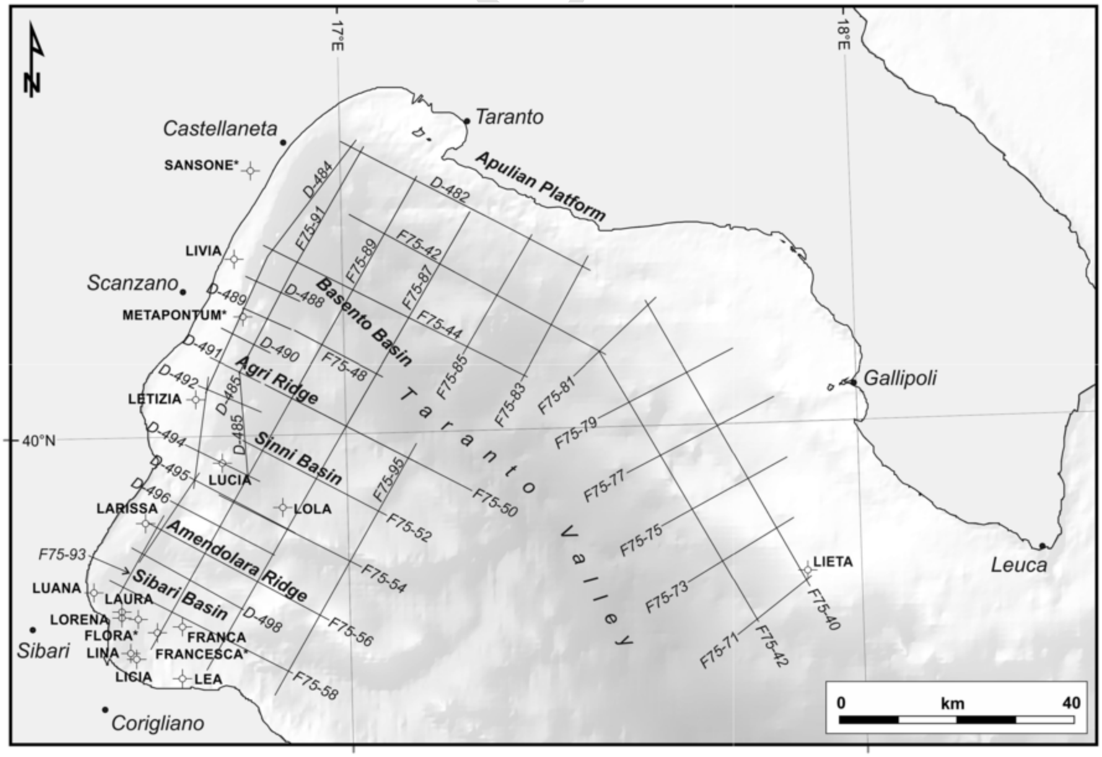


Fig. 2. Location of the analysed seismic profiles belonging to zones D and F of the VIDEPI Project (Ministero dello Sviluppo Economico et al., 2009) and the wells used for constraining the stratigraphic succession.

Table 1
List of the exploratory wells used in the present research for calibrating the interpretation of the seismic profiles. The asterisks indicate the wells for which is available the sonic log.

Name	Year	Depth [m]	Longitude	Latitude
Metapontum 001*	1991	1035	16° 48′ 03.46″	40° 10′ 45.23″
Francesca 001*	1988	1497	16° 37′ 14.20″	39° 42′ 17.40″
Flora 001*	1985	3486	16° 35′ 05.58″	39° 43′ 32.33″
Sansone 001*	1988	1179	04° 22′ 08.55″	40° 24′ 02.23″
Lucia 001	1971	3337	16° 45′ 20.28″	39° 57′ 32.17″
Lola 001	1979	1090	16° 52′ 14.20″	39° 53′ 29.10″
Larissa 001 DirBis*	1979	1540	16° 36′ 07.55″	39° 52′ 11.92″
Luana 001	1981	3364	16° 29′ 54.27″	39° 46′ 03.00″
Lorena 001	1982	1800	16° 33′ 09.13″	39° 43′ 46.49″
Lina 001	1984	1890	16° 34′ 08.17″	39° 40′ 32.22″
Franca 001	1982	2357	16° 40′ 15.09″	39° 42′ 49.59″
Laura 001	1980	4094	16° 33′ 17.00″	39° 44′ 15.62″
Letizia 001	1975	3865	16° 42′ 20.68″	40° 03′ 21.43″
Licia 001	1977	2477	16° 34′ 52.72″	39° 39′ 56.27″
Lea 001	1978	1271	16° 40′ 11.80″	39° 38′ 14.00″
Livia 001	1980	2272	16° 47′ 07.82″	40° 16′ 02.04″
Lieta	1973	590	17° 53′ 33.96″	39°46′ 38.09″

highly variable amplitude. This unit likely consists of several stacked tectonic blocks more or less internally deformed. The unit includes the Ponda Formation (Middle Miocene shales alternating with thin sandy layers and fine-grained sandstone; Flora, Laura and Lola wells) and the San Nicola Formation (Serravallian-Tortonian polygenic conglomerate with variably indurated clay layers; Filomena, Laura and Lola wells).

In stratigraphic sequence, we recognized the *Gessoso Solfifera Formation* (*GSo*) characterized by high amplitude rather continuous reflectors. According to the analysed stratigraphic logs (Flora, Lea, Licia and Lola wells), this unit consists of shaly beds with a scaly fabric, interbedded thin layers of gypsum, salt and sandstone; silty clay with alternating medium-to-coarse grained quartzitic sand, anydrite and salt of Messinian age (approx. max thickness 1800 m).

The *Gessoso Solfifera Formation-GSo* is directly overlaid by the *Palopoli Molasse Unit* (*PLP*) whose seismic facies is characterized by variable amplitude and almost absent continuous reflectors. Stratigraphic logs (Flora, Lea, Licia and Lola wells) report prevailing fine-to-medium or even coarse grained quartzitic sand, locally cemented, alternating silty clay and rare polygenic conglomerates. This unit corresponds to the post-evaporitic Messinian and part of the Lower Pliocene. The maximum thickness is about 1000 ms (about 1300 m) in correspondence of the Sinni Basin (Fig. 2).

In stratigraphic succession in most of the analysed sections is the *Santerno Formation* (*SNT*) characterized by a generally good continuity of the reflectors with a high-to-moderate frequency. The top of the unit corresponds to a reflector slightly more marked and ondulated with respect to the overlying units (*San Mauro Unit-SMU* and *Pleistocene-Holocene Unit-PtH* see lateron). The several wells (Flora, Francesca, Larissa, Letizia and Lina) document gray-green or gray-light blue clay, sometimes alternating with sand beds a few meters thick; sometimes the clays contain abundant silt. The clays have a slightly variable composition, but are always predominantly illitic. These sandy intercalations are more frequent at the basin edge and appear to have a local source. In the broader area the *Santerno Formation-SNT* contains characteristic Quaternary foraminiferal assemblages (with *Hyalinea balthica*, *Cassidulina*, and *Bulimina*, *Ammonia* and *Elphidium*), though the deepest levels are probably of Middle Pliocene age. The thickness of the *Santerno Formation-SNT* is highly variable within the accretionary wedge, say from less than 450 ms TWT (*ca.* 500 m) to >1900 ms (*ca.* 2000 m) in the Sibari Basin, while the unit progressively pinches out in the northeastern flank of the Basento Basin where it is reduced to few tens of meters close to Apulian Platform (Figs. 2 and 4).

Limited to the southern sector of the investigated area (Sibari Basin; Fig. 2), a blurred seismic facies with few poorly continuous reflectors has been recognized above the *Santerno Formation-SNT* and it has been referred to the *San Mauro Unit* (*SMU*). Due to its stratigraphic posistion, *SMU* unit is Lower Pleistocene. The Flora and Francesca wells logs report quartzitic sand layers, from fine to coarse grained, with subordinated silty shale levels and poorly cemented fine conglomerates. The observed maximum thickness is about 270 ms (about 250 m) and progressively thins, up to disappear, in correspondence of the Amendolara Ridge (Fig. 4).

In the central-northern sector of the investigated area, underlying the Apennines accretionary wedge, the deepest recognized seismostratigraphc unit is represented by the *Cupello Limestone* (*CPL*) of mainly Cretacous age and representing the Apulian carbonate platform. The corresponding seismic facies is generally characterized by linear continuous well-marked reflectors, slightly deformed in proximity of normal faults affecting this unit in the northern sector of the investigated area. These rocks consist of whitish carbonate mudstone/wackestone, showing high reflectivity with high amplitude reflectors (Letizia, Lieta and Livia wells). The maximum observed thickness of this seismostratigraphic unit is *ca.* 4000 ms (roughly corresponding to 7400 m) measured in correspondence of the Apulian Platform Domain (Figs. 2 and 4).

On top of the Mesozoic limestone are the *Calcarenite di Gravina Unit* (*CrG*) characterized by continuous well-marked reflectors. It consists of yellow-greenish coarse-grained intraclastic calcarenites, with frequent macro and microfossils (Lieta, Livia and Sansone wells) of Late Pliocene-Early Pleistocene age. It mainly accumulated along the flanks of subsiding sectors of the Apulian Foreland in a shallow water ramp setting (Tropeano and Sabato, 2000). Its thickness in the investigated area is likely limited to 150–200 ms, corresponding to some tens of meters at most. The unit progressively disappears southwestwards below the accretionary wedge. The resolution of the profiles does not allow discriminating whether the southwestwards lack of evidence on top of the Mesozoic carbonates is due to tectonic abrasion and removal by the upthrusting accretionary wedge or by an original lack of sedimentation due to the increasingly distal environment.

