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Tectonic-Sedimentary evolution of the Tuscan shelf (Italy): Seismic-stratigraphic/structural analysis of Neogenic succession in the Tyrrhenian Sea between Elba Island and Monte Argentario promontory

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ABSTRACT

A reinterpretation of the vectorized version of public vintage seismic profiles in the Tyrrhenian Sea (Italy), between Elba Island and Monte Argentario promontory, was performed to reappraise the Tuscan shelf tectonic evolution. Despite the almost flat geometry of the seafloor, seismic profiles show a corrugated morphology of the pre-neogenic deformed acoustic basement, organized in structural highs and narrow, mostly N-S and NNW-SSE basins. We identified an intimate relationship between the thrust-related structural highs and the position of the basins, principally located at the forelimb and backlimb of major antiforms, a legacy of a primarily Miocene compressional stage. During the middle Miocene, the Tyrrhenian Sea opening set up, and the extensional front migrated from west to east, progressively activating and deactivating the observed high-angle faults, blandly controlling the sedimentation within the basins. After the late Messinian, a regional collapse stage led to the deepening and widening of the basins. A progressive deactivation of all the normal faults is recorded from the lower Pliocene. After the Late Pliocene/early Pleistocene, the area turned into a passive and widespread sinking stage without any frank tectonic activity. Results show that regional thrusts shaped the main architecture of the Tuscan Shelf shallow crust, while the neogenic depocenters started to develop as thrust-top basins along the flanks of the inherited antiforms. Intriguingly and partially in contrast with previous works, no evidence of low-angle normal fault was observed. We propose an innovative model that poses new questions on the crustal-scale mechanisms responsible for Tyrrhenian extensional process-related features, also establishing a new and unique starting point for fully unraveling the tectonic evolution of this portion of central Italy's offshore domain.

1. Introduction

The Northern Apennines is an east-vergent belt that originated after the Neogene collision between Europe and the Adria microplate (Carmignani et al., 1994; Bortolotti and Principi, 2005; Marroni et al., 2017; Conti et al., 2020; Romagny et al., 2020; Jolivet et al., 2021). The orogen experienced several phases of crustal extension and out-of-sequence thrusting, whose contribution to the overall orogenic architecture is still debated (Carmignani et al., 1994; Bonini et al., 2014 and references therein).

The western sector of the northern Apennines and the northern Tyrrhenian Sea (Tuscany and northern Latium), however, still preserve the record of the initial phases of the continental collision and the late- and post-orogenic evolution (Carmignani et al., 1994; Bonini et al., 2014; Buttinelli et al., 2014; Ryan et al., 2021). The western inner sector of the belt currently exposes the lowermost and older tectonic units of the nappe stack (Rossetti et al. Pascucci, 2002; Carmignani et al., 2004; Conti et al., 2020; Ryan et al., 2021). The current geodynamic setting of the northern Apennines depicts an evolution characterized by crustal shortening, mostly occurring on the eastern parts of the belt and extension in the inner and western portions of the belt (Chiarabba et al., 2014; Faccenna et al., 2014).

The northern Tyrrhenian Sea separates the northern Apennines of the Tuscany coast, Italy, from Corsica, France (Fig. 1). The Northern

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Tyrrhenian Sea, in the western part close to the Corsica Basin, shows a deep bathymetry. In contrast, the bathymetry is shallow in its eastern region close to the Tuscan Shelf, featuring a more regular and flat geometry (Fig. 1).

The architecture of the Tuscan Shelf has been extensively investigated and is characterized by structural highs (ridges) and depressions (basins) (Bartole, 1995; Mauffret and Contrucci, 1999; Pascucci et al., 1999; Sartori et al., 2001; Cornamusini et al. Pascucci, 2002; Pascucci, 2005; Contrucci et al., 2005), and it is separated from the Corsica Basin by a significant structural-morphological high, the N-S trending Elba-Pianosa Ridge (Wezel, 1982). The careful analysis of the basins' architecture of the Tuscan Shelf provided constraints in forwarding models of the tectonic evolution of this sector of the orogeny (e.g., Pascucci Pascucci, 2002; Contrucci et al., 2005; Buttinelli et al., 2014). However, the role of the structural inheritance (i.e., the thrust stack formed in the early phase of the orogeny) has not been fully explored.

In this contribution, we present a reconstruction from the western to eastern sectors of the southern Tuscany offshore based on a new interpretation of a public data set of raster seismic reflection profiles available from the ViDEPI database (*Visibilità dei Dati afferenti all'attività di Esplorazione Petrolifera in Italia*, https://www.videpi.com/videpi/videpi.asp) vectorized with the WIGGLES2SEGY code (Sopher, 2018) and appropriately tuned with the approach described in Buttinelli et al. (2022). The reinterpretation of these reprocessed vintage seismic lines and the CROP M12A profile allowed us to highlight the sedimentary and structural features at depth and to explore better the relationship

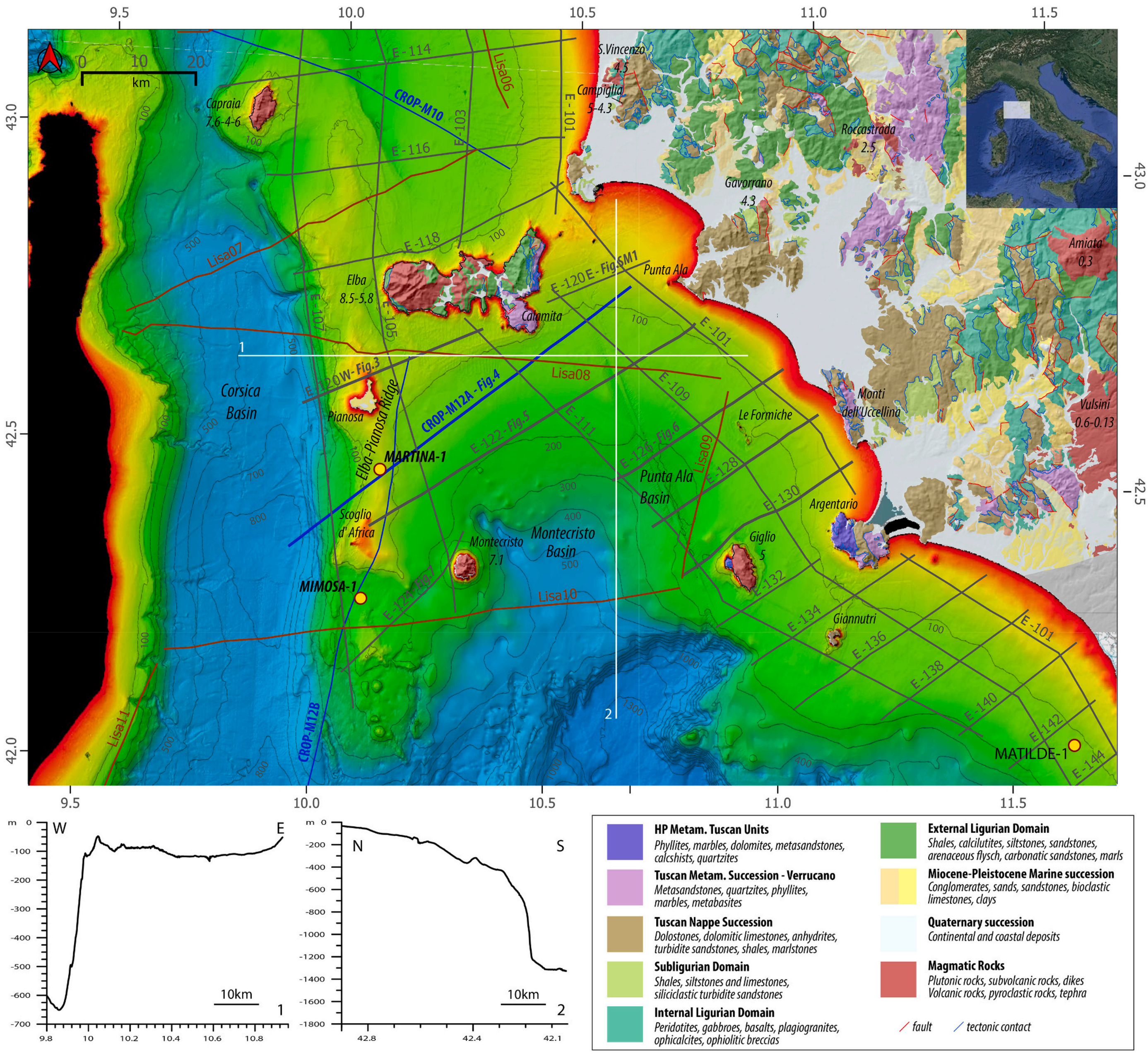

Fig. 1. Study area across the Tuscan Shelf (Italy) offshore. Seismic profile surveys are reported: solid black lines for public seismic lines available in the VIDEPI (https://www.videpi.com/videpi/videpi.asp) vectorized in the framework of this work; brown line from the Lisa project (Mauffret and Contrucci, 1999); Blue lines after the CROP project (http://www.crop.cnr.it/front-page_EN). CROP M12A profile after Tognarellli et al., 2011. Yellow circles for exploration wells are available in the VIDEPI project. Surface geology of the onshore and island areas after Conti et al., 2020. Bathymetric data after EMODnet project (contour line interval 100 m, https://www.emodnet-bathymetry.eu/). Bathymetric profiles 1 and 2 and main volcanic bodies of the area are reported (age of volcanism after Peccerillo, 2005). Map geographic reference is WGS84 GCS. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

between the thrust-related features and the sedimentary basins' evolution, which should span from the middle Miocene to the Pleistocene there. We provide a comprehensive picture of this portion of the Tuscan shelf shallow crust, proposing a new evolutionary model.

2. Geological Background

The geological evolution of the western-central Mediterranean is characterized from upper Oligocene to early Pliocene by the development of mountain belts and extensional back-arc basins (Horvath and Berckheimer, 1982; Malinverno and Ryan, 1986; Gueguen et al., 1997; Carminati et al., 2004; Doglioni et al., 2004; Faccenna et al., 2001; Jolivet et al., 1999; Romagny et al., 2020; Jolivet et al., 2021). This extensional process began within southern France and Iberia, with the drift of the Balearic Block, Sardinia, and Corsica away from continental Europe. During the early Miocene, the Sardinia-Corsica block of European continental crust underwent a counterclockwise rotation of 30° to finally collide with the Adriatic foreland (e.g., Moeller et al., 2013). The successive involvement of the Adriatic foreland lithosphere in the continental subduction process led to subduction trench eastward retreat and the present-day configuration of the NW-SE striking Apennine orogenic fold-and-thrust belt (Carmignani et al., 1994; Conti et al., 2020; D'Agostino et al., 2008).

