Key Points:

- The Ponza-Alife accommodation zone segmenting the Apenninic margin of the Tyrrhenian back-arc basin is introduced
- Structural and stratigraphic data, and seismic interpretation allowed us to unravel the evolution of this accommodation zone
- The accommodation zone originated from tearing in the downgoing plate reworking Jurassic faults that segmented the associated rift system

Segmentation of the Apenninic Margin of the Tyrrhenian Back-Arc Basin Forced by the Subduction of an Inherited Transform System

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Abstract The Tyrrhenian back-arc basin developed at the rear of the E-ward migrating Apennine fold-and-thrust belt, with northward decreasing rollback of the subducting Adria slab leading to northward fading of back-arc extension. The northern portion of the Tyrrhenian basin is made of thinned continental crust, whereas in the central/southern portion extension eventually evolved to oceanic crust production. In this framework, a long-lasting debate concerns the existence of a >200 km long transform zone along the 41st parallel, which should separate the two portions of the Tyrrhenian basin. At its eastern termination, a branch of the presumed transform zone enters the Tyrrhenian margin of the Apennine belt and occurs as an accommodation zone made of a ribbon of extensional faults and related basins. This accommodation zone, which separates areas of mutually perpendicular extension directions, is here introduced, described, and named the Ponza-Alife accommodation zone. Interpretation of seismic lines and new structural and stratigraphic data from this accommodation zone have been used to constrain the pre-orogenic and syn-orogenic architecture of the subducting plate and the Plio-Quaternary back-arc extensional stage. Our data indicate that the studied zone retraces a deep-seated transform fault system located in the subducting plate and inherited from an Early Jurassic rifting episode, which caused the lateral juxtaposition of different rift domains in the subducting plate. We propose that during collision and trench retreat, this lateral juxtaposition has controlled differential retreat of the subducting plate across the studied zone, forcing the development of the Ponza-Alife accommodation zone in the overlying back-arc basin's margin.

1. Introduction

In tectonics, the term "inheritance" includes previous structural, stratigraphic, and igneous features that are rheologically different from the surrounding rocks and/or that steer the lateral juxtaposition of different rheological domains. Inherited structures are ubiquitous in the continental lithosphere and under the effect of a given tectonic regime they can promote the development of structures differing from those that would develop in an ideal layer cake-like/cylindrical geological framework. The notion of inheritance has its roots in the Wilson's cycle, specifically in the concept of reuse of lithospheric-scale structures formed during previous rifting or collisional events (e.g., Dewey & Bird, 1970; Wilson, 1966). Since the 1980s, the systematic documentation of faults reactivated with an opposite sense of slip has shaped the idea of structural inheritance (e.g., Butler et al., 2006 and references therein), embraced by the concept of inversion tectonics (e.g., Cohen, 1982; Cooper et al., 1989; Glennie & Bogner, 1981). Positive and negative inversion tectonics, corresponding to extensional fault systems reactivated with a reverse sense of slip (e.g., Butler & Mazzoli, 2006; Granado et al., 2016; Marshak et al., 2000; Nemčok, 1995; Williams et al., 1989; Zanchi et al., 2006) and thrusts reused as normal faults (e.g., Bigi, 2006; Curzi, Aldega, et al., 2020; D'Agostino et al., 1998; Gamond, 1994; Lucca et al., 2019), respectively, are nowadays widely documented worldwide at different scales, both in fold-and-thrust belts and in extensional basins. When inherited structures are highly oblique to the shortening/stretching direction, their most striking effect is the production of a marked lateral variation in the structural style. As an example, the occurrence of salients and recesses in orogenic systems,

associated with either lateral ramps or tear fault systems, may retrace either the lateral segmentation of previous rift systems (e.g., Jammes et al., 2014; Jimenez, et al., 2013; Lacombe et al., 2003; Macedo & Marshak, 1999; Tavani et al., 2020) or the lateral pinch-out of ductile décollement levels (e.g., McQuarrie, 2004; Muñoz et al., 2013). The same concept applies to rift systems, in which the along-strike segmentation can be controlled by oblique inherited structures (e.g., Bellahsen et al., 2013; Corti et al., 2007; Festa et al., 2020; Heron et al., 2019; Konstantinovskaya et al., 2007; Mercier de Lépinay et al., 2016; Tavani et al., 2018; Zhao et al., 2020). In detail, the segmentation of rift systems can be achieved by transfer and/or accommodation zones oriented at high angle with respect to the basin bounding faults (e.g., Acocella et al., 2005; Colletta et al., 1988; Corti et al., 2007; Faulds & Varga, 1998; Gawthorpe & Hurst, 1993; McClay et al., 2002; Morley et al., 1990; Vignaroli et al., 2015), both types being sensitive to the occurrence of previous structural discontinuities.

Here, we apply the concept of structural inheritances to the large-scale interpretation of the lateral segmentation of the eastern margin of the Tyrrhenian back-arc basin (western Mediterranean Sea; Figure 1a). This basin is divided into a northern sub-basin, characterized by thinned continental crust (e.g., Jolivet et al., 1998), and a central/southern sub-basin, floored by thinned continental crust, exhumed mantle (e.g., Jolivet et al., 2021; Prada et al., 2014), and late Miocene to recent oceanic crust (e.g., Kastens & Mascle, 1990; Savelli & Ligi, 2017) (Figure 1b). Many authors propose a gradual transition between the two sub-basins, with the oceanic and exhumed mantle domains of the southern basin fading out northward into thinned continental crust (e.g., Jolivet et al., 2021). Others suggest, instead, a localized transition along a major E-W transform zone placed along the 41st parallel (Spadini & Wezel, 1994) (Figure 1b), whose development is inferred to be the consequence of a lithospheric tear fault within the subducting slab, which would retrace the ocean-to-continent transition established during Mesozoic rifting (Rosenbaum & Lister, 2004). Eastward, the supposed 41st parallel transform branches into a NW-SE striking offshore left-lateral fault system (Conti et al., 2017) and a north-eastern segment that runs ENE-WSW for more than 100 km, from the Ponza Ridge to the Formia Plain and farther west to the Alife Basin (Figures 1c and 1d). This is the Ponza-Alife accommodation zone, which is emphasized by a remarkable topographic step (see the swath profile in Figure 1c) and divides two crustal domains with extension directions at right angle, that is, NE-SW and NW-SE, respectively (Figure 1c), indicating a complex strain pattern not resolvable with a simple tearing process. From interpretation of publicly available offshore seismic lines and structural and stratigraphic data collected in the Formia Plain area, we reconstruct the kinematic evolution of this oblique accommodation zone and set constraints on both the pre-orogenic and the syn-orogenic architecture of the area, to test the reliability of models invoking the reuse of Mesozoic inherited structures.