The shallowest deposits observed in the analysed seismic profiles all over the investigated area have been here simply referred to as the *Pleistocene-Holocene Unit* (*PtH*) characterized by parallel low amplitude reflectors though quite dense and continuous. The top of *PtH* unit coincides with the sea bottom. The unit consists of shallow unconsolidated Middle Pleistocene *p.p.* to Holocene sediments reaching a maximum thickness of about 400 ms (roughly 320 m) as observed in the Basento Basin area (Fig. 2).

2.3. Velocity analysis

In order to better investigate the seismic expression of the contacts separating the above described seismostratigraphic units, the sonic logs available for 5 wells (Table 1 and Fig. 2) have been carefully analysed.

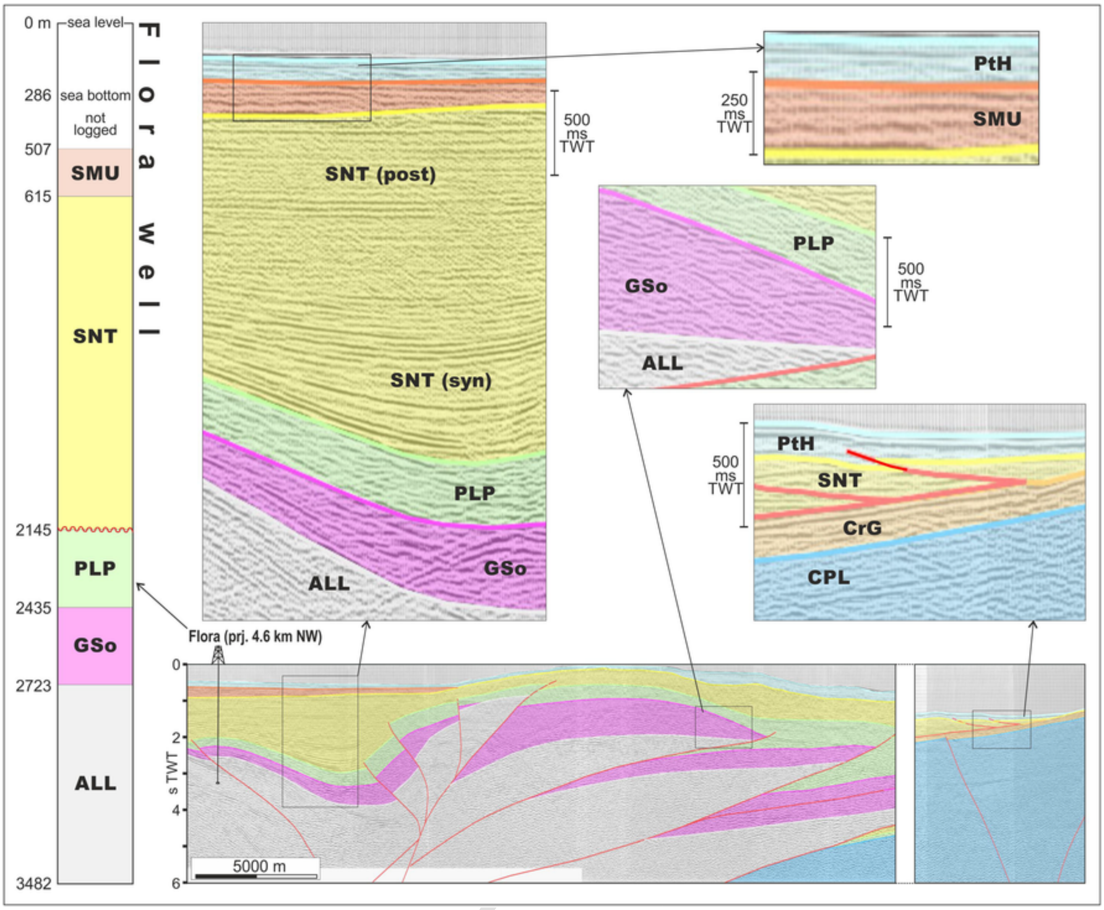


Fig. 3. Major seismostratigraphic units recognized in the present work characterized by different seismic facies. *ALL*: Allochtonous Unit; *GSo*: Gessoso Solfifera Formation; *PLP*: Palopoli Molasse Unit; *SNT*: Santerno Unit; *SMU*: San Mauro Unit; *CPL*: Cupello Limestone; *CrG*. Calcarenite di Gravina; *PtH*: Pleistocene-Holocene Unit. The stratigraphic log on the left represents the Flora well.

For each well and following a graphical procedure, we could estimate and attribute a mean velocity value to the different stratigraphic units recognized during the drilling. The velocities obtained for the same unit drilled in different wells were further averaged and these final values have been used for the time-depth conversions (Table 2). For the water layer, the commonly accepted value of 1500 m/s has been assumed.

The mean velocity values thus obtained for each unit were also applied to all selected wells (*i.e.* without sonic log) in order to convert them from depth to time. Once time converted, the wells have been projected on the nearby seismic profile(s) and this contributed to recognize and better constrain the main reflectors and hence to define the most relevant seismostratigraphic units within the study area (Fig. 3).

2.4. 2D interpretations

Following a systematic georeferencing of maps, wells and seismic profiles using a GIS software, the seismic analysis of the VIDEPI profiles was mainly carried out by creating a Move™ project and exploiting several tools of the Midland Valley's software package. The VIDEPI scanned and georeferenced profiles have been uploaded and carefully analysed in order to produce detailed line-drawings based on the recognition of strong and well-marked reflectors. The most relevant reflections usually occur at the interfaces between different stratigraphic units, where rapid changes in acoustic impedance are associated with major lithological changes. However, reflectors could be also due to multiples and refractions. At this regard, a special care was spent to recognize all possible multiple signals and refractions that were obviously neglected during the seismic analysis and interpretation.

Based on their mean orientation, the seismic profiles could be separated in two groups: the first one is characterized by lines running NE-SW at high angle with the major tectonic structures; these profiles are obviously more functional to observe deformational structures and particularly to quantify the cumulative displacement across the faults as far as the general shortening direction and hence the slip vectors associated with thrusts are subparallel to the profiles. The second set of seismic profiles investigated is almost orthogonal to the former one therefore intersecting along strike the major tectonic features. We exploited the latter profiles mainly for laterally correlating the observed structures and the several stratigraphic horizons and therefore for better constraining the overall geological interpretation. For the practical purpose of describing the different tectonic structures, the profiles are also subdivided in two areas; the first includes the grid roughly between Sibari-Corigliano and Taranto (Figs. 4 and 5) and the second a set of profiles north of the Taranto Valley, between Scanzano-Castellaneta and Leuca (Fig. 6). For the interpretation of both areas we started primarily from the profiles containing the better stratigraphic constraints provided by the projected time-converted wells. This step was crucial for calibrating the overall interpretation. We firstly interpreted all profiles separately, by tracing all reflectors, neglecting the multiples and the refractions and emphasizing those reflectors separating the recognized seismostratigraphic units described in a previous section.

Subsequently, along the intersections between profiles, we transferred our horizon picks and our fault picks to the crossing profiles, in order to obtain a coherent picture and interpretation over the entire