The extensional stresses caused by the trench migration finally triggered the opening of the Tyrrhenian back-arc basin (Malinverno and Ryan, 1986; Kastens et al., 1988; Rosenbaum et al.Pascucci, 2002). This back-arc basin developed since the middle-late Miocene (Pascucci, 2002; Buttinelli et al., 2014 and reference therein) and was accompanied by drifting and rotation of blocks, crustal thinning, normal faulting, volcanic activity, and high heat flow (Carmignani and Kligfield, 1990; Della Vedova and Bellani, 2001; Mongelli and Zito, 1991; Keller et al., 1994; Collettini et al., 2006; Rosenbaum and Lister, 2004; Rosenbaum et al., 2002).

While there is a general agreement on the present-day extensional setting of the hinterland and the central domain of the Apennines (e.g., Faccenna et al., 2014; Chiarabba and De Gori, 2016; Lanari et al., 2023), there is a lively debate about the back-arc crustal extension linked to the Mid-Late Miocene onset Adriatic slab roll-back. Notably, the discussion is around whether the formation of grabens and half-grabens (basins) accounted for uninterrupted regional extension since the Miocene (e.g., Brogi and Liotta, 2008; Jolivet et al., 1999; Martini and Sagri, 1993; Trevisan, 1950), or basins are the expressions, at least in part, of flexures formed and reworked also during compressive events ensued during the post-early Miocene evolution (e.g., Boccaletti et al., 1999; Finetti et al., 2001; Bonini and Sani, 2002; Musumeci et al., 2008; Bonini et al., 2014).

Although the model advocating continuous extension from the Miocene remains the most credited (e.gJolivet et al., 1999; Barchi, 2010), recent studies provided progressively more support to important post-early Miocene inversion episodes. In particular, there is clear evidence of compressive structures controlling the basement reactivation and shortening of Miocene and Pliocene Basins in southern Tuscany and also in Corsica (e.g., Finetti et al., 2001; Bonini and Sani, 2002; Cerrina Feroni et al., 2006; Musumeci et al., 2008; Sani et al., 2009; Benvenuti et al., 2014; Bonini et al., 2014). Moreover, field evidence suggests that the emplacement of Miocene and Pliocene plutons in the upper crust in the Tuscan Archipelago and western Tuscany occurred within an overall compression regime (Musumeci et al., 2005; Mazzarini et al., 2011; Musumeci et al., 2015; Papeschi et al., 2017, 2021; Viola et al., 2018, 2022).

Despite this, the development and evolution of the northern Tyrrhenian Sea sedimentary basins have been the historical focus of several studies since they may contain the record of the tectonic evolution of the area (e.g., Mauffret et al., 1999; Bartole, 1995; Pascucci et al., 1999 Pascucci, 2002; Pascucci, 2005; Pascucci et al., 2006; Buttinelli et al., 2014). In the Corsica sector extension started at about 13.5–15.5 Ma, in the northern Tyrrhenian Sea, seismic reflection data evidenced pre-Messinian sequences suggesting the beginning of the extensional phase (Barchi et al., 1998; Scrocca et al., 2012). The Northern Tyrrhenian Sea extension was set up during the late Miocene–early Pliocene (Zitellini et al., 1986). In western Tuscany, the formation of basins began during the late Miocene when lacustrine and marine sediments were unconformably deposited on top of pre-deformed rocks (Ambrosetti et al., 1978, 1987; Bartolini et al., 1982), allowing the reconstruction of a depositional sequence sedimented during different tectonic phases:

- First phase (middle Burdigalian - early Serravallian) represents both a transitional period from the end of compressional tectonics to the start of an extensional one recorded by the tectonic elision of part of the Tuscan Nappe (the “Serie Ridotta”; Decandia et al., 1993; Massa et al., 2017). It might also testify to a pre-narrow rift stage of evolution of the region that occurred possibly between Serravallian and Early-Tortonian (Pascucci et al., 1999; Pascucci et al. Pascucci, 2002), while in the northern Latium offshore, the beginning of extensional phase is recorded from the Late Burdigalian (Buttinelli et al., 2014).

- Second phase (upper Tortonian - early Messinian) represents the most significant development of extensional tectonics (Pascucci et al., 1999). In the northern Latium offshore, such a phase is addressed to Serravallian to early Messinian (Buttinelli et al., 2014).

- Third phase (upper Messinian – early Pliocene) indicates the transition to wide regional sinking, characterized by the tendency to fill basins and flatten all the previously articulated geometries at the late Pliocene (Figs. 1 and 2; e.g., Bartole, 1995; Pascucci Pascucci, 2002; Pascucci, 2005; Buttinelli et al., 2014). Because of these processes, several regional unconformities developed in such basins due to the changes in the depositional regimes (e.g., Bartole, 1990; Barchi et al., 1998; Bartole, 1995; Pascucci Pascucci, 2002, 2005).

In the Tuscan shelf, thrust-related structures affecting the pre-Neogene substrate have been recognized and interpreted as formed in the Aquitanian-early Burdigalian compressional phase (Pascucci et al., 1999, 2006; Pascucci Pascucci, 2002). Martini and Sagri (1993) postulated that basins initially formed in those areas in structural lows at the nose of the already developed thrust-related antiforms (i.e., the “narrow rift stage” of Pascucci Pascucci, 2002). Alternatively, for the onshore of western Tuscany, basins have been interpreted as top-trust basins formed during late Miocene - Early Pliocene compressional tectonic phases (e.g., Boccaletti and Sani, 1998; Bonini, 1998; Boccaletti et al., 1999; Bonini and Sani, 2002).

3. Dataset and Seismostratigraphic interpretation

The seismic profiles acquisitions concerning the study area were made between the 1960s and 1970s by the Azienda Generale Italiana Petroli (AGIP) S.p.A. mainly through the use of an Aquapulse type source, with a shot interval between 13.33 m and 26 m and groups of 240 geophones. The data processing sequence consisted of deconvolution pre-stack, normal move out, 1200% stack, and application of a time-variant filter.

The dataset used in this study belongs to the VIDEPI database (https://www.videpi.com/videpi/sismica/zone.asp?zona=ZE). The image versions of the seismic profiles have been processed with the WIGGLES2SEGY code (Sopher, 2018) appropriately tuned with the approach described in Buttinelli et al. (2022) for such a sector of Italy to obtain vectorized digital SEG—Y. The SEG-Y profiles were also processed via deconvolution and AGC filtering within the OpenDTect environment to enhance the signal-to-noise ratio further. The time domain SEG-Y dataset span from 0 to 3 s twt.

The CROP M12-A is the most extended seismic profile of the area (Fig. 1, Tognarellti et al., 2011). Its acquisition and processing procedures allowed for observing the deeper portions of the crust (Scrocca et al., 2003).

Before the interpretation, a cross-check between the stratigraphy of the area and the seismostratigraphy of the seismic profile was performed by exploiting first the publicly available Martina-1 and Mimosa-1 wells

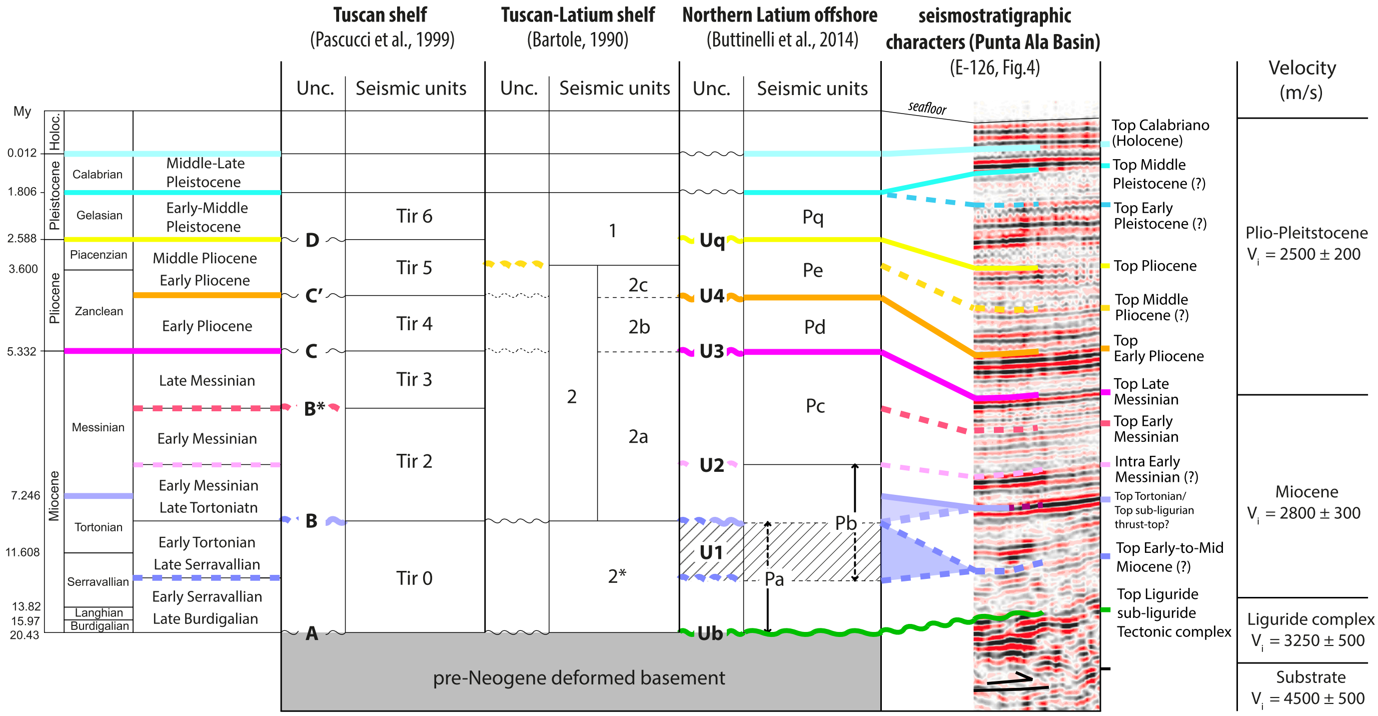

Fig. 2. Correlation chart between Tuscan Shelf seismic units already recognized by literature and their seismostratigraphic characters as observable within the Punta Ala basin on E-126 seismic profile (modified after Buttinelli et al., 2014). Interval velocity values (after Brogi and Liotta, 2008; Buttinelli et al., 2014; Mirabella et al., 2022) used for the Mimosa-1 and Martina-1 wells stratigraphy tie on seismic profiles and the time-to-depth conversion of the interpretation are reported.

information (https://www.videpi.com/videpi/pozzi/dettaglio.asp?cod=3524, https://www.videpi.com/videpi/pozzi/dettaglio.asp?cod=3689, respectively) and taking into account the wells stratigraphy reinterpretation reported by Cornamusini and Pascucci, 2014. Martina-1 is in correspondence with the Elba-Pianosa Ridge, to the South of Pianosa Island and a few km north of CROP M12A. Mimosa-1 is 10 km south of the "Scoglio d'Africa," near the available E-124 seismic profile (Fig. 1). The seismic tie of the Martina-1 well was done both on the E-120 W (Fig. 3) and CROP M12A (Fig. 4) profiles by checking the procedures already done by Tognarelli et al. (2011) and using the velocity scheme reported in Fig. 2. Mimosa-1 seismic tie was performed with the same approach on the E-124 profile (Fig. 7).