2. Geological Framework

The Apennines form the Neogene to present counter-clockwise rotating northern limb of an orocline, cored by the Tyrrhenian back-arc Basin (Figure 1a), and developed by the differential E-ward retreat of the subduction zone along which the Alpine Tethys and part of its southern passive margin (i.e., Adria) have been subducted underneath Europe (Figures 1a and 1b) (e.g., Boccaletti et al., 1990; Carminati et al., 2010; Dewey et al., 1989; Doglioni, 1991; Faccenna et al., 2014; Malinverno & Ryan, 1986; Mazzoli & Helman, 1994). Folding and thrusting in the Apennines affected the sedimentary successions belonging to different Mesozoic rift domains established on Adria during Late Triassic to Early Jurassic rifting (e.g., Bosellini, 2004; Santantonio & Carminati, 2011). Slivers of ophiolites and deep-water sediments deposited in the Alpine Tethys ocean, named Liguride complex, sit at the topmost portion of the tectonic pile in the northern and southern Apennine arcs (Figure 1b) (e.g., Knott, 1987; Marroni et al., 1998; Ogniben, 1969). These two arcs are characterized by slightly different syn-orocline vertical axis rotations (e.g., Cifelli & Mattei, 2010; Cifelli et al., 2016) (Figure 1b) and joined in the central Apennines, the study area of this work, which is characterized by the remarkable absence of ophiolites and, according to many (e.g., Centamore et al., 2007), of the Liguride complex in general.

The Tyrrhenian side of the central Apennines is characterized by NW-SE elongated ridges of shallow-water carbonates (Figures 1c and 1d), divided by fault-bounded valleys where syn-orogenic to post-orogenic materials are exposed. In the SW coastal part of the belt and in the offshore, a set of Plio-Quaternary volcanic edifices also occurs. Two major physiographic discontinuities occur in this area (Figure 1c): to the west the
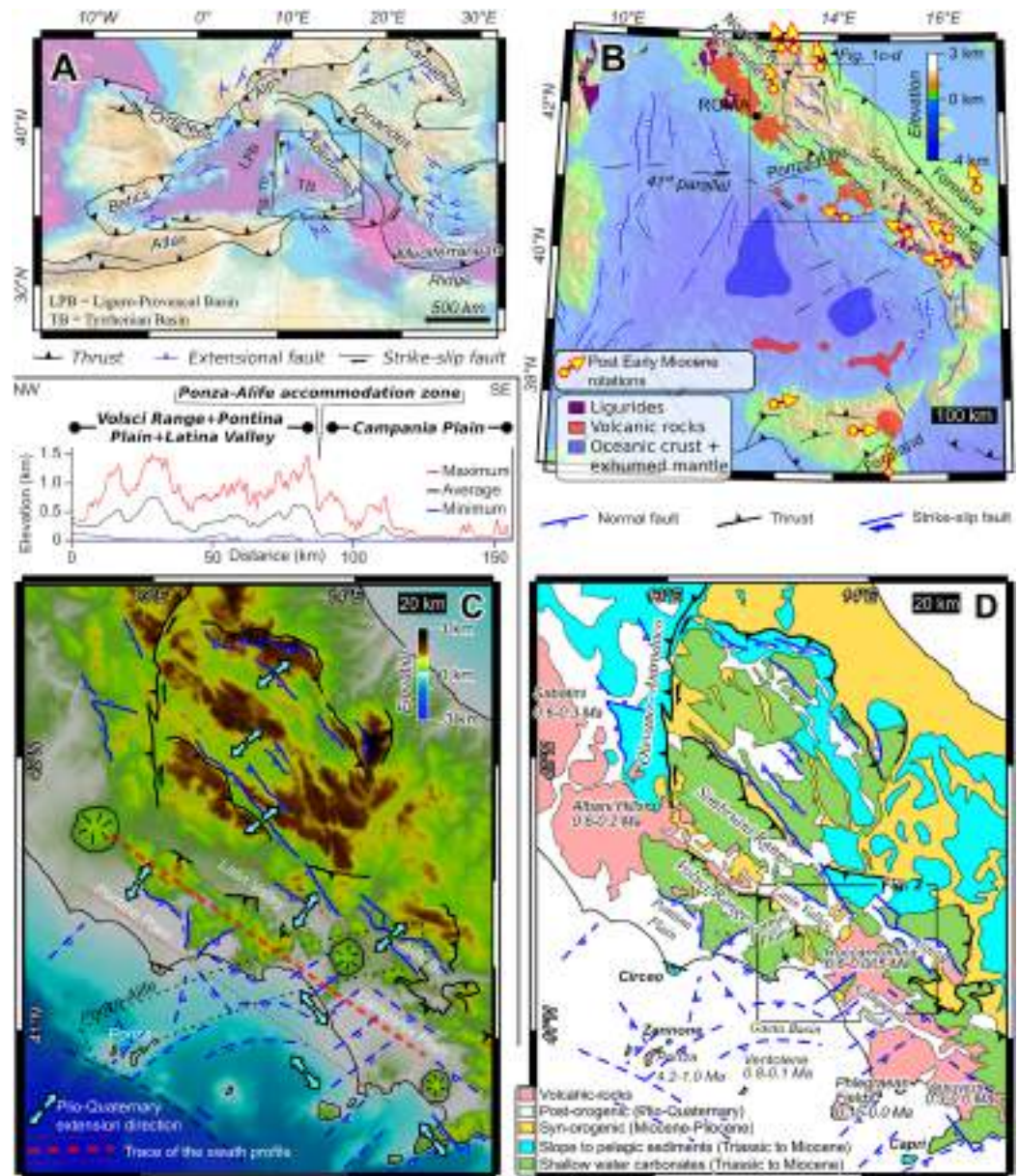
Figure 1. Structural schemes of: (a) the western Mediterranean area and (b) Tyrrhenian Basin. Vertical axis rotations are from Cifelli and Mattei (2010) and refer to fixed Africa. (c) Simplified geological map of the central Apennines (offshore faults modified from Acocella & Funiciello, 2006; Casciello et al., 2006; Conti et al., 2017; Cuffaro et al., 2016; Martorelli et al., 2016; Milia et al., 2013). Ages of volcanic rocks are from Acocella and Funiciello (2006) and Conti et al. (2017) and references therein. (d) Along-strike swat profiles with maximum, minimum, and average elevation along the trace shown in panel c (25 km wide window).

N-S striking Olevano-Antrodoco Fault, which defines the limit between the northern and central Apennines; to the south-east the WSW-ENE elongated Ponza-Alife accommodation zone. Across the Ponza-Alife zone, the mountain front is shifted in a left-lateral sense, and the Campania Plain is laterally juxtaposed to the Volsci Range.

In the following subsections, we outline the geological history for this part of the Italian peninsula, from Early Jurassic to the present day.