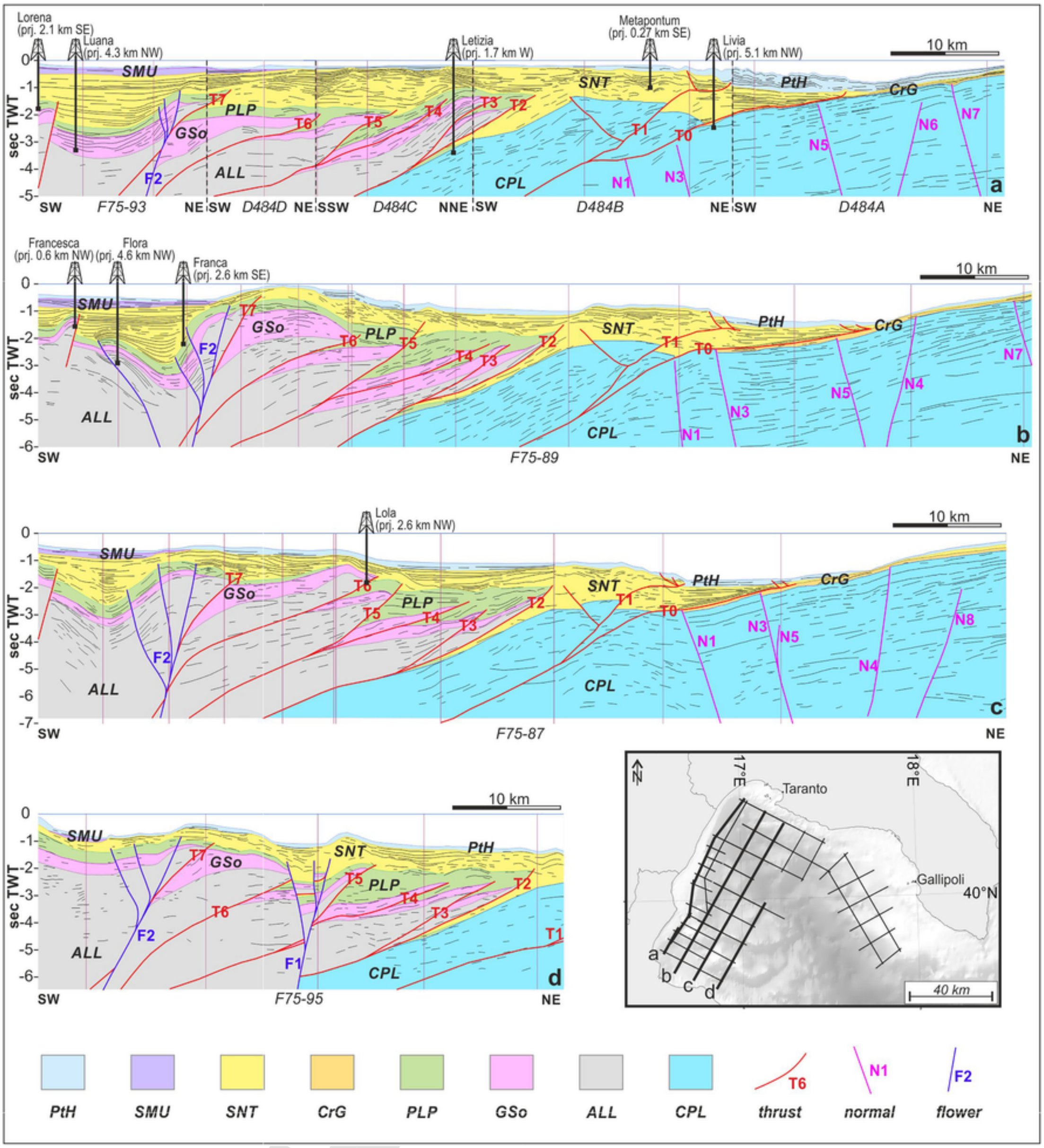


Fig. 4. Examples of interpreted seismic profiles oriented NE-SW, that is roughly orthogonal to the major tectonic structures and subparallel to the slip direction of thrusts. Vertical thin bars indicate the intersection with other profiles. See inset map for profiles location. Labels of seismostratigraphic units as in Fig. 3.

grid of seismic lines and especially a 3D consistency of all detected reflectors.

2.5. Pseudo-3D model

The following procedural step was the creation of the surfaces of the major tectonic elements, of the seismostratigraphic units, and therefore the creation of a time-based structural model. This step was achieved by interpolating the interpreted profiles. By selecting single horizons or faults we separately performed a gridding analysis (minimum curvature) and then reassembled all the obtained surfaces into the Move™ project. The areal extent covered by the entire model is about 7.200 km^2. Perspective views of the 3D tectonic-geological models of the accretionary wedge and the normal fault system affecting the Apulian block are represented in Figs. 7 and 8, respectively. A systematic depth conversion of all profiles is beyond the goal of this research as far as it would not significantly affect the overall characteristics of the 3D tectonic model and hence the discussion and major conclusions of the following sections.

3. Evolution of the accretionary wedge

For the reconstruction of the 3D geological model of the accretionary wedge (Fig. 7) we selected 25 seismic sections (Fig. 2) and interpreted them following the above described methodological approach. These profiles show a well-defined fold-and-thrust belt system striking NW-SE (Fig. 4), in geometric continuity with the Southern Apennines chain outcropping on land (*e.g.* Catalano et al., 2004). It essentially consists of some major SW-dipping low-angle reverse faults altogether generating a NE-vergence imbricate fan system. In order to facilitate their description, the major reverse tectonic structures have been labelled, from SW to NE, T7 to T0, respectively (Figs. 4 and 9). Accordingly, these tectonic structures together with all rocks and sediments affected by contractional deformation or horizontally trans-

Table 2
The principal stratigraphic units considered in the investigated area. The average seismic velocities attributed to the stratigraphic units have been estimated from the available sonic logs (see Table 1).

Stratigraphic unit	Label	Maximum thickness [m]	Age	Velocity [m/s]
Pleistocene-Holocene	PtH	320	Pleistocene-Holocene	1600
San Mauro unit	SMU	250	Lower Pleistocene	1875
Santerno unit	SNT	2000	Middle Pliocene-Pleistocene	2125
Calcarenite di Gravina	CrG	220	Upper Pliocene-Lower Pleistocene	2225
Palopoli Molasse	PLP	1300	Messinian *p.p.*-Lower Pliocene	2520
Gessoso Solfifera Fm	GSo	1800	Messinian	2950
Allochtonous unit	ALL	2000	Middle Miocene	3075
Cupello Limestone	CPL	7400	Mesozoic	3735

ported NE-wards form the external offshore part of the Southern Apennines accretionary wedge.

3.1. Wedge propagation

By taking into account the geometry of the recognized tectonic structures and the distribution of the considered stratigraphic units and particularly their lateral thickness variations on both sides of the faults, it is possible to recognize and distinguish, four major evolutionary phases contributing to the overall growth of the accretionary wedge towards the foreland (Fig. 10).

In particular, from southwest towards northeast, the 3D geological model (Fig. 7) shows that thrust T7 separates a footwall block characterized by a relatively thick *GSo* unit (with an apparent maximum thickness of about 1200 ms, *ca.* 1770 m, in section F75-89; Fig. 4b), gradually thinning northeastwards towards the foreland (progressive pinch-out geometry), which has been overthrusted by the stratigraphically underlying *ALL* unit (Fig. 4). It is noteworthy that in the hanging-wall block the *Gessoso Solfifera Formation-GSo* is systematically thinner with respect to the footwall, ranging between 300 and 600 ms. Moreover, in correspondence of the first 2 km southwest and closer to the fault intersection the *GSo* completely disappears. We interpret these important lateral stratigraphic variations as a consequence of the synsedimentary activity of the T7 fault mainly during the deposition of the *Gessoso Solfifera Formation-GSo* corresponding to the Messinian *p.p.* Accordingly, the continuous relative subsidence of the footwall block produced accommodation space infilled by the coeval deposits, while the uplift characterizing the hanging-wall block and particularly the crest of the fault-related fold locally caused the lack of, or a highly reduced, sedimentation of the *GSo* unit. In the frame of the interplates convergent system, and as a consequence of this deformational phase, the Southern Apennines foredeep shifted NE of T7, while in the hanging-wall block coeval deposition of the *GSo* unit characterized by a lense-shape geometry (in section view; Fig. 4) persisted in a piggy-back setting (Ori and Friend, 1984). We refer to this satellite basin as the Sibari Basin (Fig. 10a). The horizontal component of motion estimated across fault T7 ranges between >4.6 and >5.5 km along three out of four SW-NE seismic profiles (Fig. 11), while in the fourth profile (line F75-89), the strong interference with the subsequent out-of-plane strike-slip faulting associated with the transpressional flower structure (see discussion below) does not allow to estimate with confidence the amount of shortening. Accordingly, the above values should be considered minimum ones.

Similar observations could be carried out in correspondence of thrusts T6 and especially T5. In this case the stratigraphic unit affected by an abrupt lateral variation across these faults is the *Palopoli Molasse*. It shows a thickness up to 1000–1100 ms (*ca.* 1260–1390 m) in the footwall block of T5 which is reduced to only 300–400 ms (*ca.* 440–500 m) in correspondence of the hanging-wall of T6, while in section F75-87 the *PLP* unit seems to completely disappear on top of T6 (Fig. 4c). Taking into account the age of the *Palopoli Molasse Unit-PLP*, these faults were likely growing and marking the boundary between the accretionary wedge and the foredeep basin in a time span between latest Messinian (the socalled post-evaporitic period) and Early Pliocene. During a late stage of the same time interval, also thrust T4 was probably active as a frontalmost flat segment representing an aborted propagating tip of the imbricate fan system. During this deformational phase the vertical motion affecting the internal part of the former *syn-GSo* foredeep was inverted (*i.e.* uplifted), therefore forming a large scale (*ca.* 10–15 km-wide) tectonic high (Amendolara Ridge) definitely separating the Sibari Basin from the Early Pliocene foredeep basin whose depocenter was in the meantime shifted further to the northeast (Fig. 10b). Shortening associated with thrust T6 progressively increases southeastwards from 4.0 to 5.5 km, while on T5 it decreases in the same direction from 5.3 to 3.7 km basically compensating each other along the strike of the wedge (Fig. 11). As concerns the very low-angle thrust T4, the horizontal component of sliding slightly increases southeastwards from almost 4.0 km to about 5.6 km.

The subsequent major evolutionary step involving the offshore sector of the Southern Apennines is well documented by analogous lateral variations characterizing the *Santerno Formation-SNT* across thrust T2 (Fig. 4). Indeed, the thickness of the *SNT* seismostratigraphic unit is generally limited to 500–700 ms (*ca.* 530–740 m) in the hanging-wall block of this low-angle reverse fault, while it reaches the 1500 ms (*ca.* 1590 m) in its footwall sector. Although affected by a later deformational event, the typical asymmetric geometry (in section view) of this Late Pliocene to Early Pleistocene foredeep basin, progressively pinching out towards the Apulian Foreland, is still clearly visible in the NE-SW seismic profiles (Fig. 4a, b, c). In this case, however, the hanging-wall uplift caused by the newly generated thrust was not sufficient to completely separate the deposition in two distinct depocenters and therefore only a subtle satellite basin formed in the internal sector of the accretionary wedge with respect to T2. Nevertheless, some coeval reactivation of older thrusts (see discussion below) contributed to the growth of an already existing piggy-back basin (Sinni Basin; Fig. 10c). As concerns the amount of shortening accumulated along thrust T2, the lack of resolution especially at depth of the available seismic profiles does not allow constraining it with good confidence. A tentative estimate of the horizontal component possibly ranges between 9 and 15 km, but it could be even more (*e.g.*, lines D485 and F75-91; Fig. 11).