The interpretation performed on the seismic dataset was then time-to-depth converted to check the geometry of the detected structural elements; moreover, the main thrusts were modeled by forward modeling for a geometrical-kinematic validation (Fig. 8 and Figures SM1-SM4 in supplementary material).

According to literature data (e.g., Bartole, 1990; Pascucci et al., 1999; Cornamusini et al. Pascucci, 2002; Cornamusini and Pascucci, 2014; Conti et al., 2020), the stratigraphy of the Tuscan Shelf can be then divided into groups:

i) Tuscan Metamorphic units (Bartole, 1990) not reached by the Martina-1, outcropping at the Monte Argentario promontory, on the western part of the Giglio island, and in the Monti dell'Uccellina and eastern Elba (Fig. 1); ii) sedimentary succession of the Tuscan Nappe principally made of Jurassic limestones (Pascucci et al., 1999) not reached by Martina-1 well, but outcropping along the coast of Tuscany, in the eastern sector of Elba Island (Bartole, 1990; Conti et al., 2020), on the Formiche di Grosseto, and the Scoglio d'Africa (Cornamusini et al. Pascucci, 2002); iii) An Internal Ligurian Domain succession with ophiolite suite and Mesozoic sedimentary cover that outcrops at Elba island and southern Tuscany (Pertusati et al., 1993; Meneghini et al., 2020); iv) An External Ligurian Domain succession with no ophiolite suite at the base represented almost exclusively by sandstones and conglomerates (Cretaceous-Eocene Helminthoid Flsych auct.), with an origin from the next Adria continental margin (Marroni et al., 2001, Conti et al., 2020). Outcrops of these units are located on the Elba island; v) Eocene-Oligocene succession composed by clays, marls, and arenaceous turbidites and attributed to the Sub-Ligurian Complexes (Sensu Conti et al., 2020): these successions are encountered and differentiated in the Martina-1 and Mimosa-1 wells.; vi) an Epiligurian succession, spanning in age from the middle Eocene to the late Miocene/earliest Pliocene, sedimented within minor basins (Conti et al., 2020) placed onto the Ligurian/sub-Ligurian thrust sheets and constituted of a great variety of lithological terms (marls, clays, turbidite sandstones, breccias, and sedimentary melanges) as a result of the tectono-sedimentary variability within the basins; vii) a late Miocene succession consisting of pre- and *syn*-evaporite (Late Messinian) units deposited on top of the Epiligurian Successions (Conti et al., 2020). Since those successions are deposited on top of structural high, they may lack the primary evaporitic facies. These units are represented by continental clays, sandstones, conglomerates, and limestones; viii) post-orogenic marine and continental terrigenous deposits of the Middle/Lower Miocene-Pleistocene age are extensively crossed by Martina-1 well and constitute the primary outcropping sequences of the Pianosa island (Cornamusini et al., 2002).

In this study, groups i) and ii) have not been differentiated since they were not the main target of this work. The top groups iii) iv) and v) were marked as the regional unconformity defining the acoustic basement and the beginning of the post-orogenic Neogenic sedimentation.

The Neogene sedimentary sequences of the Tuscan Shelf, belonging to group vi), have been extensively studied in the last decades (e.g., Bartole, 1990; Pascucci et al., 1999; Cornamusini et al., 2002; Buttinelli et al., 2014) to define the inception of the northern Tyrrhenian Sea opening and to track its extensional evolution, also correlating the offshore and onshore data. Following such interpretations, this sedimentary sequence was divided into at least 6 or 7 sedimentary cycles, which can also be recognized on seismic profiles as a series of

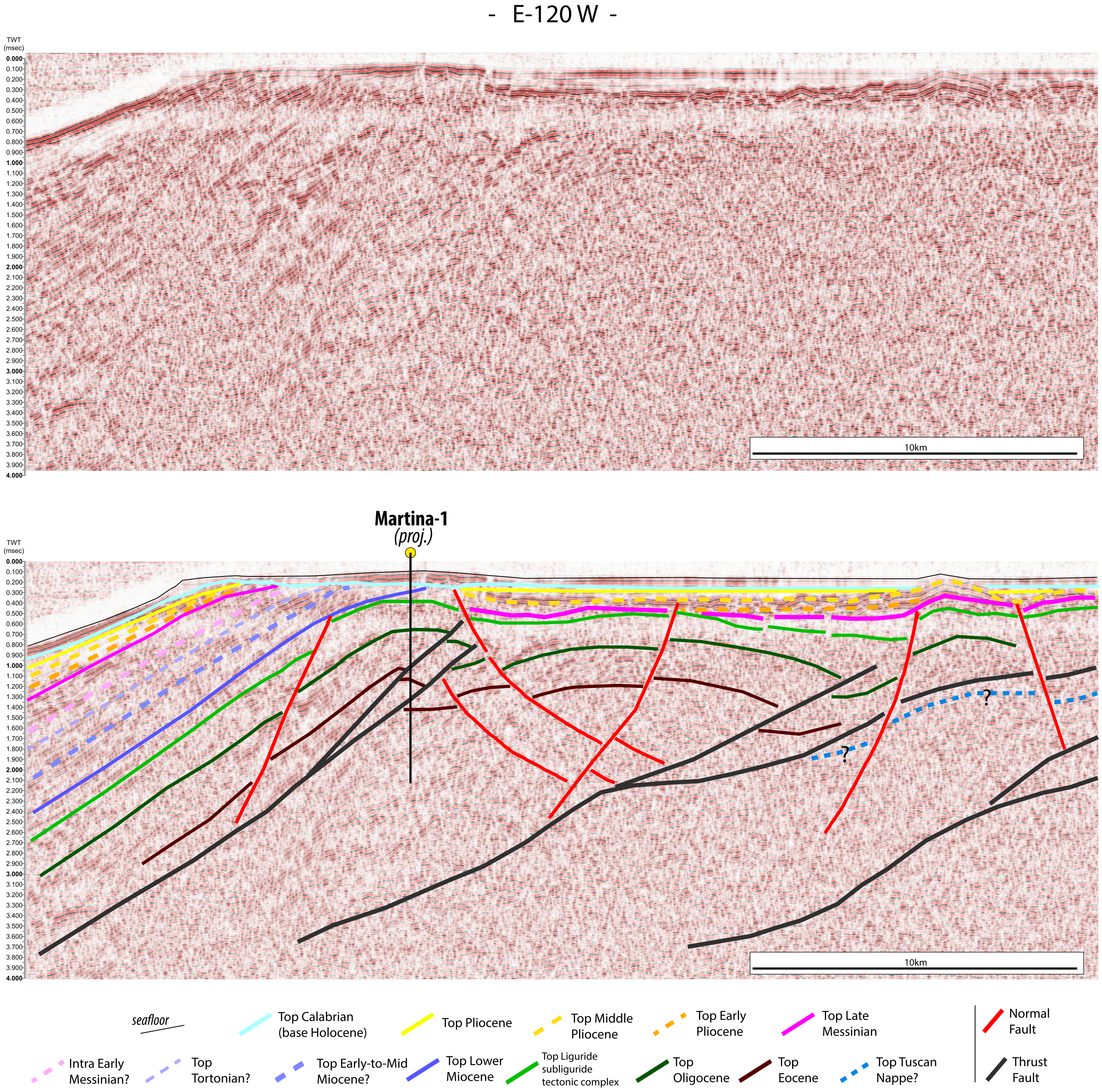

Fig. 3. Uninterpreted and interpreted versions of the E-120 W seismic profile (see Fig. 1 for location). Vertical exaggeration 2×.

seismostratigraphic units separated by unconformities (Fig. 2). Within the Neogene sedimentary sequence, it is also possible to group the seismostratigraphic units in two primary cycles, which are deposited within sensibly different depositional environments related to the basin's shapes evolution: a lower cycle (with subordinate units) that possibly deposited from the lower-middle Miocene up to the late Messinian, and an upper cycle deposited between the Pliocene and the Quaternary (Fig. 2).

The pre-Neogene deformed acoustic basement is generally characterized by non-continuous and usually chaotic reflectors with variable amplitude, primarily in the lower portions of the seismic profiles (Figs. 2 and 3 to 7). The Neogene sedimentary sequences of the Tuscan Shelf are featured by almost continuous, regularly spaced, generally parallel reflectors, with amplitudes from low to great, often prograding. They are typically positioned in the upper portions of the seismic profiles (Fig. 2 and Figs. 3 to 7).

4. Results

All the available seismic profiles between Elba Island and Monte Argentario promontory (Fig. 1) were interpreted to unravel the actual shallow crustal setting of the Tuscan Shelf. Here, we present the interpretation focusing on tectonic structures and basins' internal depositional architectures (Figs. 3, 4, 5, 6, and 7). The Tuscan Shelf in the studied area can be divided into four main physiographic and structural elements from west to east: the Corsica Basin, the Elba-Pianosa Ridge – Montecristo Basin, the Punta Ala Basin, and the Giglio High- Giglio Basin - Formiche Basin respectively (Figs. 1 and 8).