2.1. Early Jurassic Rifting

This rifting stage was associated with the breakup of Pangea and, in the central Mediterranean area, it evolved into the continental separation between Africa-Adria and Europe (e.g., Channell et al., 1979), with the Alpine Tethys oceanic basin developed in between these two plates (e.g., Marroni & Pandolfi, 2007; Mohn et al., 2012). In the central Apennines, the Early Jurassic rifting caused the dismembering of a former Triassic-Early Jurassic intracratonic carbonate platform into horst and graben structures. Early Jurassic palaeobathimetry was maintained during the thermal subsidence stage following rifting, and persistent carbonate platforms and pelagic basins developed during the Middle Jurassic to Cretaceous post-rift period (Bosellini, 2004; Cardello & Doglioni, 2015; Cosentino et al., 2010; D'Argenio et al., 1975; Ogniben, 1969; Patacca & Scandone, 2007; Santantonio & Carminati, 2011). At the regional scale, and despite thrusting and folding, the boundaries between the carbonate platform and pelagic basin domains can be still recognized, being oriented both N-S and E-W (Figure 1d), in accordance with the N-S and E-W orientation of syn-rift Jurassic extensional faults exposed in the area (e.g., Calabrò et al., 2003; Cardello & Doglioni, 2015; Castellarin et al., 1978; Fabbi, 2015; Pierantoni et al., 2013; Storti et al., 2018). Despite their obliquity with respect to the NE-SW oriented shortening, many of these Jurassic faults have also been reactivated during the Neogene compressional regime. The most relevant of these reactivated faults is the right-lateral transpressive Olevano-Antrodoco Fault (e.g., Castellarin et al., 1978; Tavani & Cifelli, 2010) (Figure 1d).

2.2. Neogene Convergence

In the framework of Europe-Africa convergence, Neogene NE-SW oriented shortening led to the development of the Apennine fold-and-thrust belt. In the central Apennines, the innermost exposure of the thrust system occurs in the Zannone Island (Figure 1d), where siliciclastic foredeep sediments of likely the Oligocene-early Miocene age have been overthrust by Triassic-Eocene carbonates during the early Miocene (Curzi, Billi, et al., 2020). Toward the NE, the foredeep basins become progressively younger, and the syn-orogenic sediments in the footwall of the Volsci Range thrust are Burdigalian (Sabbatino et al., 2021) to Messinian in age (e.g., Centamore et al., 2007; Cosentino et al., 2002). Thrusting in the Volsci Range started during the Tortonian (Cavinato & Celles, 1999; Cardello et al., 2021; Cipollari & Cosentino, 1995). The Messinian age of a mélange in the footwall of the SE termination of the Volsci Range (Figure 2) (Accordi et al., 1967) and the lateral continuity with the Massico Mt. toward the south-east, where out-of-sequence thrusting at 5.1 ± 3.7 Ma (U-Pb dating) is documented (Smeraglia et al., 2019), suggest that thrusting of the Volsci Range could have lasted up until earliest Pliocene time (Cardello et al., 2021).

2.3. Miocene to Quaternary Back Arc Extension

E-ward retreat and coeval arching of the Apennine subduction zone are commonly invoked to explain the occurrence of extensional deformation and volcanism at the rear of the eastward propagating compressive front (e.g., Cavinato & Celles, 1999; Doglioni, 1991; Faccenna et al., 2004; Jolivet et al., 2009; Patacca et al., 1990; Royden et al., 1987), with tomographic investigations having enlightened a possibly segmented geometry of the subducting slab (e.g., Chiarabba et al., 2008; Rosenbaun & Piana Agostinetti, 2015). On the upper plate, since the Miocene, crustal stretching led to the opening of the triangularly shaped Tyrrhenian back-arc basin (e.g., Jolivet et al., 1998; Mattei et al., 2002; Sartori et al., 2001, Figures 1a and 1b). The central portion of the basin is floored by exhumed mantle and Messinian to Pleistocene oceanic crust (e.g., Jolivet et al., 2021; Kastens & Mascle, 1990; Mascle & Rehault, 1990; Sartori et al., 2004; Savelli & Ligi, 2017; Scrocca et al., 2012), whereas the eastern margin of the basin, that is, the Apenninic margin, is mostly affected by <1 Ma to present potassic volcanism developed during extension (e.g., Acocella & Funiciello, 2006; Carminati et al., 2010; Conti et al., 2017; Serri et al., 1993) (Figure 1d). In the eastern Tyrrhenian margin, active extensional tectonics migrated E-NE-ward (e.g., Bartole, 1995; Cavinato & Celles, 1999) from late Miocene-Pliocene offshore and onshore basins developing on thinned continental crust to the west (e.g., Bellotti, et al., 1997; Bruno et al., 2000; Casciello et al., 2006; Cipollari et al., 1999; Conti et al., 2017; Cosentino et al., 2006; Curzi, Billi, et al., 2020; Milia & Torrente, 2015; Milia et al., 2009) to actively extending intramontane basins located in the axial zone of the belt (e.g., Cavinato & Celles, 1999; Cosentino et al., 2017; Galadini & Messina, 2004; Valente et al., 2019), where NE-SW oriented extension has produced earthquakes
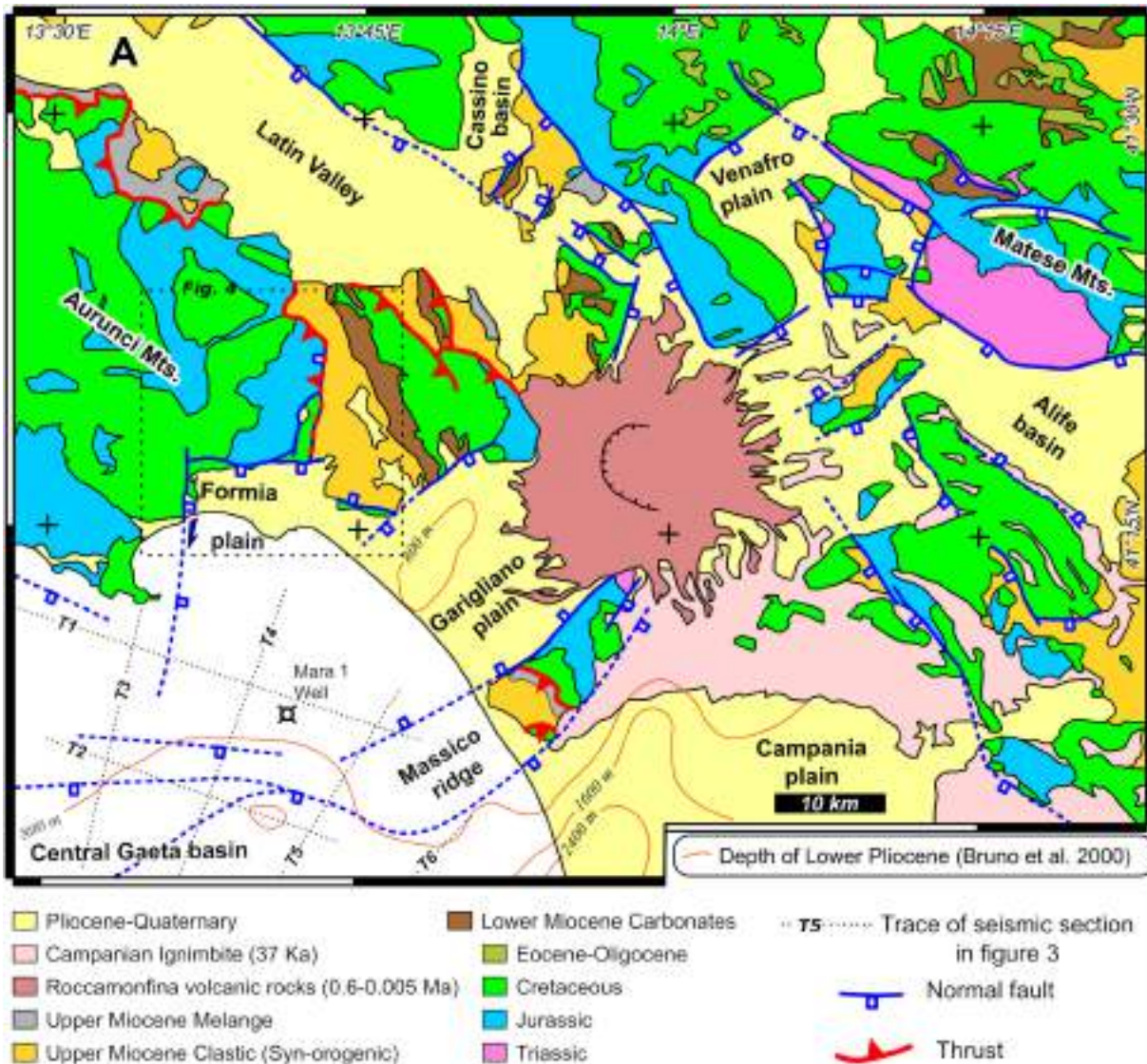
Figure 2. Simplified geological map of the area across the Latium and Campania regions.