The last advancing phase of the accretionary wedge is distinctly recorded by the socalled *Pleistocene-Holocene Unit-PtH* showing a marked thickness variation in correspondence of thrust T1. In particular, the Late Pleistocene-Holocene seismostratigraphic record is commonly limited to 100–150 ms (*ca.* 80–120 m) in the hanging-wall, but it increases up to 400–600 ms (*ca.* 320–480 m) northwards. It should be noted that the area characterized by a reduced thickness of this unit occurs in correspondence of, and is clearly caused by, a pop-up structure bounded to the southwest by a backthrust (T1R) originating from T1 at 3100–3400 ms depth within the *Cupello Limestone-CPL* unit (Fig. 4a, b, c). From a tectonic point of view, the progressive approach of the wedge towards the Apulian Foreland and therefore the entrance of

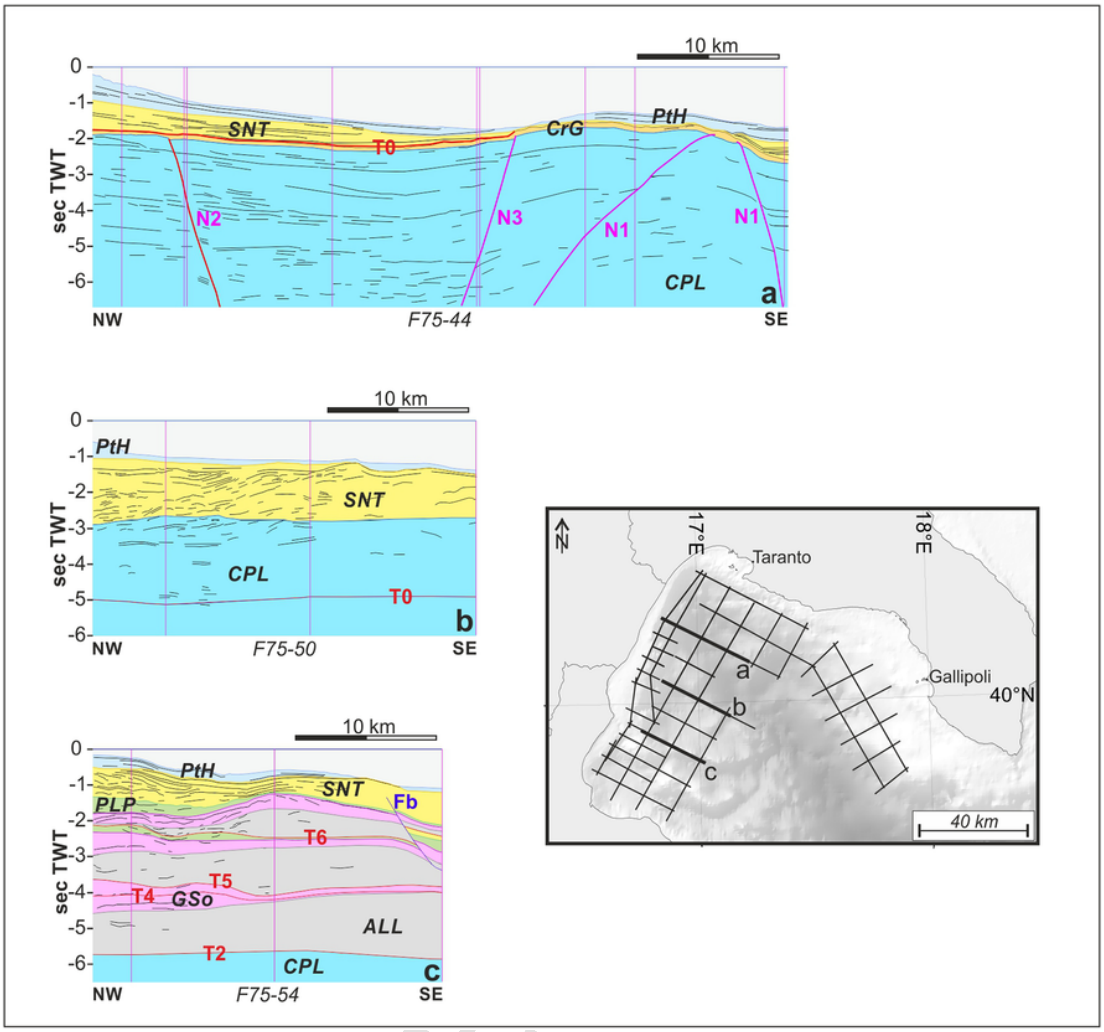
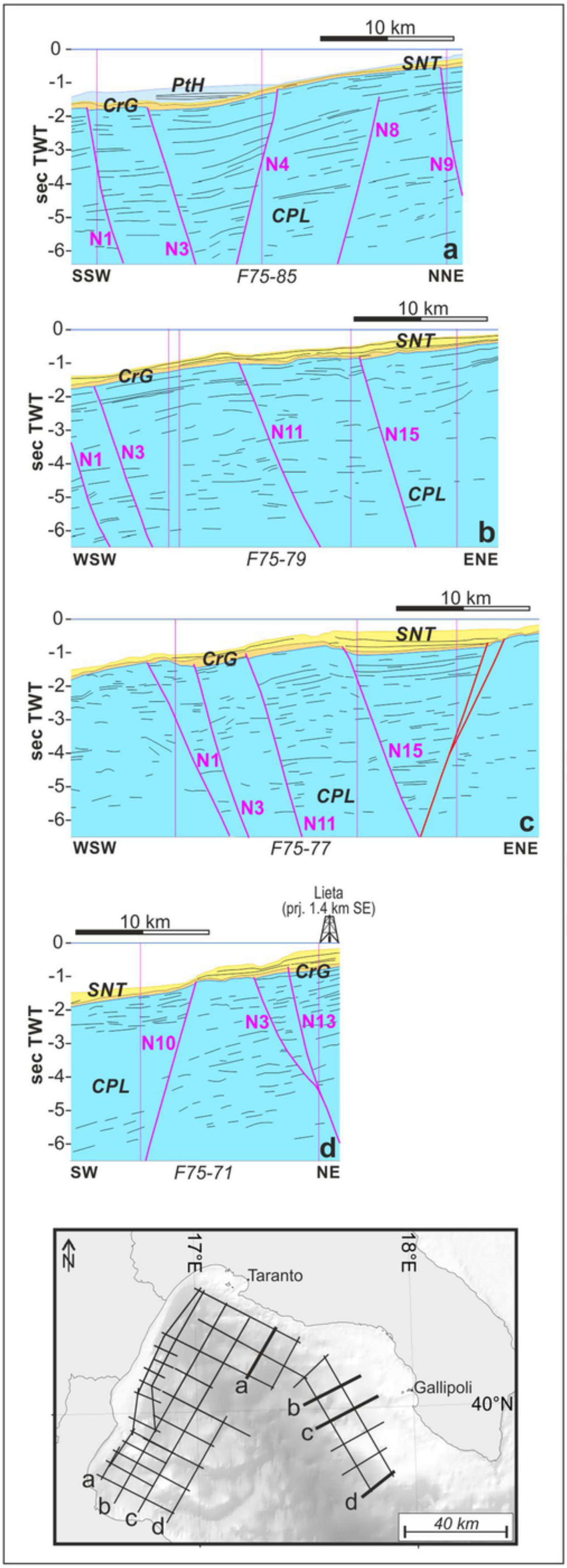


Fig. 5. Examples of interpreted seismic profiles oriented NE-SW close to the Apulian coast and documenting a normal fault system. Vertical thin bars indicate the intersection with other profiles. See inset map for profiles location. Labels of seismostratigraphic units as in Fig. 3.

a normal thickness crust (*e.g.* 30–35 km; Faccenna et al., 2014 and references) into the subduction system have hindered and strongly reduced the regional subsidence necessary for the maintenance and migration of a marine foredeep as basically occurred in the previous 10+ Ma. Indeed, during this last deformational phase a real foredeep with a clear depocenter has been not formed and beyond the minor lateral thickness variations above described affecting the *PtH* unit, none of the coeval depressed areas have the typical asymmetric shape (in section view) as observed for the previous evolutionary stages (Fig. 10d). With reference the top of the Mesozoic limestones the throw of the intermediate-angle NE-dipping reverse fault is about 150 ms, while along the major SW-dipping fault the throw is 300–400 ms (*ca.* 280 and 560–740 m, respectively). As far as both faults are blind (Fig. 4a, b, c), the amount of slip obviously decreases updip. In terms of horizontal component, the shortening associated with the entire pop-up is about 1.1–1.4 km (Fig. 11).

Similar to the late Messinian-Early Pliocene accretionary phase, during which the tip of thrust T4 was propagating forward with a basically flat setting, it seems that also thrust T0 has very recently started to propagate towards the foreland (Fig. 12). In this case, this structural behaviour (*i.e.* flat setting) is facilitated by the occurrence of a strong mechanical contrast between the gently dipping Mesozoic limestones together with the thin *Calcarenite di Gravina Unit-CrG* on their top, and the overlying poorly consolidated prevailing clays of the *Santerno Formation-SNT*. The amount of sliding accumulated at present is certainly limited and could be tentatively inferred only indirectly from some minor ramp segments characterizing the tip sector of the thrust (Fig. 12). Accordingly, the shortening associated with T0 is likely in the range of few hundred meters and this contribution should be added to that of the previously discussed pop-up therefore reaching the 1.5–1.9 km for the Middle-Late Quaternary contractional phase (Fig. 11).