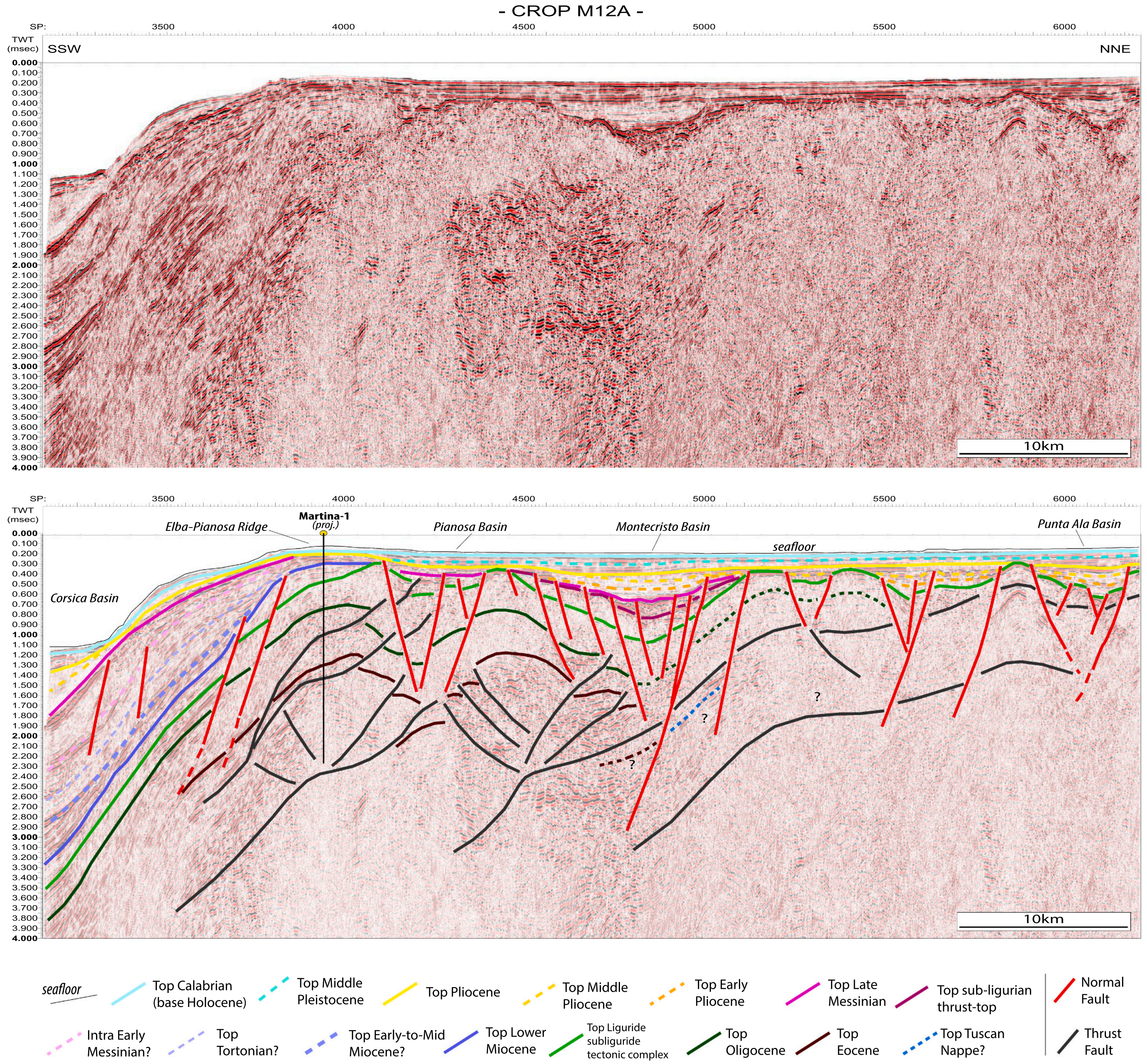

Fig. 4. Uninterpreted and interpreted versions of the CROP M12-A seismic profile (see Fig. 1 for location). Vertical exaggeration 2×.

4.1. *Corsica Basin*

The Corsica Basin is visible on the E-120 W, E-124, and CROP M12A profiles (Figs. 3, 4, and 7) that image only its eastern portion. According to literature data, the extensional activity of the Corsica basin started in the Oligocene and lasted until the early Miocene (Mauffret and Contrucci, 1999; Pascucci, 2005). Cornamusini and Pascucci (2014) suggested that the extension started before the Tortonian. In the eastern portion of the basin, we identified a continuous Miocene sedimentation, perhaps starting during the lower Miocene and topped by a prominent Late Messinian reflector (see Thinon et al., 2016; Moeller et al., 2013; Gaullier et al., 2014, Loreto et al., 2021 for further details on the identification of late Messinian units in those areas). In this area, the Messinian reflector is affected by normal faulting, while a frank marine Pliocene-Quaternary sedimentary sequence lies unconformably above the Miocene succession. The lower part of the Plio-Quaternary units shows a wedge that thins toward the East (Fig. 3). The seafloor morphology of the Corsica basin, combined with the seismic interpretation of this work, points to the presence of normal faults offsetting the most recent seismic units, also potentially propagating up to the sea bed there.

4.2. *Elba-Pianosa Ridge – Montecristo Basin*

The Elba-Pianosa Ridge-Montecristo Basin is a 70 km long N-S trending structure characterized by a prominent morphological ridge to the west (Elba-Pianosa Ridge, Pascucci, 2005), associated with an adjacent shallow basin to the east (Montecristo Basin). The southern emergence of the Elba-Pianosa Ridge is represented by the Scoglio d'Africa (Figs. 1 and 5).

The four WSW-ENE trending E-120 W, CROP M12-A, E-122, and E-124 seismic profiles allow the defining of the architecture of this structure (Figs. 3, 4, 5, and 7), even if the persisting flat morphology of the seafloor masks a buried complex structural setting.

Normal and reverse faulting is, in fact, rather pervasive throughout the area below the seafloor, revealing an alternation of buried structural

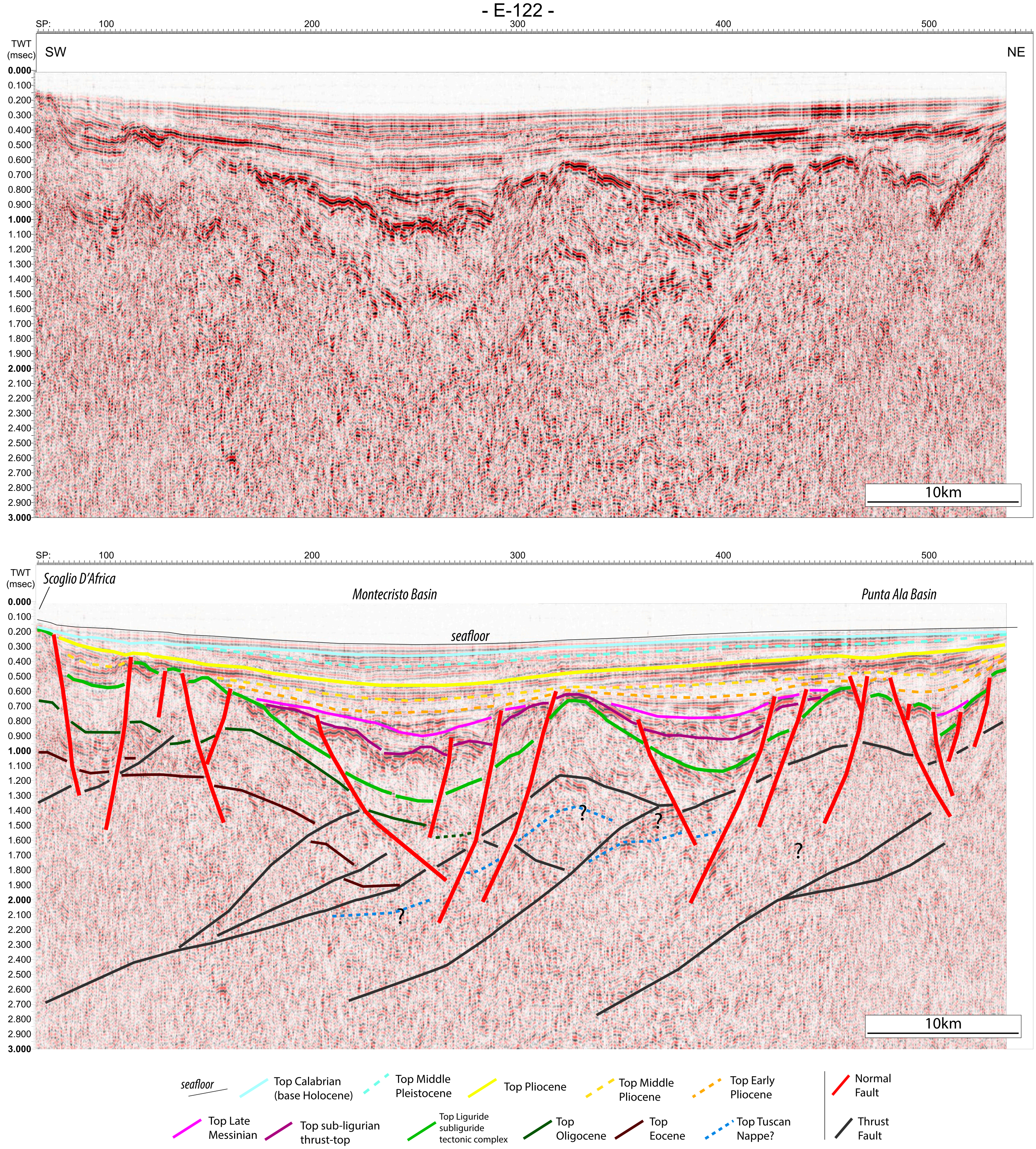

Fig. 5. Uninterpreted and interpreted versions of the *E*-122 seismic profile (see Fig. 1 for location). Vertical exaggeration 2×.

highs and lows. Larger normal faults are located at the borders of the structural highs, not controlling the basins' deposition (Fig. 3). In the area close to the Elba Pianosa Ridge (within the small Pianosa Basin), we identified at least four seismostratigraphic unconformities corresponding to the top of the pre-Neogene deformed acoustic basement, the late Miocene top, the top Pliocene and the mid-Pleistocene top (Figs. 3 and 4). This interpretation follows the outcropping constraints of the Pianosa island (e.g., Cornamusini et al., 2014, Fig. 1) and the Martina-1 stratigraphy that has been tied to the seismic profiles (Figs. 3 and 4). We interpreted the Elba Pianosa Ridge as a thrust-related non-cylindrical anticline resulting from the activity of two thrusts (Figs. 3, 4, 7, SM2, SM3, and SM4). In particular, in the northernmost sectors of the study area, it has a less prominent vertical aspect, where the action of a single thrust substantially generated its original shape, then deformed by the activation of an external one (Figs. 8a,b, SM2 and SM3). This process allowed the preservation of part of the Miocene deposition on