with Mw > 6 in recent years (e.g., Bernard & Zollo, 1989; Boncio & Lavecchia, 2000; Chiarabba et al., 2009; Cello et al., 1997; Galadini & Galli, 2000; Montone et al., 1999).

2.4. The Ponza-Alife Plio-Quaternary Accommodation Zone

A major ENE-WSW trending accommodation zone of the Plio-Quaternary extensional system occurs in the area across the border between Latium and Campania regions in central Italy. It broadly extends from the offshore Ponza ridge (to the west) to the Alife Basin (to the east), passing through the Formia Plain (Figures 1c, 1d and 2).

This accommodation zone divides an area to the NW, where regional extensional faults are mostly NW-SE striking and accommodate the margin-perpendicular, NE-SW oriented, extension (e.g., Roberts et al., 2002), from an area to the south, where the Campania and Garigliano plains, and the Massico and Ponza ridges are formed due to the along-margin, NW-SE oriented, extension (e.g., Billi et al., 1997; Casciello et al., 2006) (Figures 1c, 1d and 2). The Alife and Venafro Plain basins developed since the late Early Pleistocene - early Middle Pleistocene in the hanging wall of nearly NW-SE-striking fault systems (Amato et al., 2017; Valente

et al., 2019) (Figure 2). These basins are bounded also by transverse (NE-SW-striking) and oblique oriented (both E-W and N-S-striking) strands. Toward the west, the Alife Basin boundary fault has Triassic carbonates in the footwall and Miocene clastics in the hanging wall and, farther west, it splits into two segments: the northern one that strikes NNE-SSW and the western one that strikes about E-W and westward joins with transverse (NE-SW-striking) extensional faults. Both the Venafro Plain and the Alife Basin are bounded to the SW by NW-SE-elongated ridges of Jurassic to Cretaceous carbonates. The two ridges are separated by transverse horst and graben structures, partly linking with the Alife Basin boundary fault. These structures regionally form a recess of the NE-SW striking extensional fault system that has in its hanging wall the Latin Valley and the Campania Plain basins, where instrumental seismicity is almost absent. The latter basin developed since the Early Pleistocene (Cinque et al., 2000; Santangelo et al., 2017; Sartori et al., 2001), and despite the general NW-SE and NE-SW trend of main faults, it also includes Quaternary E-W striking extensional faults (e.g., Cerrone et al., 2021). The onset of extension in the Latin Valley basin is dated to the late Pliocene (Galadini & Messina, 2004). The Cassino Basin is also part of this system and formed within a relay zone between two NW-SE-striking faults (the northeastern one showing evidence of Quaternary activity; Galadini et al., 2001). To the SW of the Latin Valley, the Aurunci Mts. represent the southernmost portion of the Volsci Range (Cardello et al., 2020; Centamore et al., 2007; Cosentino et al., 2002). The Aurunci Mts. are bounded to the SE by a set of N-S and E-W, and NE-SW striking extensional faults, defining a S- to SE-dipping system that has in its hanging wall a basin formed by the Formia and Garigliano plains (Figure 2) (e.g., Billi et al., 1997; Iannace et al., 2013; Milia et al., 2013). This basin is divided from the Quaternary Campania Plain to the SE by the Massico Ridge, a NE-SW-trending horst exposing Mesozoic carbonates overlain by a Miocene tectonic mélange (Smeraglia et al., 2019).

Notably, the Ponza-Alife accommodation zone intersects two volcanic districts. To the west, the western Pontine Islands emplaced between 4.2 and 1 Ma along a horst-and-graben structure within the segmented margin between Latium and Campania (e.g., Cadoux et al., 2005; Carminati et al., 2010; Conti et al., 2017). To the east, the Roccamonfina volcano developed along host-and-graben structures of the Garigliano plain (e.g., De Rita & Giordano, 1996) and its activity is dated at the Middle-Late Pleistocene (0.7–0.05 Ma) (Di Brozolo et al., 1988; Rouchon et al., 2008). Both districts have a subcrustal magma source (e.g., Conticelli & Peccerillo, 1992), pointing to the deep roots of the accommodation zone.

3. Methods and Materials

To unravel the structural architecture of the Formia Plain and to establish its relationships with the supposed 41st parallel zone, we applied a multidisciplinary and multiscale approach that integrates: (a) interpretation of available seismic lines, (b) geological mapping, and (c) structural analysis.

Publicly available seismic lines in the offshore area between the Formia Plain and the Gaeta Basin have been interpreted (Figure 3). These lines have been acquired in the 1980s by the Western Geophysical Co. for Agip (now ENI) company and are available via the Videpi project (see data availability). The top Messinian - base Pliocene boundary is well recognizable in all these vintage lines as a boundary dividing the overlying Plio-Quaternary laterally continuous reflectors from the underlying Mesozoic to Messinian package, where no clear and laterally coherent reflectors can be easily individuated (e.g., Bruno et al., 2000; Conti et al., 2017; Milia & Torrente, 2015; Milia et al., 2013). Picking of the top Messinian-base Pliocene reflector allows to identify major faults, many of which are exposed onshore.