All observed thrusts, and particularly the major ones, forming the above described imbricate fan system obviously extend downdip well below the lower limit of the analysed seismic profiles and they likely merge into a deeper common sliding surface that basically represents the interface mechanically separating the underthrusting Adria Plate, to the NE, from the lithospheric blocks of European pertinence, to the SW. In the latter blocks should be also included all rock volumes progressively incorporated within the Southern Apennines accretionary wedge following each evolutionary step as above described. This surface was referred to as the basal detachment by Caputo et al. (2010), where 0.6–1.7 km of slip have been independently estimated for the last *ca.* 600 ka. These values are in good agreement with the results of the present paper relative to the Middle-Late Quaternary deformational event.



◀ **Fig. 6.** Examples of interpreted seismic profiles oriented NW-SE, that is roughly parallel to the major tectonic structures used for laterally correlating the various tectonic structures and stratigraphic units observed in the orthogonal set. Vertical thin bars indicate the intersection with other profiles. See inset map for profiles location. Labels of seismostratigraphic units as in Fig. 3.

3.2. *Out-of-sequence contractional structures*

Accretionary wedges are always in dynamic equilibrium (*e.g.* Davis et al., 1983; Dahlen et al., 1984) and even small changes in some of the governing parameters may induce important behavioural adjustments (*e.g.* Singh et al., 2012). For example, either a dip-angle increase of the sliding surface(s) caused by the progressive roll-back of the lower plate or the arrival within the major shear zone (commonly referred to as principal deformation zone) of more competent rocks could increase the overall resistance along the basal thrust. In order to restore the dynamic equilibrium of the whole accretionary wedge, internal deformation is thus required and it is generally accommodated by out-of-sequence contractional faulting and/or the reactivation of older, more internal, thrusts. When the latter phenomenon occurs, additional slip is commonly accumulated on these structures. As above mentioned, although the formation and growth of thrusts T6 and T5 mainly took place during the deposition of the *Palopoli Molasse Unit-PLP* (latest Messinian-Lower Pliocene), from seismic profiles F75-87, F75-89 and D484C (Fig. 4a, b, c) it is clear that these structures have been reactivated also during the early deposition of the *Santerno Formation-SNT* (*i.e.* Middle Pliocene) as far as the lower part of the *Santerno Formation* is displaced of several hundred meters at the tip of both T6 and T5, but especially, the Pliocene seismostratigraphic unit is reduced to only 300 and 450 ms on top of the anticlines associated with T6 and T5, respectively, therefore documenting a revival of the fault-related folding process.

On the other hand, the folding of the *Pleistocene-Holocene Unit-PtH* unit (as well as the sea bottom) in correspondence of the T6-related anticline (for ex. F75-89; Fig. 4b), suggests that even during Late Quaternary this fault accumulated some additional amount of shortening. With reference to the bottom of the *Santerno Formation-SNT*, the cumulative out-of-sequence horizontal component of displacement is 1000 and 500 m across thrusts T6 and T5, respectively. Some internal layering within the *Santerno Formation-SNT* in correspondence of the tip of thrust T4 likely suggests that some re-activation could have occurred along it, though the induced deformation is partly hindered by the almost flat geometry of this fault.

3.3. *Flower structures*

Also thrust T7 has been slightly reactivated during the Pliocene deposition as far as the *SNT* unit shows a local thinning in correspondence of its hanging-wall block, while the presence of the *San Mauro Unit-SMU* and its progressive pinch-out northeastwards document the persistence of a depressed area corresponding to the Sibari Basin (in the role of a piggy-back basin), which was further deepening during Late Quaternary. However, in this sector of the investigated area, thrust T7 and probably also the deeper part of thrust T6 have been subsequently affected and partly disrupted by a prevailing transpressional regime. Indeed along the southwestern flank of the Early Pliocene Amendolara Ridge a typical positive flower structure has developed (F2 in Figs. 4 and 9) whose activity certainly postdates the purely contractional tectonic features and certainly continues in the Quaternary as suggested by the stratigraphic growth relations. This structure has been previously investigated by other researchers emphasizing its Quaternary activity and the transpressional behaviour (*e.g.* Del Ben et al., 2008; Ferranti et al., 2014; Milia et al., 2017). In general, this structure

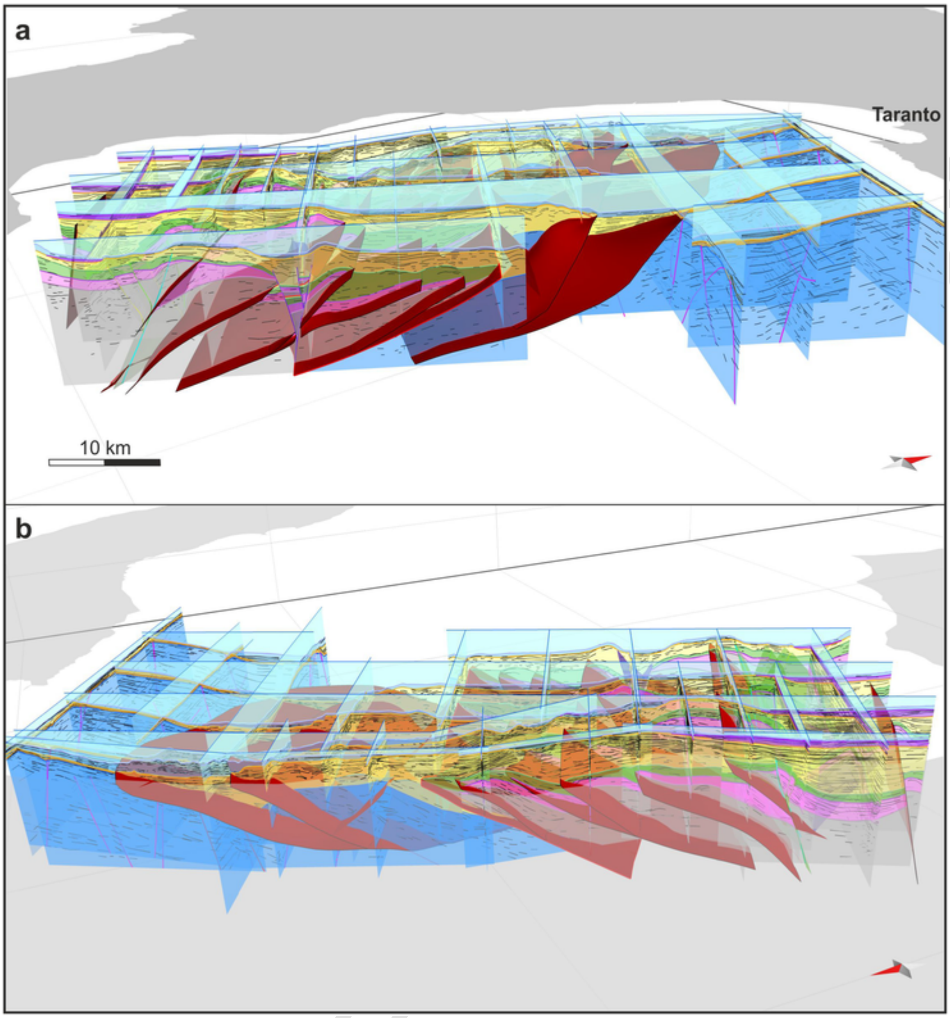


Fig. 7. 3D perspectives of the geological and tectonic model of the accretionary wedge; views from ENE (a) and WNW (b). In gray are the coastal areas surrounding the Gulf of Taranto.

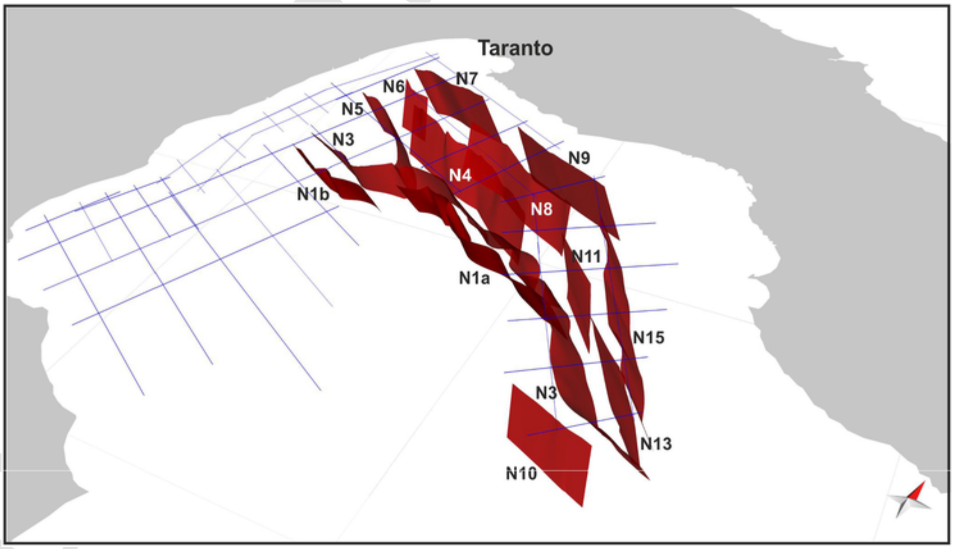


Fig. 8. 3D perspectives of the geological and tectonic model of the normal faults system affecting the investigated area; view from SE. In gray are the coastal areas surrounding the Gulf of Taranto..