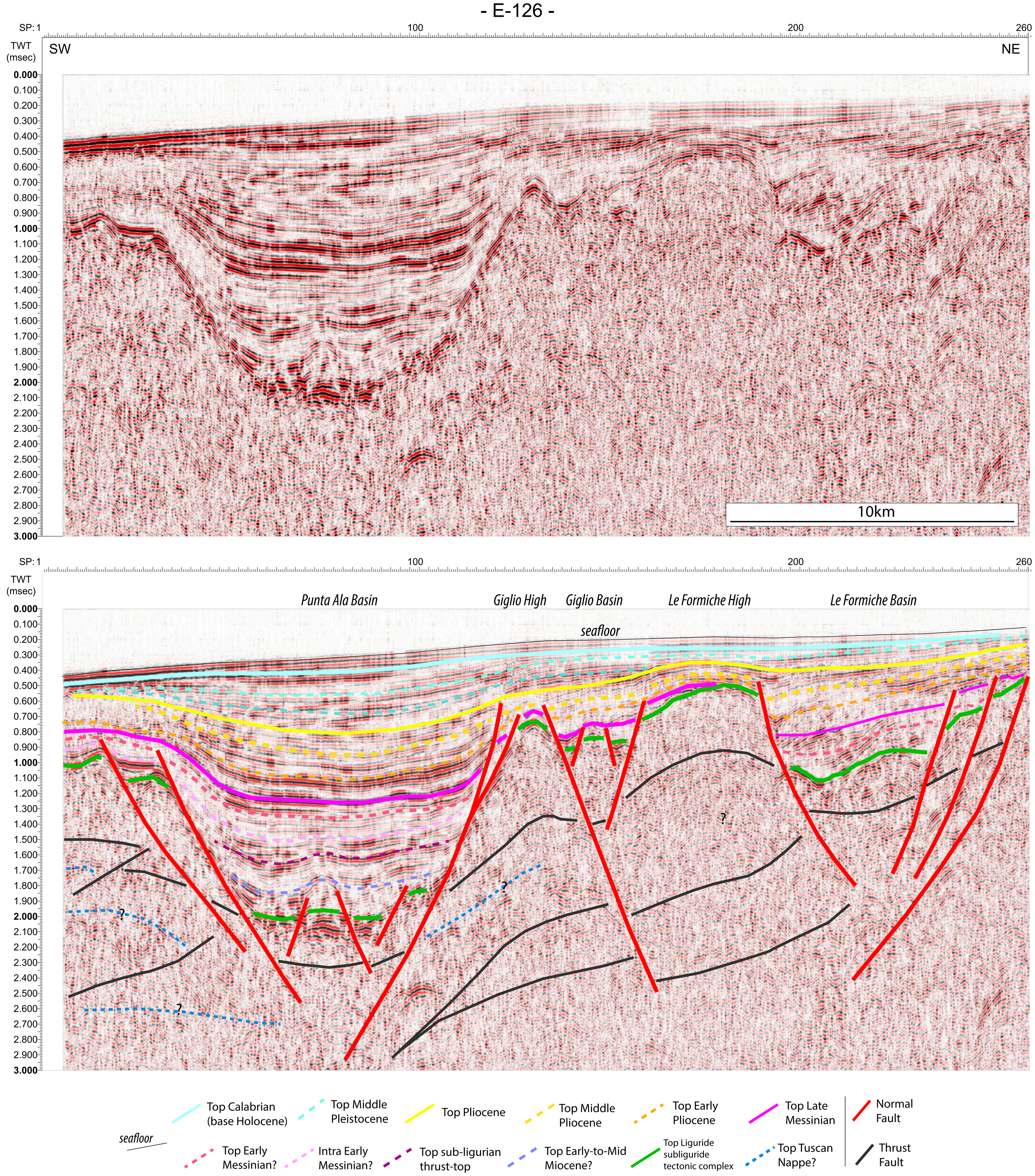

Fig. 6. Uninterpreted and interpreted versions of the E-126 seismic profile (see Fig. 1 for location). Vertical exaggeration 2×.

top of the antiform culmination, which agrees with the surface geology of Pianosa Island and the Martina-1 well stratigraphy. To the south, close to the Scoglio d'Africa and Montecristo Island, the Elba Pianosa Ridge was due to the action of two (perhaps synchronous) splays of a major thrust, which produced an antiform with a relatively high vertical aspect ratio (Figs. 7, 8d and SM4). This process brought the top-Oligocene horizon very close to the surface (or even exposed these units forming an island), causing a lack of deposition or erosion of Miocene units, in agreement with the Mimosa-1 well stratigraphy.

In correspondence with the forelimb of such a thrust-related anticline, the Montecristo Basin is defined by a sedimentary sequence from the late Miocene to Plio-Quaternary separated by five unconformities (Figs. 2, 3, and 4), whose age was calibrated by previous works (Bartole, 1990; Pascucci et al., 1999; Buttinelli et al., 2014, Fig. 2). Differently

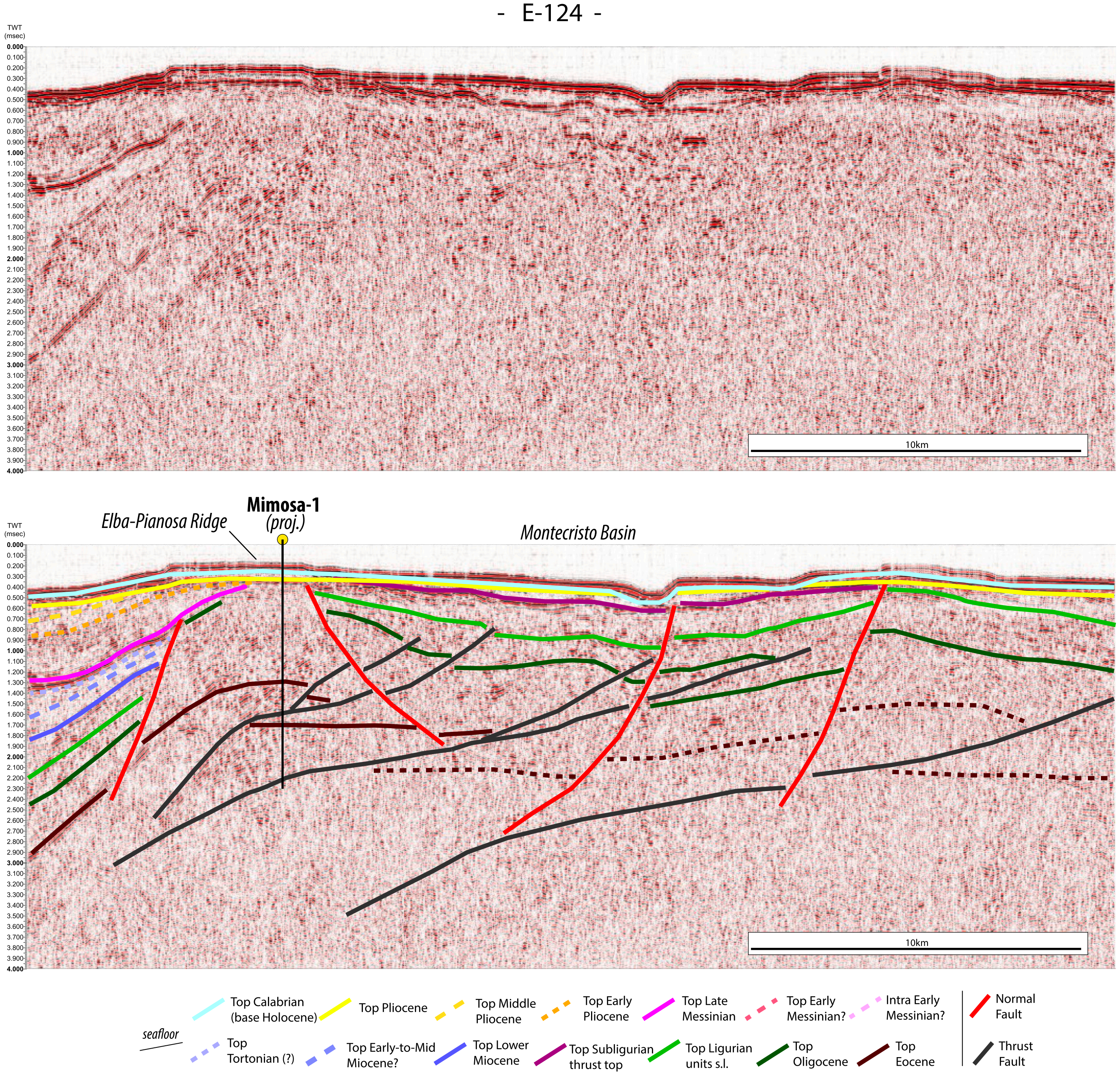

Fig. 7. Uninterpreted and interpreted versions of the E-124 seismic profile (see Fig. 1 for location). Vertical exaggeration 2×.

from the smaller Pianosa Basin, below the Neogenic sequence and above the sub-Ligurian acoustic basement, we also identified a sedimentary sequence whose architecture may suggest the presence of a basin deposited as a thrust-top/satellite environment (sensu Ricci Lucchi, 1986, sensu Ori & Friend, Figs. 3, 4 and 5). Moreover, to the north, the Montecristo basin is defined by a single primary depression (Fig. 4). In contrast to the south, its evolution started as two separated small basins that coalesced during the middle Pliocene (Fig. 5). These basins initially developed with a symmetric shape (with no apparent control of normal faulting) and were separated by a structural high in correspondence with a deeper thrust-related anticline (Fig. 5). Successively, the basins were affected by normal faulting, cutting only the late Miocene and the early Pliocene deposits. Intriguingly, such master faults are mostly west-dipping and lie on the backlimb of thrust-related structural highs. During the middle Pliocene, the normal faults within the Montecristo basins were almost deactivated, while fault-controlled subsidence and deposition continued within the Punta Ala and Corsica basins (Figs. 3 and 4).

Regarding tectonic structures, it is possible to depict a series of deep and in-sequence large thrusts affecting the pre-Neogene deformed basement, probably organized in stacks. Those thrusts refer to a compressional phase that occurred during the Early and middle Miocene (at least during the deposition of the thrust-top basin at the base of Montecristo Basin) before extension on the entire area set up, contributing to the upheaving of some portions of the crust (e.g., the present Elba-Pianosa ridge, Cornamusini and Pascucci, 2014).