Geological fieldwork was aimed at providing new constraints on the stratigraphic and structural setting of the Formia Plain area in a new geological map and stratigraphic scheme (Figure 4). In detail, our stratigraphic investigation has focused on the Messinian to Pliocene succession, whereas information about the underlying stratigraphic sequence has been retrieved entirely from published works (e.g., Chiocchini & Mancinelli, 1977). A new informal lithostratigraphic unit, the Villa Treglia conglomerate (underlying the Messinian salt-bearing shales and sandstones), has been here introduced and the relationship with the overlying formations is illustrated. We have also supplied new data on the nature of the blocks made of pelagic sediments cropping out in the study area. The geological map presented in Figure 4 is largely based on the geological map from Bergomi et al. (1969). Our original work has consisted in improving existing maps for the areas surrounding the Campodivivo, Fammera, and Formia faults (Figures 6–8). The
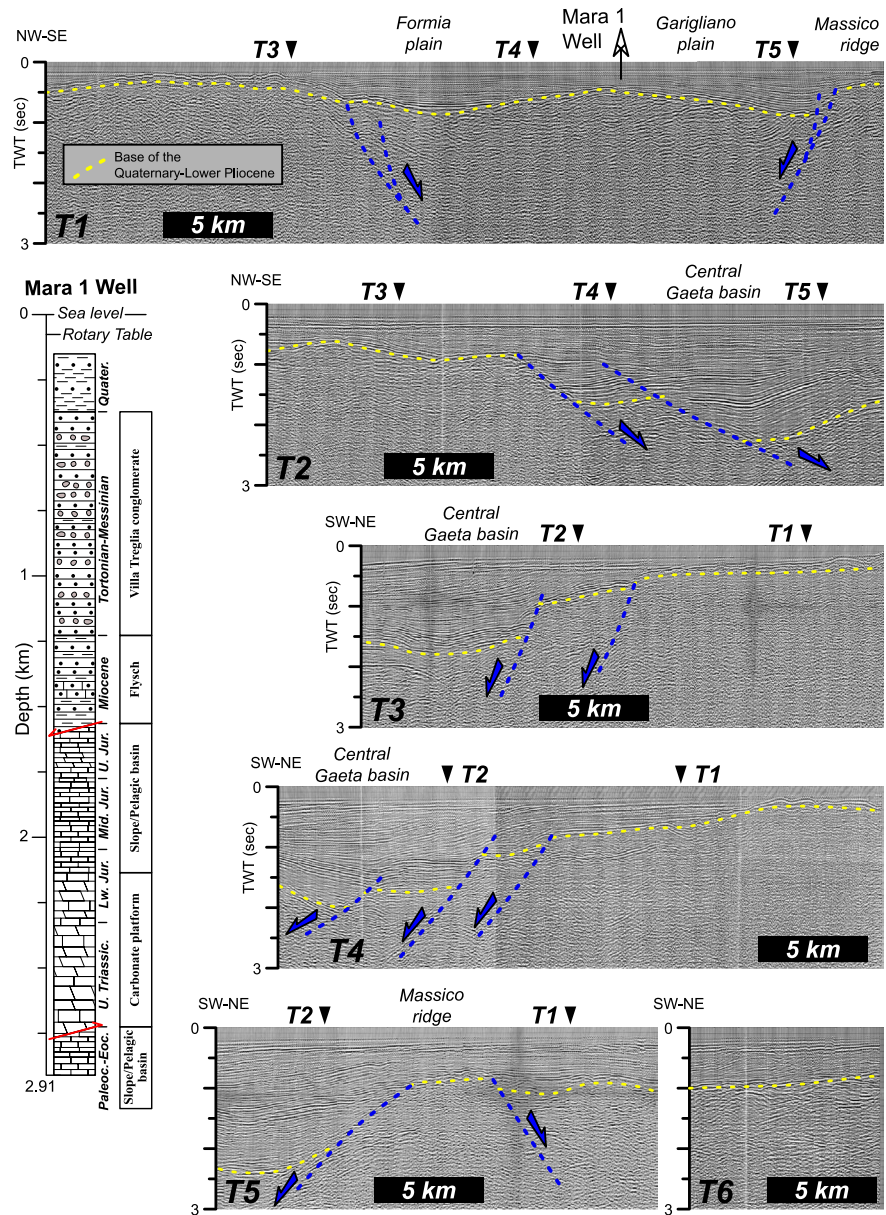
Figure 3. Interpreted seismic profiles (traces of the profiles are in Figure 2) and stratigraphy of the Mara 1 well.

geological-structural investigations have been carried out along the trace of these fault systems, to constrain their structural architecture in terms of spatial distribution, geometry, and kinematics. The areas including the three main fault systems have been surveyed, using the classical field mapping and meso-structural analysis, to investigate the geometry of the fault systems and of fault-bounded blocks, to produce the original maps and cross sections of Figures 6–8. Results of the above-mentioned field work are illustrated below.