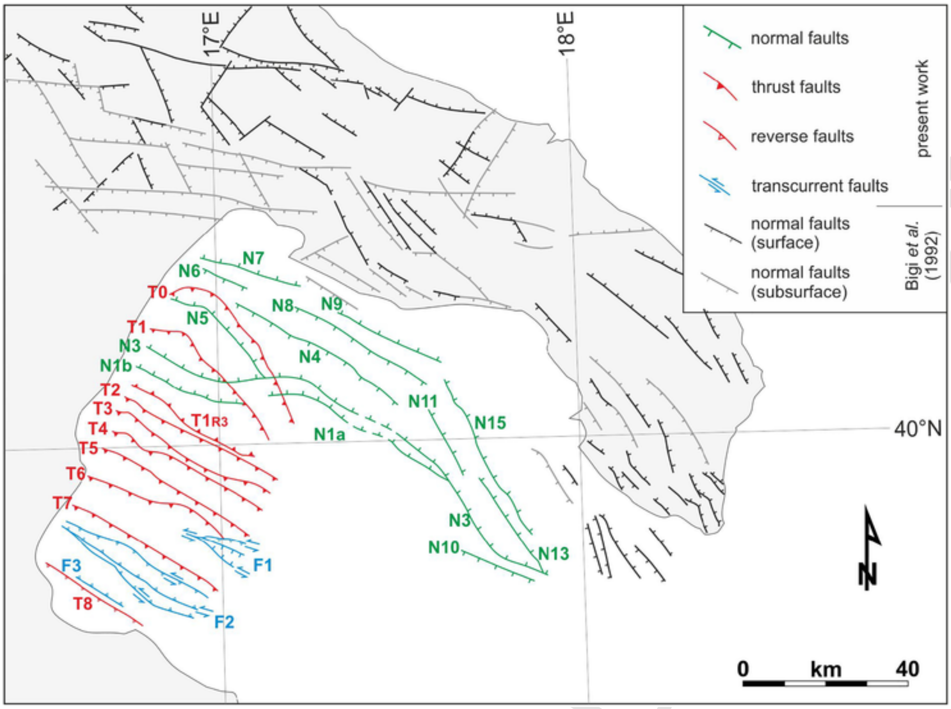


Fig. 9. Structural map of the investigated area based on the interpretation of the seismic profiles (thin gray lines) and the reconstruction of a 3D geological-tectonic model (Fig. 6). Normal faults from Bigi et al. (1992) are also reported.

is referred to as Amendolara Fault System, however this labelling could be somehow misleading due to the large overlap with the thrust-related anticline structure (Amendolara Ridge) that mainly formed in late Messinian-Early Pliocene in a purely contractional setting.

Close to the intersection between F75-95 and F75-54 profiles it is possible to observe another tectonic structure characterized by a prevailing transcurrent kinematics (F1 in Figs. 4d and 9). In this case, however, transtension prevails as suggested by the occurrence of a negative flower geometry. Although in section view the strike-slip kinematics imply out-of-plane movements of the fault blocks (relative to the orientation of the seismic profile), by taking into account the affected lithologies, it is clear that also this flower structure post-dates the thrusting activity of T6, T5 and T4, which has been attributed to the Middle Pliocene (including also the out-of-sequence pulses). Similarly, the lower part of the *Santerno Formation* is clearly affected by normal (oblique-slip?) faulting, while the *Pleistocene-Holocene Unit-PtH* and even the sea bottom seems to be deformed by large scale folds likely associated with upward propagating shear components of the flower structure (Fig. 4d). On the other hand, all these structures bearing a strike-slip component of motion have been suggested to be still active (Del Ben et al., 2008; Ferranti et al., 2014).

3.4. Long-term slip-rates and Present-day kinematics

As an additional exercise, we tried to estimate the mean slip-rate on the basal detachment, separating the upper from the lower plate, during Messinian-Quaternary (Fig. 13), by assuming that all the deformation observed in the seismic profiles was somehow a consequence of sliding on the deeper interplate surface. The inferred values range between *ca.* 4 and *ca.* 7 mm/a, which are in line with the results of Basili and Barba (2007) for the Northern Apennines during middle Miocene-Quaternary and with those of DeMets et al. (1990) and Nocquet (2012) for the present-day kinematics in this sector of the Central Mediterranean. Moreover, considering the low-angle setting of the major sliding surface within the "near-trench domain" (*sensu* Maesano et al., 2017; Fig. 1b), these values are roughly representative of the shortening rate along this sector of the chain interposed between the Southern Apennines and the Calabrian Arc system.

The same approach also shows a clear slow down during the Middle-Late Quaternary. At this regard, based on the interpretation of palaeomagnetic data, Mattei et al. (2007) suggested that the transition from the subduction to the collision processes across the investigated area of the Gulf of Taranto occurred sometimes between Early and Middle Pleistocene. Taking into account the overall geodynamic system, convergence and hence compression certainly persisted somehow longer, that is to say, also in Late Quaternary. This is in agreement with the Middle-Late Quaternary contractional deformation (*i.e.* thrusting) documented by the analysis of uplifted and tilted marine terraces (Caputo et al., 2010). But above all, a persisting thrust activity up to the latest Quaternary and possibly up to Present is clearly documented by the present research in correspondence of the most external sector of the accretionary wedge (Fig. 12).

By combining the observed slow down of the thrusting activity since Middle Quaternary along the most external low-angle structures and the coeval setup of a major transcurrent component in the internal part of the accretionary wedge (cfr. flower structures; Figs. 4 and 6), it seems that the Present-day oblique convergence between the SW and NE sectors of our investigated area (Fig. 10d) is affected by a large-scale strain partitioning, where the strike-slip component is mainly accommodated along the Amendolara Ridge (*e.g.* Del Ben et al., 2008), while (almost) pure contraction (*i.e.* dip-slip kinematics) occurs on the upper segment of the interplate surface (Fig. 14). Based on crustal scale reconstructions across the southernmost sector of the emerged Apennines wedge (Casero et al., 1991; Pieri et al., 1997; Menardi Noguera and Rea, 2000; Butler et al., 2004; Scrocca et al., 2005; Roure et al., 2012), the interpretation of offshore deep seismic profiles (Van Dijk et al., 2000; Del Ben et al., 2008; Zecchin et al., 2015) and the results presented in this paper, the two major tectonic features (*viz.* flower structure and basal thrust) likely meet at a depth of *ca.* 15–22 km offshore the Calabrian coast (Fig. 10d). Such values are also in perfect agree-

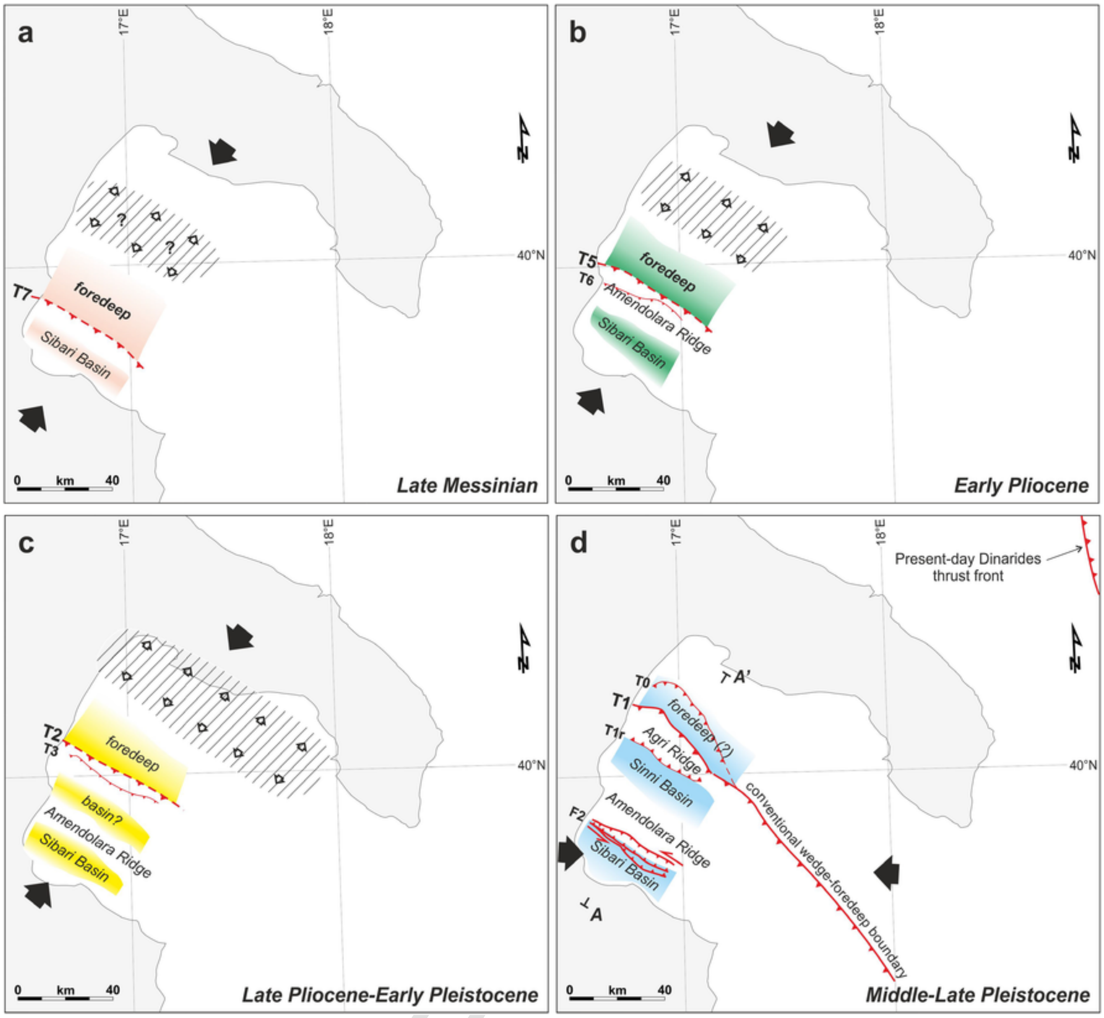


Fig. 10. Sketches showing the evolution of the accretionary wedge (a–c) characterized by the periodic migration of the thrust front, the shift of the foredeep basin together with the creation and growth of piggy-back basins or secondary depocenters. In (d) the persistent thrusting during the Middle-Late Quaternary is likely due to the kinematic partitioning in the frame of a newly established oblique convergence (*e.g.* Del Ben et al., 2008) and represents the contractional (*i.e.* perpendicular) component of motion, while the transcurrent component is taken up by the Amendolara flower structure. Section A-A' is represented in Fig. 14.

ment with the reconstruction proposed by Maesano et al. (2017) for the Ionian subduction surface and the rheological modelling proposed by Boncio et al. (2007) for the transcurrent tectonic setting of the Southern Apennines.