4.3. Punta Ala Basin

The NNE-SSW trending Punta Ala basin developed south of the Punta Ala promontory toward the west of Giglio Island (Fig. 1). It had a

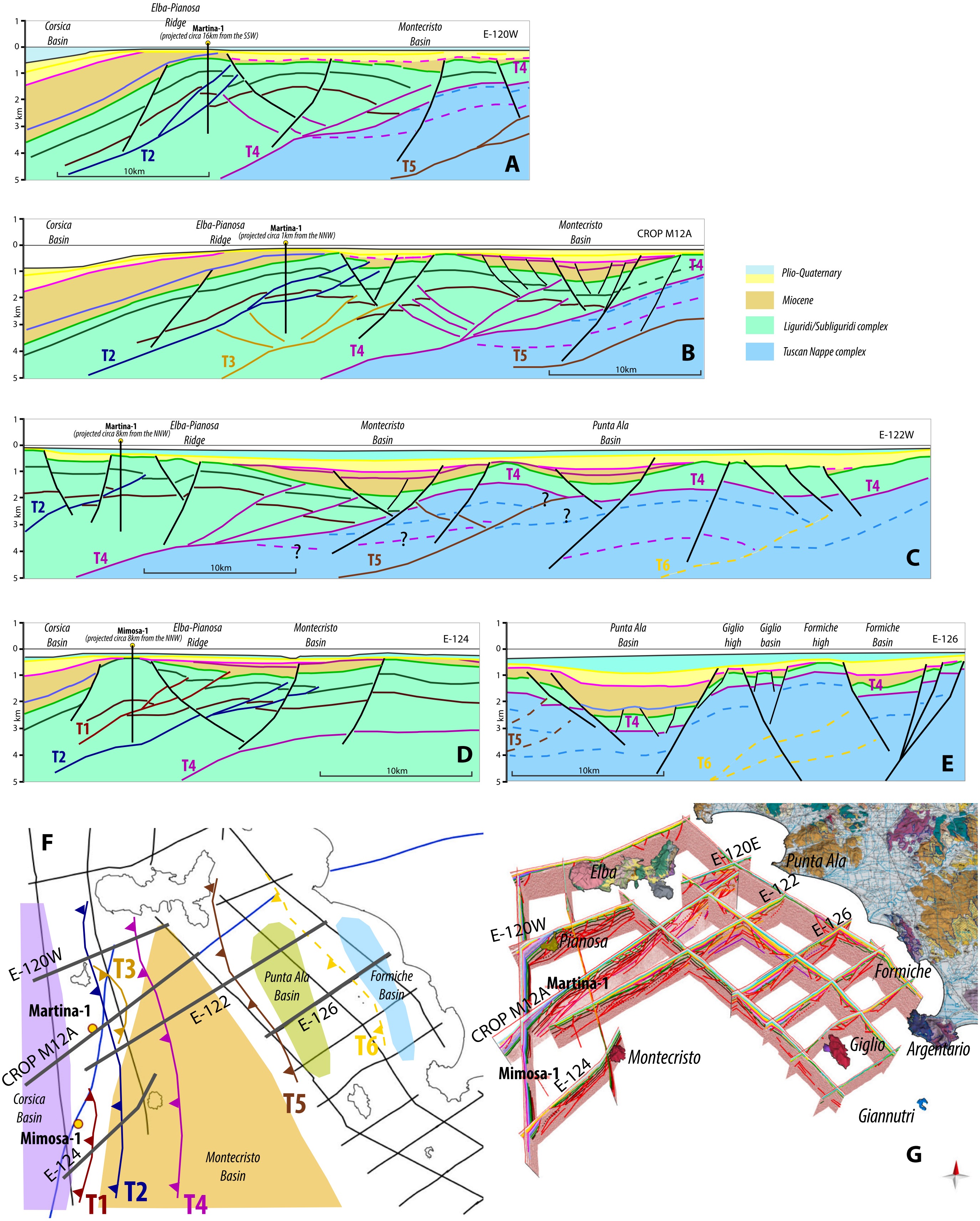

Fig. 8. A-E) Depth conversions of the intepreted seismic profiles (see Fig. 2 for the velocity model used and Figs. 3–7 for horizons definition and supplemetary material for the sections geometrical validation); F) Structural map of the main thrusts at the near Top of Subliguridi/Liguridi Complex is proposed to highlight the relationship between thrusts and main basins of the area; G) 3D view of the analyzed seismic reflection profiles.

different extensional evolution than the Montecristo basin. Considering the seismostratigraphic definition of units already described (Fig. 2), several unconformities were recognized within the basin (Figs. 5 and 6). Punta Ala basin possibly started developing as a symmetrical basin in the lower Miocene, subsiding until the late Messinian without an explicit fault control (Fig. 6, SM1B). Afterward, large high-angle normal faults activated and deformed the previous deposits, perhaps slightly controlling the Pliocene sedimentation. The seismofacies of the sedimentary units in the Punta Ala basin are characterized by an alternation of reflectors with regular amplitudes and frequencies, which can be interpreted as the formation of an inland basin similar to those outcropping in the current mainland of Tuscany (e.g., Martini and Capezzuoli, 2014). After the late Messinian, the active Tyrrhenian extension progressively migrated eastward, and the whole Tuscan shelf went under a general regional and widespread collapse after the late Pliocene-early Pleistocene. At this stage, the Punta Ala basin registered the deactivation of the bordering normal faults. Notably, even with the relatively wide time range of evolution of the Punta Ala basin (from early Miocene to present times, circa 15 My), the amount of subsidence and the related depositional rates are pretty small (circa 1500 m of sediments between the base and the top Pliocene). Considering these seismo-structural characteristics, we interpret that the Punta Ala basin started developing on the forelimb of a thrust-related structure (Figs. 5 and 6).

4.4. Giglio High - Giglio Basin - Formiche Basin

Giglio High is located East of Punta Ala Basin, representing an N-S trending structural high bordered by the normal faults whose activity postdates the middle Pliocene (Fig. 6). It emerges in the southernmost portion of the study area, representing the current Giglio Island (Fig. 1). Le Formiche High represents an analog structure of Giglio High, located East of the Giglio Basin, characterized by outcropping Liassic carbonates of the Tuscan Nappe (Fig. 6). Seismic data show that the Le Formiche high has still emerged during the early Pliocene to the south of the study area (Fig. 6), pointing to an N-S trending of the high featured by a northward plunge. Conversely, the Giglio High emerged during the Late Messinian and soon drowned after the early Pliocene. These structural highs are located above thrust-ramp structures and deformed the late Messinian horizon. Giglio and Le Formiche basins probably began their activity in the early-mid Miocene for Giglio and, more frankly, mid-Miocene for Le Formiche.

Giglio basin evolved symmetrically as Punta Ala, at least up to the late Messinian. From the early Pliocene to the late Pliocene, an E-dipping fault dominates the sedimentation, while a pair of synthetic W-dipping faults seem to control its evolution up to the middle-late Pliocene. Conversely, the Le Formiche basin seems to have a different history than other basins because its first phases have a substantially asymmetrical evolution slightly controlled by a main E-dipping fault (Fig. 6). During its development from the middle Miocene, a series of antithetical structures to the master fault were activated up to the early Pliocene, which, however, never managed to balance the activity of the master fault. In the specific case of the structural high to the W of the Le Formiche basin, we can hypothesize it as the last remnant of an island during the late Miocene-Early Pliocene. Subsequently, even those areas that have emerged finally drowned. Further, we have no control over the outermost W-dipping fault bordering Le Formiche basin, which is also close to the coast of southern Tuscany. Le Formiche and Giglio High are genetically related to the same deep thrust. Giglio and Le Formiche Basins conversely represent two other basins developed on a backlimb and forelimb of a possibly younger and outer thrust structure with respect to the Elba-Pianosa one. The Giglio and Le Formiche basins seem younger than the Punta Ala one in this area, starting their activity not before the late Tortonian (Figs. 4 and 6). Their general shape is different from the Punta Ala basin since they are more asymmetrical while dominated by more pervasive normal faulting at the level of the acoustic basement. Their activity proceeded even after the middle-late Pliocene, perhaps characterized by the deposition of condensed sequences on the structural high. We can find some slight clues concerning fault activity after the late Pleistocene when the whole area went into a stable condition of regional subsidence, with the generation of a regional unconformity that flattened all the previously articulated geometries up to the present seafloor. The seismic profiles located in the central-southern part of the study area allow defining the relationship between all the Tuscan Shelf basins already defined.

Even in the sector shown by these seismic profiles, it is challenging to delineate the geometry of the deep thrusts, which, however, seem to be more visible in correspondence with the structural highs culminations (e.g., Le Formiche high, Fig. 6), where they are positioned at shallow levels.

It was, therefore, possible to follow the southern culmination of both the basins and the structural highs of the Tuscan Shelf up to the island of Giglio to the south.

In this area, the Formiche Basin resembles the Montecristo Basin of the northernmost sector, East of the Elba-Pianosa ridge (Figs. 3 and 4). This similarity is strictly connected to the positioning of the basin concerning the geometry of the thrust ramp located at depth. Its western part, close to the Giglio island, looks like a small basin on the forelimb of the thrust that generates such structural high, while Le Formiche basin seems to be positioned on the backlimb of the outermost thrust to the east.

In this area, the thrusts are shallower, pointing to the geometry of major thrusts featured by closures toward the north (Elba) and south (Giglio). We generally see Montecristo-like basins corresponding with the shallow thrust flats and forelimbs. Moreover, where we see the full development of a basin, there is a strong connection with the inherited depocenter in correspondence with old thrust ramps (e.g., Figs. 3 and 4 for the Montecristo Basin). Similar interpretations have been made for many basins on shore that seem to be systematically developed between thrust anticlines (Baccinello, Velona, Siena-Radicofani basins, Bonini et al., 1999, 2014; Bonini and Sani, 2002; Benvenuti et al., 2015), where sedimentation is controlled by thrust activity and not by normal faults.

5. Discussion

The evolution of the Tuscan Shelf is a good example of tectonics controlled by structural inheritance. Despite the current flat seafloor, a series of extensional basins can be recognized as developed on a complex acoustic basement that constitutes the legacy of previous compressional phases that affected the whole area. We focused on the seismostratigraphic and structural analysis of the principal Neogenic basins of Montecristo, Punta Ala, Giglio, and Le Formiche (from W to E in the study area, respectively, Figs. 1 and 8), from their inception up to the present day, and their relationship with a series of thrust-related antiforms defining the first order shape of the substratum onto which the basin developed.

The reinterpretation of reprocessed vintage seismic lines also allowed precise imaging of the area's main normal faults (Figs. 3, 4, 5, 6, and 7). Notably, the normal faults share some common features: i) they cut across the basin substrate and also across the basin deposits (e.g., Fig. 5); ii) they often root on the thrusts beneath the basins; iii) they had very limited throws (less than 0.2 TWT s for the fault cutting into the basin's basement and less than 0.1 TWT s for the faults affecting deposits). As a consequence of this latter point, the sedimentation within the basins is not controlled by the activity of the normal faults (e.g., Figs. 4 and 5), as none of the commonly observed markers of synsedimentary extension (wedge-shaped deposition against the faults, asymmetric subsidence of the basins, e.g. Fucino basin, Caielli et al., 2023, Patruno and Scisciani, 2021; South Apulia Fault system, Maesano et al., 2020) were observed on the basin margins. On the contrary, the overall geometry observed within the basin is characterized by a progressive thinning toward the structural highs as typically imaged for thrust-top basins (e.g., in the Plio-Pleistocene thrust-top and foredeep basins of the Po Plain, Amadori et al., 2019).

Our results show that the sedimentary basins' location, evolution, and internal geometries are structurally controlled mainly by the main thrusts. Basins generally formed on the hanging wall of deep and large thrusts with usual flat-ramp-flat geometry and an apparent in-sequence enucleation toward the eastern-outer sectors, both in the backlimb and forelimb structural positions of the thrust-related antiforms. Generally, the basin located on the forelimb is slightly more asymmetrical than the backlimb (at least in the first phases of evolution). Furthermore, we also hypothesized the presence of thrust-top basins formed during the thrusts propagation, slightly older or coeval with the Neogene basins. In this general structural arrangement, almost all the positive structures observable in the Tuscan Shelf are culminations of Neogene antiforms (or ramp stacks), and basins seem to be systematically developed between thrust anticlines (e.g., Bonini et al., 1999, 2014; Bonini and Sani, 2002; Benvenuti et al., 2015).