4. Results

4.1. Offshore Seismic Interpretation

At its SE termination, the seismic line T1 (Figure 3) crosses the north-western boundary fault of the Massico Ridge (sections' trace is in Figure 2), whereas to the NW it crosses the S-ward prolongation of the N-S Formia Fault (Figure 3). Seismic section T2 crosses two major extensional faults having a throw of ∼1 s. The seismic sections T3 and T4, oriented at a right angle with respect to the seismic section T2, display
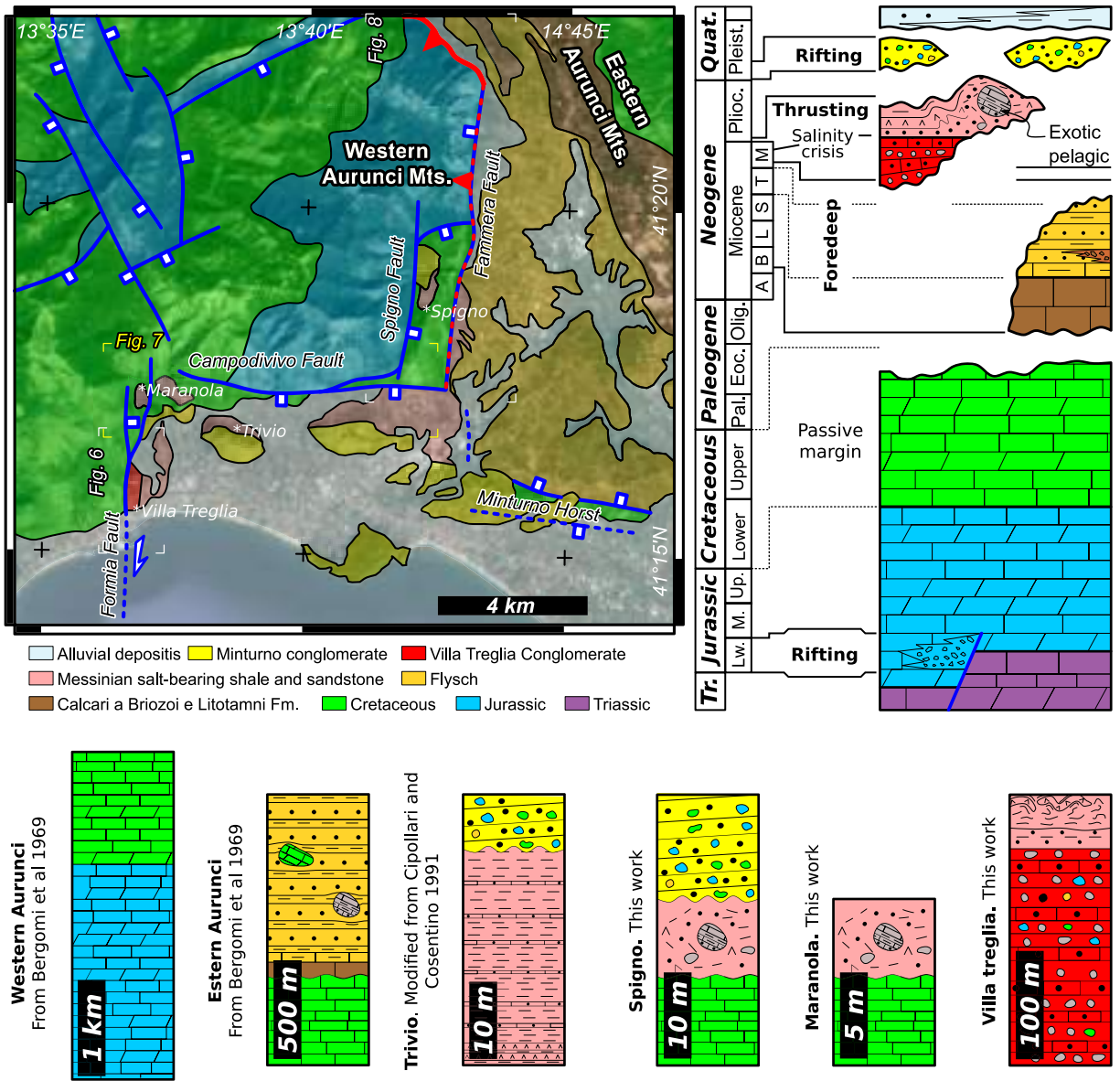
Figure 4. Geological map and stratigraphic scheme of the Formia Plain and surrounding areas, with stratigraphic columns used to build the stratigraphic scheme. Location of the Spigno section: Latitude 41.315434°; Longitude 13.705400°. Location of the Maranola section: Latitude 41.290791°; Longitude 13.610728°. Base of the Villa Treglia section: Latitude 41.262900°; Longitude 13.612869°.

extensional faults having a throw of 0.5 to 1 second, which we correlate with the two faults imaged in the section T2 (Figure 3) (correlation of faults in the different profiles is driven by the assumption that faults with a throw >0.5 s in a given profile must occur in the neighboring, <10 km distant, seismic profiles). Additionally, an incipient fault, having a throw of ∼0.1–0.2 s, is crossed by sections T3 and T4, whereas it cannot be recognised in section T5. The latter seismic line crosses two faults: the southern fault has a throw >1 s and westward splits in the two major faults seen in the seismic section T2; the northern fault is the north-western boundary fault of the Massico Ridge. The seismic section T6 does not intersect any relevant fault, meaning that the south-eastern boundary fault of the Massico Ridge and the major S-dipping faults seen on seismic section T5 join. In summary, off the Formia Plain we can trace the Formia Fault and both the NE-SW-striking faults bounding the Massico Ridge. This latter system links westward with a set of E-W-striking faults, whose cumulative displacement exceeds 1 s (Figure 3).

Further constraints on the offshore portion of the area are provided by the Mara 1 deep well (Figure 3; https://www.videpi.com/videpi/pozzi/dettaglio.asp?cod=3488). The Mara 1 well encountered 200 m of Quaternary sediments overlying a ~900 m-thick unit made of shales, sandstones, and polygenic conglomerates of uncertain age, which we correlate with the Tortonian-Messinian Villa Treglia conglomerate exposed in the Formia Plain and discussed in the next subsection. The clasts of the conglomerates contain planktic and benthic foraminifera, sponge spicules, radiolarians, aptychi, ammonites, nummulitids, rudists, suggesting that their source is to be sought in Mesozoic and Cenozoic successions both of deep and shallow water. This unit overlies 300 m of Miocene flysch, which is underlain by 1,200 m of Triassic to Jurassic carbonates. The top of Jurassic carbonates is brecciated. This and the missing section at the top of Jurassic carbonates suggest that the contact between Mesozoic and Miocene rocks is by faulting with extensional kinematics. The Mesozoic section consists of about 600 m of Middle to Upper Jurassic limestones and dolomitic limestones dominated by pelagic fauna (aptychi, sponge spicules, crinoids, radiolarians, Saccocoma, and thin-shelled bivalves). This unit is underlain by about 600 m of Upper Triassic to Lower Jurassic shallow-water dolostones and dolomitic limestones with bivalves, ostracods, gastropods, dasycladalean calcareous algae, and rare benthic foraminifers. Triassic shallow-water carbonates are soled by a thrust fault having in its footwall <200 m of Paleocene-Eocene brownish to whitish mudstones and wackestones, with a fossil association containing shallow-water benthics (miliolids, Nummulites sp., Alveolina sp., Discocyclina sp., Amphistegina sp., coralline red algae) along with planktic foraminifers, sponge spicules, and radiolarians. This association is suggestive of either middle to outer ramp environment or of resedimentation of shallow-water microfossils into a relatively deeper water environment.