If we also take into account the brittle-ductile transition depth in correspondence of the investigated area as recently proposed by either Petricca et al. (2015) and Chiarabba and De Gori (2016), it is clear that the deeper ductile shear zone (Fig. 14) locally acts as an oblique-lateral ramp (Maesano et al., 2017). However, when shear strain (*viz.* creeping) reaches upwards the seismogenic crustal layer (*i.e.* above the BDT) the motion is kinematically partitioned because the stick-slip mechanism is more efficient on fault planes with pure kinematics, either dip-slip and strike-slip (*e.g.* Beck, 1986; McCaffrey, 1992; Wesnousky and Jones, 1994; Enlow and Koons, 1998; Bowman et al., 2003: Allen et al., 2017) as it is also largely documented in several oblique convergent settings (Jones and Wesnousky, 1992; Guang et al., 1993; Holdsworth et al., 1998; Cembrano et al., 2005; Vernant and Chéry, 2006; Bemis et al., 2015; Daout et al., 2018).

4. Synorogenic flexural faulting

As above discussed, the accretionary wedge and the Apulian Foreland are separated by thrust T0. Underlying the basal detachment, however, several normal faults have been observed (Fig. 4a, b, c). They are clearly visible in all NE-SW oriented profiles closer to the Apulian coast (Fig. 5), not affected by thrusting. Altogether, they form a complex and highly segmented system of normal faults affecting the western Apulian platform (Figs. 8 and 9).

It is noteworthy that similar extensional structures have been also mapped onland, where a similar pattern and general trend could be envisaged (Bigi et al., 1992); these structures are also represented in Fig. 9 for reference and comparison. Within the area investigated on the basis of the seismic profiles, the overall length of the mapped offshore fault system is >120 km (Fig. 9). Although the reconstructed 3D geometry and particularly the lateral continuity of the single structures could be biased by the spacing of the available seismic profiles, the length of the single segments typically ranges between 15 and 50 km.

The mean orientation of the fault system shows a marked change in strike from 90°–130°N in the northwestern sector of the investigated area to 110°–140° towards the southeast. Moreover, the northwestern subsystem mainly forms an ESE-WNW trending roughly symmetric, though geometrically complex, major graben >30 km in width with 2–3 synthetic faults on both sides (N1, N3, N5 *versus* N4, N6, N8). Towards the coastline, the northeastern shoulder of the graben is further delimited by two right-stepping antithetic faults (N7 and N9) thus generating a *ca.* 5–8 km-wide minor horst structure. Taking into account

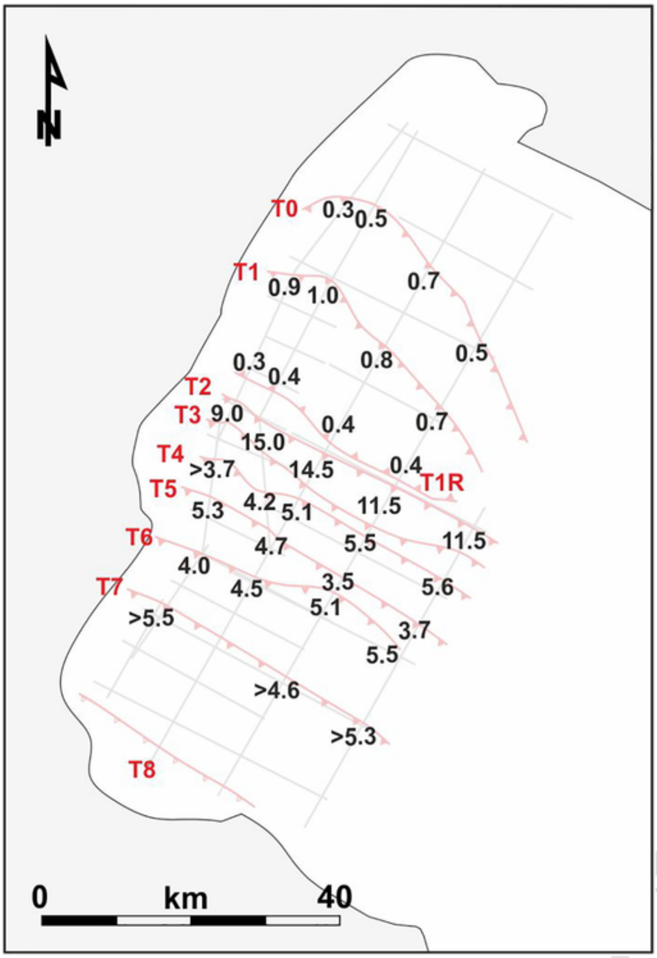


Fig. 11. Horizontal slip component (in km) along the major thrusts estimated from the NE-SW seismic profiles.

the occurrence of some parallel faults mapped onland along the coastal sector (Bigi et al., 1992), the latter faults (N7 and N9) contribute to generate another important graben structure oriented almost E-W, west of Taranto, and *ca.* NW-SE along the Apulia coast (Fig. 9).

As mentioned above, in the southern sector of the investigated area, the overall trend of the recognized tectonic structures is mainly (N)NW-(S)SE and most of the observed normal faults are NE-dipping. Considering the occurrence of some antithetic mapped faults (Bigi et al., 1992), also in this case, a 15–20 km-wide graben structure could be recognized close to the coastal sector (Fig. 7).

Finally, in the southernmost investigated sector another minor horst structure (5–10 km-wide), bounded by faults N3 and N10 could be recognized.

Concerning the possible period of activity of these extensional structures, they do not seem to be active since (Middle?-)Late Pleistocene as far as they cut nowhere the *PtH* unit (Fig. 5). In contrast, they commonly affect the *Calcarenite di Gravina-CrG* unit and locally also the lowermost part of the *Santerno Formation-SNT* when this overlies the *CrG* unit. Accordingly, the observed normal faulting has mainly occurred during Pliocene and Early Pleistocene, though it could have started somehow before.

In some cases, for example faults N6, N8 and the central sector of N3, the visible displacement affects only the Mesozoic limestones without reaching the top of the *CPL* unit thus documenting the presence of even older high-angle planes within the extensional fault system (Fig. 9). This suggests that some of the Neogene-Quaternary extensional tectonic structures were probably inherited from older (likely Mesozoic) deformational events and reactivated during the evolution of the accretionary wedge in the frame of a local second-order tensile stress field developed in the extrados of the Apulian lithosphere flexural folding.

It is noteworthy that the normal displacement observed in the profiles and affecting the Pliocene-Quaternary deposits is generally quite limited, say less than 100 ms (*ca.* 80 m), while there is no stratigraphic control for possible older and larger displacements affecting the Mesozoic limestones (Fig. 5).

5. Conclusions

The present research essentially deals with a systematic geological interpretation of several seismic reflection profiles for a total length of *ca.* 1100 km carried out in the Gulf of Taranto for hydrocarbon exploration. The importance of this study resides in the fact that the investigated offshore sector represents the area connecting the continental Southern Apennines with the Calabrian Arc. Thanks to the availability of a grid of intersecting sections, the investigation allowed to recognize and reconstruct the 3D geometry of the principal Neogene-Quaternary seismostratigraphic units and the major tectonic structures affecting them (Fig. 7). Moreover, the analysis of both faults and associated folds combined with the lateral thickness variations characterizing the mapped stratigraphic units (Figs. 4 and 6), allowed to reconstruct the late Neogene-Quaternary evolution of the accretionary wedge.

Major results and conclusions from the above analysis could be summarised as follows:

1) The geometric and chronological constraints document a systematic migration of the thrusting from the internal towards the external sectors of the wedge (Fig. 10). The migrating deformational process was essentially associated with a leading-imbricate thrust system with a general NE-younging direction, whereas some major events could be recognized and distinguished. They likely correspond to major 'jumps' in the overall contractional system characterized by a rapid forward propagation of the new frontal fault-branch(s) and a subsequent slow accumulation of the shortening along the new fault splay(s) (*viz.* cumulative slip) and possibly within the hanging-wall block as well (*viz.* fold growth). As above described, this 'cyclic' phenomenon caused the occurrence of repeated sudden shifts of the foredeep depocenter and the development of satellite basins on top of the moving accretionary wedge (Fig. 10).
2) Together with this NE-wards migration of the contractional deformation and the consequent advancing of the wedge, the slab of the lower plate was retreating (*e.g.*, Doglioni, 1993) and the effect on the outer sector (*i.e.* extrados) of the lithospheric-scale fold was the creation of normal faults striking parallel to the coeval thrusts and likely caused the reactivation of the optimally oriented faults inherited from the Mesozoic events (Fig. 10).
3) From a geodynamic point of view, during the persisting convergence the area was characterized by alternating periods of smooth sliding on the low-angle basal detachment, with periods of partial coupling when instead internal wedge contractional deformation accumulated. During the former periods, the magnitude of the horizontal maximum stress axis was probably reduced due to continuous relaxation, while it temporarily increased during the coupling periods. Accordingly, this 'cyclic' mechanism could have affected a much broader area where the occurrence of alternating deformational pulses (or phases) could have been recorded. For example, the out-of-sequence faulting previously described is probably associated with such broader contractional events (coupling periods). Conversely, during the 'relaxed' periods, the extensional tectonic regime affecting the peripheral bulge developed in the flexed Adriatic Foreland could have locally prevailed (Di Bucci et al., 2011).