The sedimentary record shows that the basins are all N-S to NN*E*-SSW oriented (Figs. 1 and 8) and have primarily developed since the early-mid Miocene. The basins also experienced a N-S to NNW-SSE-striking high-angle normal faulting, mostly after the Late Messinian, which did not control the deposition, in a way somewhat different from what described the late Miocene basins of southern Tuscany (Bossio et al., 1993). In this context, there is also evidence that the west-dipping normal faults generally cut deeper into the crust than the east-dipping ones and show a geometry suggesting a possible connection with the deep ramps of the inherited thrusts (Figs. 5, 6, and SM1). It is also relatively clear to observe a rejuvenation of the basins toward the east, which denoted a stepward and eastward migration of the Tyrrhenian extensional front in those areas, as already defined by literature (Buttinelli et al., 2014 among others, and references therein).

5.1. Geometry and position of the basins

The Montecristo and Punta Ala basins did not develop before the Messinian to the south of Elba island due to their structurally inherited upheaved position (Figs. 3 and 4), marking a potential exposure by the emergence before the late Miocene. The Montecristo Basin is located in correspondence with the forelimb of such a thrust-related anticline and possibly started its evolution developing as a thrust-top/satellite basin, without any clear fault control, in a way somewhat similar to several intermountain basins currently found within the central Apennines (e.g. Fucino basin, Caielli et al., 2023). This is also because its evolution started as two separated small basins that coalesced during the middle Pliocene-early Pleistocene (Figs. 5, 6, and 8). After the inset of a more frankly extensional stage over the whole Tuscan shelf after the early Pliocene, its evolution was controlled by west-dipping normal faults with a slightly more pronounced asymmetry. Intriguingly, such faults lie on the backlimb of thrust-related structural highs. The largest Punta Ala basin in the study area is located at the eastern edge of the Elba-Pianosa ridge upheaved shallow crust. This basin developed on the backlimb of an N-S regional thrust longer than 20 km along strike (Figs. 5, 6, and 8).

The Punta Ala basin is the most developed among the basins of the study area, with the most resolved sedimentation internal architecture considering the available seismic dataset. We could recognize several unconformities within the Punta Ala basin (Figs. 3 and 6). This means that even with the change in local depositional dynamics, the basin keeps the symmetry constant throughout its evolution up to the early Pliocene. This process points to subsidence (and sedimentation) not so controlled by normal faults bordering the basin. Those somewhat slightly drove a partial collapse after the late Miocene when they developed as rooted on the ramp portion of a previously formed thrust.

Giglio and Le Formiche Basins conversely represent two basins more clearly developed on a backlimb and forelimb of possibly younger and outer/external thrusts (Figs. 6 and 7). Giglio basin essentially evolved with a bowl-shaped style as Punta Ala, at least up to the late Messinian, while le Formiche basin started with an asymmetrical evolution controlled by a W-dipping fault, then evolved as controlled by a main E-dipping one. This evolution is interpreted as resulting from a switch from initial development in a forelimb position of an inherited thrust-related antiform to a more evident basin growth over a thrust ramp reactivated in extension, namely in a backlimb position of the thrust that generated the structural high of the Monte Argentario and the Monti dell'Uccellina. A progressive in-sequence enucleation of two large contiguous thrusts should have caused this configuration. Even for Giglio and Le Formiche, the main faults visible at this resolution scale are all sutured since the early Pliocene.

5.2. Sediment thickness

The Tuscan shelf basins discussed in this work have a relatively long evolution period of about 14 million years (at least from early/middle Miocene to late Pliocene). Considering the thickness of approximately 1600–1700 m (Fig. 8e), this means a very low average sedimentation rate of ~0.1 mm/y. In the structurally higher areas, such as the Monte Cristo basin immediately to the south of Elba island (Fig. 8b,c), on the other hand, approximately 600–800 m of sediments are modeled, pointing to a sedimentation rate of 0.06–0.08 mm/y. These results show a much lower sedimentation rate than that reported by previous authors (Bartole, 1995; Bertini et al., 1991). Notably, there were few supply areas around these basins. This could also be one of the motivations for the observed reduced thickness, which is in any way comparable with the thickness of the inland basins.

5.3. Structural control of basin development

For the entire northern Tuscan shelf sector of the study area, it seems that basins developed efficiently when positioned at the convergence between the forelimb and backlimb of contiguous thrusts (e.g., the Montecristo Basin), reaching shallow crustal levels (Fig. 8). On the other hand, the Punta Ala Basin seems frankly controlled by its structural position on the backlimb of a thrust, with its main depocenter located on the vertical of a deeper thrust ramp (Figs. 5 and 6), which perhaps conditioned the generation of normal faults on its flanks after Miocene. In the same way, the Giglio and le Formiche basins seem more strictly controlled by the geometries of the deep thrusts. Despite seismic profile interpretation being more devoted to unraveling Tuscan shelf basins evolution, some strong constraints on thrust structures can be defined. Thrust structures can be recognized by looking at peculiar high amplitudes of low-frequency seismostratigraphic signals. As an example, on CROP M12A below the Elba-Pianosa ridge and Pianosa basin, we found clear hanging wall and footwall cut-offs that can be associated with large-scale thrusts. Although not as straightforward as for this profile, thrust structures are found throughout the entire Tuscan Shelf at various depths on the dataset shown in this work.

Since the late Pliocene-early Pleistocene, the whole Tuscan Shelf has undergone regional subsidence, the main deformation shifted to the east (following the stepward evolution of the Tyrrhenian Sea), and almost all the normal faults were deactivated. Regional subsidence caused the widespread coalescence of the Punta Ala, Giglio, and Le Formiche basins, finally shaping the flat morphology of the current Tyrrhenian Sea seafloor. Such subsidence persisted and caused the gentle and very slow deposition of most young units and the shallow sea depth (around 100-130 m) from the Elba-Pianosa ridge to the Tuscany and Latium coastline toward the east.

In this view, there should be a connection between (i) the inset of a basin on an early Neogene thrust-related structure, (ii) the evolution with symmetrical and asymmetrical geometry, and (ii) the generally observed lower sedimentation rates. Though the deposition rates were meager from the Miocene to the early Pleistocene, those might eventually accelerate from the Lower Pleistocene. This should result from the Calabrian slab roll-back that drastically changed the Tyrrhenian Sea's large-scale dynamics (Faccenna et al., 2001).

Conversely, before the lower Pleistocene, the basin growth was much more attributable to local extension controlled by the structural inheritance, where the already depressed thrust-related paleomorphologies received few sediments. Thus, we can forward that the position of Neogene sedimentary basins might coincide with a forelimb syncline between two thrust ramps. This interpretation also fits the recognition of a possible thrust-top basin below the Montecristo basin. Such an architecture is also coherent for the timing and sediments architectures with the Serravallian Arenarie di Manciano found very close to the east on land.

5.4. *Thrust geometry and time evolution*

Considering the quality of the available dataset, it was possible to define the geometries of numerous thrusts throughout the Tuscan Shelf sector (Fig. 8). First, the geometry of the thrusts varies, moving from North to South. Generally, they have an NNW-SSE trend and are more superficial in the border sectors toward the N and the S (e.g., Elba-Pianosa Ridge and near the island of Giglio, where they are recognized at 1.5–1.7 s TWT, Figs. 3 to 7). On the other hand, they are deeper (about 3 s TWT) in the western and central sectors, where the major developments of the basins are found (Figs. 3 to 5).

This setting supports that the entire Tuscan shelf between the Elba Pianosa ridge and Montecristo basin up to the SE areas of Elba has always been raised by regional thrusts (Fig. 8; see also the supplementary material for the geometrical-kinematic validations).

The structural map of the Tuscan Shelf reports the traces of the six main thrusts recognized in the seismic dataset (T1, T2, T3, T4; T5 and T6 from west to east; Fig. 8F). The forward modeling, tied to the Martina-1 and Mimosa-1 wells (Fig. 1), reinforced the calibration of six geological sections produced depth converting the seismic interpretations (Figs. 8A-E and SM1-SM4 in supplementary material). The thrusts have been modeled and checked in the calibrated sections (Figures SM1-SM4 in supplementary material). The main thrust, responsible for the most considerable crustal shortening, is the T4 (Figs. 8A, B, C, D, E). T4 put the sub-Ligurian Eocene-Olicene units over the Tuscan Nappe, accounting for more than 80 km of horizontal displacement (Figures SM2, SM3, SM4 in supplementary material), also justifying the surface structural setting of the Tuscany inland to the East (Fig. 1). For this reason, T4 should be considered mainly active from the early Miocene in the late Aquitanian-Burdigalian. The T1 and T2 are interpreted as trailing edge thrusts of T4 (Figs. 8A-E and SM2, SM3; SM4 in supplementary material) and assumed active since the Burdigalian-Langhian. The T3 thrust is a splay of T4 (Figures SM2, SM3, SM4 in supplementary material). The uplift of the Elba-Pianosa Ridge (Figures SM2, SM3; SM4 in supplementary material) is modeled as due to the activity of the T1, T2, and T3 thrusts that are thus assumed to be active until the Langhian- late Tortonian (e.g., Cornamusini and Pascucci, 2014). The T5 thrust (Figures SM2, SM3, SM4 in supplementary material) formed after the T4. It is interpreted as Langhian-Serravallian, assuming it cut across the thrust-top sequences we interpreted at the base of Montecristo Basin (Fig. 8C). Such succession can be ascribed to an analog of the Manciano sandstones exposed in the onshore area (Bossio et al., 1998; see the seismic unit seq1 in Pascucci et al., 1999). The T6 is the easternmost thrust (Fig. 8F). It is modeled as an in-sequence thrust (Figures SM2, SM3; SM4 in supplementary material), conservatively interpreted as Serravalian-Tortonian.