4.2. Stratigraphy of the Formia Plain

The stratigraphic scheme shown in Figure 4 results from the integration of published and newly presented stratigraphic sections. The lower part of the sedimentary succession exposed in the Aurunci Mts. includes a 3–4 km-thick sequence of Jurassic to Upper Cretaceous shallow-water limestones and dolostones, belonging to the so-called Latium-Abruzzi carbonate platform (Chiocchini & Mancinelli, 1977) (Figure 4), which represents the northern sector of the Apennine Carbonate Platform. These rest on top of Triassic limestones and dolostones, exposed in the Matese Mts. to the NE, in the Massico Ridge to the east (Figure 2), and found in the Mara 1 well to the south (Figure 3). In the eastern Aurunci Mts., the syn-orogenic sequence unconformably overlaying the above-described Mesozoic carbonates starts with the 100 m-thick Miocene ramp carbonates (Calcari a Briozoi e Litotamni Fm.), which in the central and southern Apennines mark the onset of flexural subsidence and the development of the Miocene foredeep basin (Sabbatino et al., 2021 and references therein). This formation is followed by a <100 m-thick sequence of Serravallian-Tortonian marls (lumped with the flysch in the map and stratigraphic column of Figure 4) and by >3 km of Tortonian flysch deposits. Conglomeratic levels occur at the base of the flysch sequence north of the Fammera Fault (Bergomi et al., 1969, Figure 3). Olistoliths of carbonates also occur within the flysch (Bergomi et al., 1969). To note that these olistoliths are made of both shallow-water carbonates, which are exposed in the surrounding mountain ranges, and pelagic carbonates, the source area of which is not exposed. In the southern portion of the eastern Aurunci Mts., in the Minturno Horst area (Figure 4), the above described Mesozoic to Miocene sedimentary succession is unconformably covered by the Minturno conglomerate (Bergomi et al., 1969; Catenacci & Molinari, 1965), dated to the Early Pleistocene (Cosentino et al., 2006). The Minturno conglomerate is made by cemented angular clasts of shallow-water carbonates. These shallow-water carbonates are exposed in the western Aurunci Mts. To the west of the Fammera fault (e.g., Trivio and Spigno stratigraphic section, Figure 4) the Minturno conglomerate unconformably overlies the Messinian Argille con gessi (shales with gypsum) Fm., which is made of poorly consolidated salt-bearing shales (Cipollari & Cosentino, 1991) and includes gypsarenites to m-sized gypsum blocks (Figure 5f). These shales pass downward to a poorly consolidated sandstone (Villa Treglia section, Figure 4). The salt-bearing shales and the underlying sandstone are here lumped together for mapping purposes, and named "Messinian salt-bearing shales and sandstones," as it is arduous to divide them in the field. This unit is preserved only in few exposures (for location see Cipollari & Cosentino, 1991), as it mostly crops out as a sedimentary mélange (resulting from its postdepositional disruption and remobilization) made of mud-supported conglomerate, which includes well-rounded clasts of exotic pelagic carbonates and sandstones, or as a mix of sandstone and clay with m-sized olistoliths of pelagic sedimentary rocks (Figures 5a and 5b). The blocks of
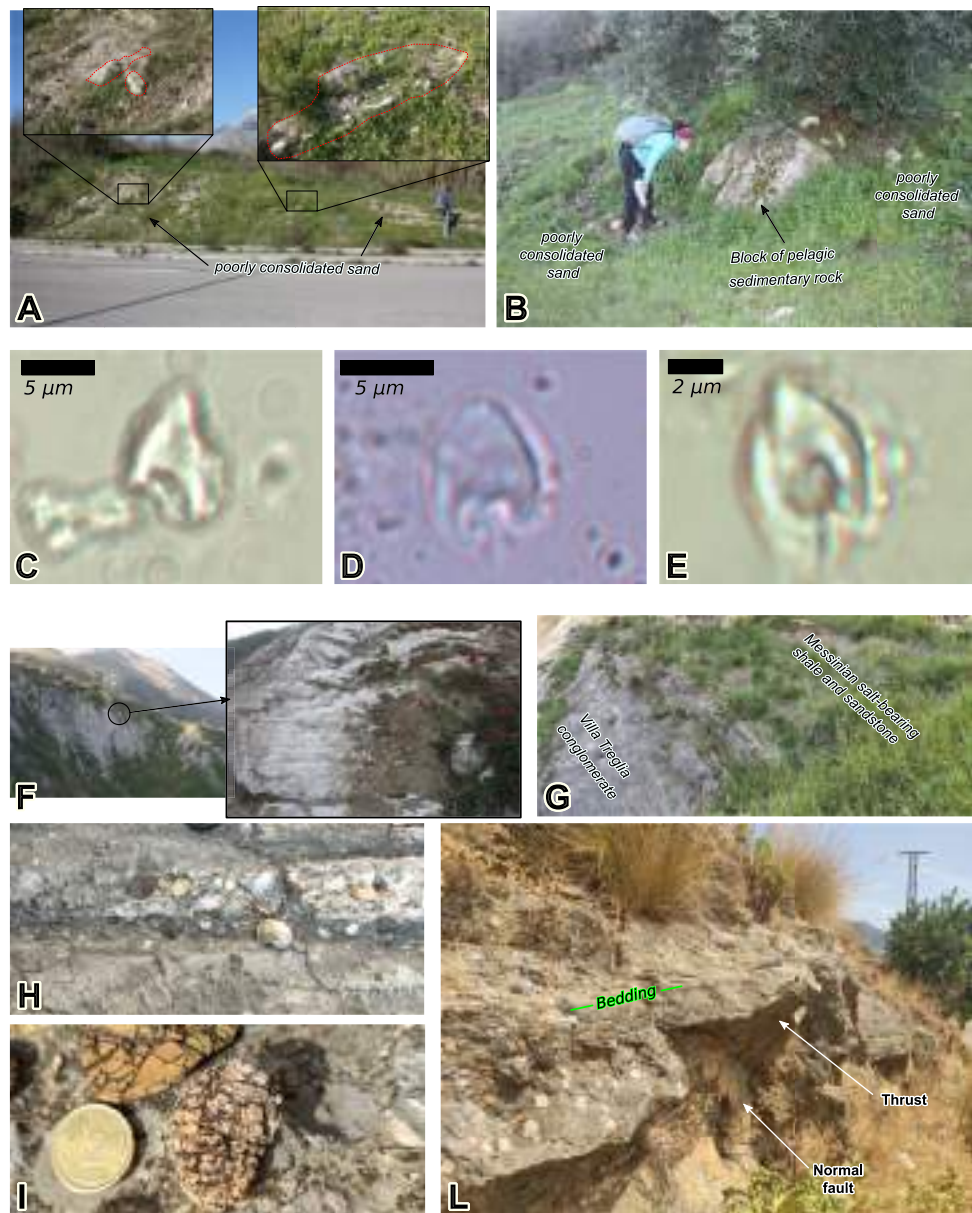
Figure 5. (a) Sedimentary mélange formed by poorly consolidated sand of the lower portion of the Messinian salt-bearing shales and sandstones, with insets showing m-sized blocks of pelagic limestones (Location 41.274694°N, 13.710114°E). (b) Block of pelagic limestone embedded within poorly consolidated sand of the lower portion of the Messinian salt-bearing shales and sandstones, Spigno section. Microphotographs showing calcareous nannofossils found in the Messinian salt-bearing shales and sandstones: (c) *Amaurolithus primus*, (d, e) cf. *Amaurolithus primus* (primitive morphotypes) (samples location in Figure 8a). (f) Panoramic photo and close up view of a Gypsum block at the topmost portion of slightly mixed and disrupted Messinian salt-bearing sandstones and shales in the Villa Treglia section (Location of the block 41.269094°N, 13.613944°E). (g) Conformable stratigraphic contact between the Messinian salt-bearing sandstones and shales and the underlying Villa Treglia Conglomerate in the Villa Treglia section (Location of the contact 41.267289°N, 13.612959°E). (h) Detail of the Villa Treglia Conglomerate showing a conglomerate level sandwiched between two calcarenite levels. (i) Detail of a pink granite clast within the Villa Treglia conglomerate. (l) Gently dipping strata of the Villa Treglia conglomerate affected by a brittle normal fault cutting and displacing a previous brittle thrust (Location of the contact 41.261963°N, 13.611167°E).
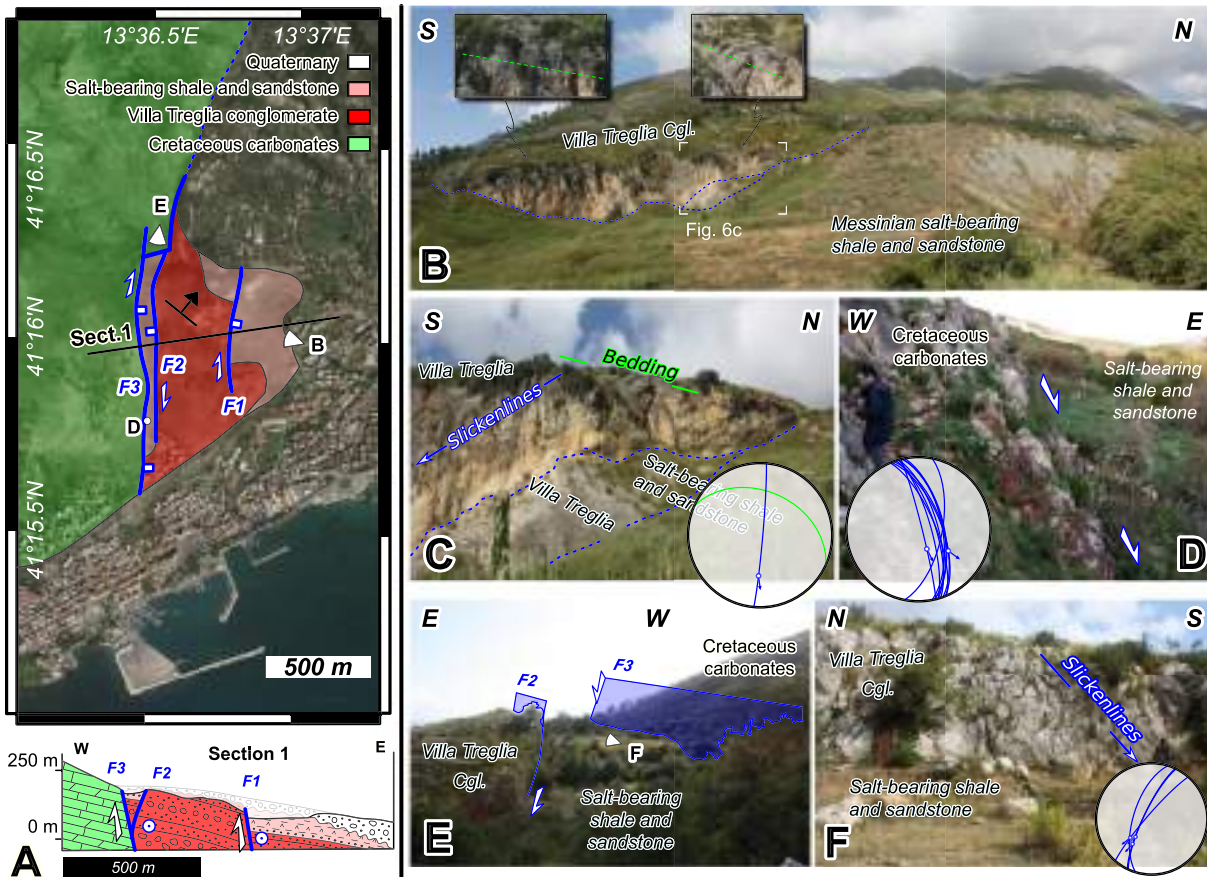
Figure 6. Geology of the southern portion of the Formia Fault. (a) Geological map and cross section. (b) Panoramic photo of the easternmost segment of the Formia Fault system (F1) with the Villa Treglia Conglomerate in the western block and the Messinian salt-bearing shales and sandstones in the eastern block. (c) Close up view of F1, showing oblique-slip striations. (d) Detail of the westernmost fault (F3). (e) Panoramic photo of the transtensive graben formed by the F2 and F3 segments. (f) Close up view of the F2 fault, showing oblique slip striations. Stereographic projections on Schmidt net, lower hemisphere.