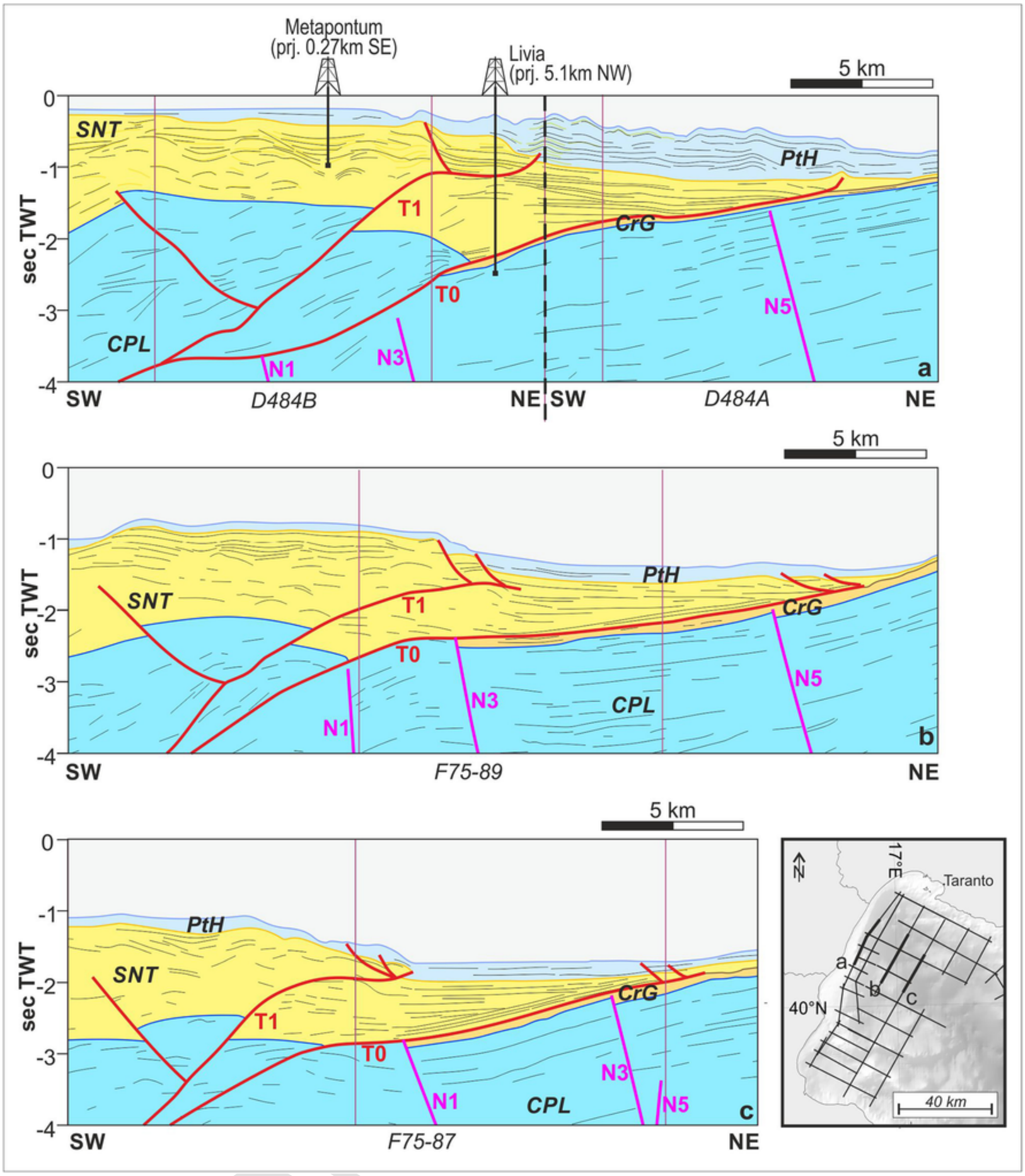
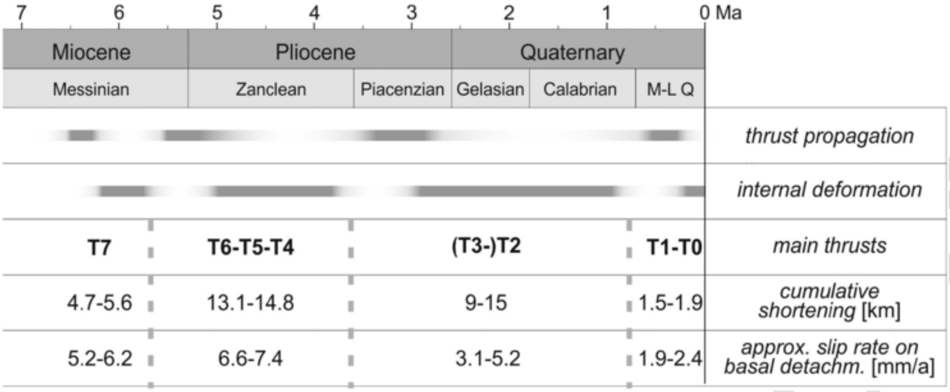


Fig. 12. Detail of the NE-SW trending seismic profiles in correspondence of the frontalmost sector of the accretionary wedge documenting the recent activity of thrust T0. See inset map for seismic profiles location.

4) The estimated slip-rate mean values on the deeper interplate surface during Messinian-Quaternary vary between *ca.* 4 and *ca.* 7 mm/a (Fig. 13) and show a clear slow down, but no zeroing, during the Middle-Late Quaternary in agreement with the progressive transitional process from subduction to collision suggested by Mattei et al. (2007) in the area of the Gulf of Taranto.
5) Standing on the above conclusions and as a final inference, we suggest that thrusts T0-T1 could represent an important seismogenic source (Fig. 14). At this regard, based on a rough estimate of width and length of the basal thrust above the BDT (Petricca et al., 2015; Chiarabba and De Gori, 2016), both of some tens of kilometers, and assuming the worst case scenario of a complete reactivation, the maximum expected magnitude could be in the range 6.8–7.3 (Wells and Coppersmith, 1994). Although its likelyhood is very low and whatever the case of a complete or partial reactivation, the occurrence of this seismogenic source should deserve further investigation in the future as far as it could strongly affect the seismic hazard assessment of the broader region, which is close to inhabited coastal areas, where industrial activity and several critical facilities are also present. Moreover, the occurrence of a strong earthquake in a shallow thrust system could also directly (*i.e.* coseismic displacement/deformation of the sea bottom) or indirectly (*e.g.* triggered submarine landslide) induce a tsunami with devastating effects, particularly for the many low coastal sectors surrounding the Taranto Gulf. The tsunamigenic potential of this tectonic structure should be also taken into account and consequently the associated hazard for the area.

Uncited references

Bertotti et al., 1997



main thrusts	T7	T6-T5-T4	(T3-)T2	T1-T0
cumulative shortening [km]	4.7-5.6	13.1-14.8	9-15	1.5-1.9
approx. slip rate on basal detachm. [mm/a]	5.2-6.2	6.6-7.4	3.1-5.2	1.9-2.4

Fig. 13. Synoptic table of the recognized compressional tectonic events affecting the offshore Southern Apennines accretionary wedge since Messinian, the activated thrusts, the corresponding cumulative shortening (in km) and the approximate slip rate along the basal detachment (in mm/a).

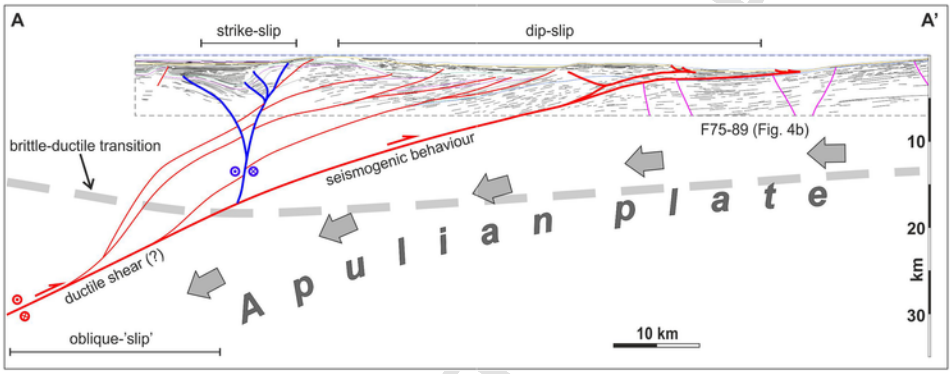


Fig. 14. The Gulf of Taranto accretionary wedge mainly developed in a purely contractional setting till Middle Quaternary, but it is presently involved in an oblique convergence (Fig. 10d) that likely caused the kinematic partitioning in the seismogenic layer with the development of prevailing strike-slip structures (*e.g.* West Amendolara flower) and the persistence of dip-slip reverse faults (T1 and T0 thrusts; Fig. 12). The partitioning at depth possibly begins in correspondence of the brittle-ductile transition (from Petricca et al., 2015), while below the BDT the ductile shear zone well documented by Maesano et al. (2017) (Fig. 1b) and separating the two plates likely represents a lithosperic ramp with an oblique kinematics.

Coward et al., 1999
Di Stefano et al., 2011
Grad et al., 2009

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