In our modeling, the younger thrusts T5 and T6 (Fig. 8F) carry on the already-formed thrust stack. A comparison with known geological data in Elba Island and on the onshore of western Tuscany (Fig. 1) may further constrain the Tuscan shelf tectonic evolution. Notably, in the Calamita peninsula, eastern Elba Island (Fig. 1), the contact aureole of the Porto Azzurro pluton recorded the thermal peak of the granite emplacement at 6.4 Ma during the Messinian (Musumeci et al., 2011) coeval to the regional crustal shortening (Musumeci et al., 2015; Papeschi et al., 2017, 2021, 2022). The absolute isotopic ages of the thrusts exposed in the Calamita peninsula are 6.14 Ma and 4.9 Ma (K—Ar on authigenic illite, Viola et al., 2018), suggesting that the activity of the T6 thrust can be extended to the Messinian. In this context, we also possibly suggest that the main thrust T4 may have been reactivated in the Pliocene, as the Zuccale Fault (post 4.9 Ma; Viola et al., 2018, 2022), namely an out-of-sequence thrust during the activity of T6 or an easternmost thrust such as that postulated for the emplacement of the Gavorrano granite (Fig. 1) at about 4.5 Ma (Musumeci et al., 2005). Such an outermost thrust that probably spreads onshore may justify the outcrop of the Monte dell'Uccellina and the Monte Argentario promontory, where the deepest metamorphic terms of the Apennine stack are now exposed (Conti et al., 2020; Fig. 1). This may also mean that the early stage of basin growth in those areas could correspond to the generation of piggyback/thrust-top basins, not directly controlled by high-angle faults (e.g., the Montecristo one). As already noted in previous works of literature (Bartolini, 2003), and considering the stratigraphy of the emerged areas such as the island of Pianosa and Elba (Cornamusini et al., 2014), there are indications that the Tuscan Shelf, like much of the northern Apennines, was essentially a submerged portion of the Apennines chain at least up to the Upper Pliocene, featured by few N-S trending islands. The island of Pianosa can be considered the culmination of a positive thrust structure (Fig. 4) rather than the uplift of the footwall of a low-angle *E*-dipping structure (Cornamusini and Pascucci, 2014) because of the exposed middle-upper Pleistocene younger terms of the entire sedimentary sequence instead of deeper and more ancient exhumed terms. The western Elba corresponds to the northernmost exposure of the Elba-Pianosa ridge positive structure. Apatite fission-track data on the igneous rocks of the Monte Capanne pluton are consistent with a late Pliocene-early Pleistocene (2–3 Ma) uplift (Bouillin et al., 1994).

In our opinion, the difference between the Tuscan Shelf and the central Apennines is that there was not much topography at the time of the construction of the crust that today represents the Tuscan Shelf. We see the emergence of only small portions of the crust (islands of Pianosa, Scoglio d'Africa, Elba, Giglio, and Le Formiche rocks, Fig. 1) in a morphological context of lagoons of an archipelago, without a consistent expression of an emerged chain. Thus, we suggest that during the post-Aquitanian-late Pliocene, the most effective mechanism for the growth of the orogenic wedge was the eastward propagation of in-sequence ramp-dominated thrusts rather than the development stacking of low-angle thrusts, even leading to the complete doubling of sedimentary sequences. Such a process was already described for the hinterland (Tyrrhenian side) of northern Apennines, where late Tortonian – late Pliocene large-scale thrusting and folding resulted in the coeval deformation of overlying late Miocene-early Pliocene sedimentary basins simultaneously to the emplacement of Pliocene granite intrusion at the core of ramp anticline (Bonini and Sani, 2002; Cerrina Feroni et al., 2006; Moratti and Bonini, 1998; Musumeci et al., 2005; Balestrieri et al., 2013; Benvenuti et al., 2014). The development of the Tuscan Shelf basins described in this work also closely resembles that of the intermontane basins of the central Apennines (e.g., Fucino, Norcia), which developed with a high level of control by pre-existing and inherited structures (e.g., Buttinelli et al., 2021; Di Bucci et al., 2021, and the results of the recent RETRACE-3D project-http://www.retrace3d.it/contenuti.html; Caielli et al., 2023). The seismicity of recent decades of the central Apennine is localized or controlled by inherited thrust ramps reactivated and inverted in the current extensional regime (Buttinelli et al., 2021), supporting a similar tectonic evolution for both the outer (Central Apennines) and the inner (Tuscan Shelf basins) orogen in different times.

Some literature schemes have underlined our observations, highlighting the migrating Tyrrhenian deformation front from W-SW to E-NE in the same areas following the flexural retreat of the Adriatic lithosphere (Meletti et al., 1995). In this plausible scenario, we suggest that the areas outside the preformed orogenic wedge (e.g., the Messinian basins of southern Tuscany) would represent inherited intermontane depressions and not rift and/or retro-arc areas as commonly assumed. Furthermore, we cannot exclude the propagation of late Messinian – early Pliocene out-of-sequence thrusts and back-thrusts (as documented in the nappe stack of eastern Elba island, Musumeci et al., 2015; Viola et al., 2018, 2022).

Finally, our general results point to a scenario where the compressional structural inheritance basically controlled the basin formation in the Tuscan Shelf. At the same time, the generalized subsidence after the late Pliocene-early Pleistocene was possibly dominated by the increased rapid roll-back of the Calabrian slab (Rosenbaum and Lister, 2004; Buttinelli et al., 2014) when the whole Tuscan Shelf reacted as a unique block, the basins coalesced, and from this moment the extensional regime that dominates until the present day was established.

This scenario seems to be substantially different from those modeled by diffuse extension on the continental-wide rifting crust (e.g., basin and range, Rosenbaum et al., 2008 and references therein), aiming at different crustal dynamics with very localized basins' formation that, at least in its initial.

stages can hardly be related to the crustal rifting processes as invoked for the northern Tyrrhenian Sea.

6. Conclusions

We focused on reanalyzing a large set of publicly available enhanced vectorized versions of offshore seismic profiles in the northern Tyrrhenian Sea to better point out the tectonic evolution of the Tuscan Shelf, which is an excellent example of structural inheritance. Despite the current flat morphology of the seafloor masking the underlying structural setting, several sedimentary basins developed on an acoustic basement deformed by compressional phases. We focused on the Punta Ala, Giglio, and Le Formiche basins, whose evolution and internal geometries were structurally controlled by thrusting and folding, at least in the initial phases. Basins formed on the hanging wall of large regional thrusts with flat and ramp geometry, which can be generally observed below the basins, and evolved in a symmetric or asymmetric style depending on their position with respect to the back limbs and forelimbs of inherited thrust-related antiforms.

There is strong evidence that the Tuscan Shelf developed essentially as an orogenic wedge without a significant topographic expression up to the Upper Pliocene, featured by a few N-S trending islands' alignments. The early stage of basin growth in those areas could correspond to the generation of piggyback/thrust-top basins since their positioning in a high morphological context is not directly controlled by any faults. This scenario perfectly aligns with the interpretation of a thrust-top basin in the Montecristo Basin area. Thus, significant Burdigalian-Langhian regional thrusts have raised the Elba Pianosa ridge and Montecristo basin to the Elba island's Southeast areas. The activity of the other thrust found in the area can be indirectly dated before the Messinian. The narrow basins of Punta Ala, Giglio, and Le Formiche are mostly N-S to NNE-SSW oriented, extending even for 50 km, and have a small thickness of deposits corresponding to meager sedimentation rates if compared to their relatively long period of evolution (from early-middle Miocene to early Pleistocene). The deformation was set up probably in the Lower-Middle Miocene in the southernmost sectors of the Tuscan Shelf while propagating toward the northeast and persisted until the late Pliocene. Notably, over the analyzed seismic dataset, there are no hints of shallow low-angle East-dipping normal faults controlling the evolution of the entire shelf. Since the late Pliocene-early Pleistocene, the whole Tuscan Shelf has undergone generalized subsidence associated with the deactivation of the main faults within the basins. The Calabrian slab's roll-back dynamics and the Tyrrhenian Sea's development might dominate such a new phase. In the proposed evolutionary model, the western-northern sector of the transect across the Tuscan Shelf shows a later basin inception (Late Messinian) than the eastern one (lower-middle Miocene). This setting can be interpreted as if the northern and western portion of the Tuscan Shelf crust (Elba-Pianosa ridge and Elba Island to the east) was structurally more raised (and emerged) up to the late Miocene by a more effective thrust activity. Moreover, we cannot exclude an out-of-sequence thrusting stage in the late Miocene-early Pliocene, thus leading to a late Messinian basin formation. The mechanism behind the development of the Tuscan Shelf basins finally resembles that of the intermontane basins of the central Apennines, which developed with a high level of control by pre-existing and inherited structures. Considering the results of this work, the classic framing of the Tuscan Shelf basins' evolution in a context of continental rifting should be deeply re-evaluated.

CRediT authorship contribution statement

M. Buttinelli: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **F. Mazzarini:** Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Formal analysis, Conceptualization. **G. Musumeci:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **R. Maffucci:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **F. E. Maesano:** Writing – review & editing, Validation, Formal analysis, Conceptualization. **I. Cavirani:** Investigation, Data curation, Conceptualization. **P. Diviacco:** Data curation.

Declaration of competing interest

Corresponding author, on behalf of all the authors of the submission, disclose any financial and personal relationships with other people or organizations that could inappropriately influence or bias their work. All the authors declare no financial or scientific conflicts of interest concerning the paper's results.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mauro Buttinelli reports was provided by National Institute of Geophysics and Volcanology.

Data availability

All the data and codes used in this work are publicly available and freely accessible. All the links to get those are reported within the manuscript. Batymetric data can be downloaded from the European Marine Observation and Data Network (EMODnet) website (https://emodnet.ec.europa.eu/en). The entire dataset of seismic profiles used in this work is publicly available: uninterpreted and interpreted versions of vectorized seismic data is provided directly within the contribution in high resolution formats. Original raster data can be downloaded from ViDEPI project (Visibility of petroleum exploration data in Italy) website (https://www.videpi.com/videpi/videpi.asp). Direct link to seismic profiles shown in the figures are provided as follows: CROP M12A (Fig. 4) seismic data is available within the Tognarelli et al., 2011 data, while the original raster is available at this URL: https://www.videpi.com/deposito/videpi/crop/F_15_M12A.pdf Line E-120 W (Fig. 3): https://www.videpi.com/videpi/sismica/dettaglio.asp?codice=E-120WLine E-120E (Figure SM1A):https://www.videpi.com/videpi/sismica/dettaglio.asp?codice=E-120ELine E-122 (Fig. 5):https://www.videpi.com/videpi/sismica/dettaglio.asp?codice=E-122Line E-126 (Fig. 6):https://www.videpi.com/videpi/sismica/dettaglio.asp?codice=E-126Line E-124 (Fig. 7):https://www.videpi.com/videpi/sismica/dettaglio.asp?codice=E-124Line E-128 (Figure SM1B):https://www.videpi.com/videpi/sismica/dettaglio.asp?codice=E-128Line E-130 (Figure SM1C): https://www.videpi.com/videpi/sismica/dettaglio.asp?codice=E-130 Mimosa-1 and Martina-1 well stratigraphy available on the ViDEPI dataset: (https://www.videpi.com/videpi/pozzi/dettaglio.asp?cod=3689, https://www.videpi.com/videpi/pozzi/dettaglio.asp?cod=3524, The vectorization code used to manipulate the original raster seismic data is publicly available following the requests reported in Sopher, 2018.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tecto.2024.230211.

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