pelagic sedimentary rocks are made of micrites with Cretaceous to Paleocene planktic foraminifera (Bergomi et al., 1969), fine-grained calcarenites, and marls, whereas clasts of chert are extremely rare. Absence of exotic blocks in the few well-preserved exposures of the Messinian salt-bearing shales and sandstones, indicates that these blocks were incorporated into this sedimentary mélange in post-Messinian time. The Messinian age of both shales and sandstone in the mélange is broadly supported by the composition of the calcareous nannofossil assemblage. In detail, we carried out a qualitative evaluation of the assemblages on three samples listed in Table S1. In the three samples collected, in a poor assemblage dominated by Cretaceous reworked forms, no strong evidence of Messinian biostratigraphic markers was found, except for a single specimen of *Amaurolithus primus* (Figure 5c) and two primitive morphotypes of the same species, here indicated as cf. *Amaurolithus primus* (Figures 5d and 5e). This tenuous biostratigraphic result was expected, given the paleoenvironmental setting in the Mediterranean during that time interval. Indication of an alternative younger age (early Pliocene) for these sediments is not supported at all by the nannofossil assemblages observed, because it would imply the presence of diversified taxa as those recorded in the Mediterranean at the return to normal marine condition after the Messinian salinity crisis. The few taxa observed in the studied samples are listed in Table S1. The mélange of Messinian salt-bearing shales and sandstones rest unconformably on top of the Cretaceous shallow-water carbonates (Spigno and Maranola sections, Figure 4), whereas the poorly deformed facies (Figure 5f) is conformably overlying a >200 m-thick succession made of alternating carbonate conglomerates and calcarenites with an overall fining-upward trend (Villa Treglia section; Figure 4), having in its upper few meters (transitional to the Messinian sandstone) thin marls layers (Figure 5g). This informal lithostratigraphic unit is here named Villa Treglia conglomerate. The clasts in the conglomerate beds are typically well-rounded (Figure 5h) and are made of the
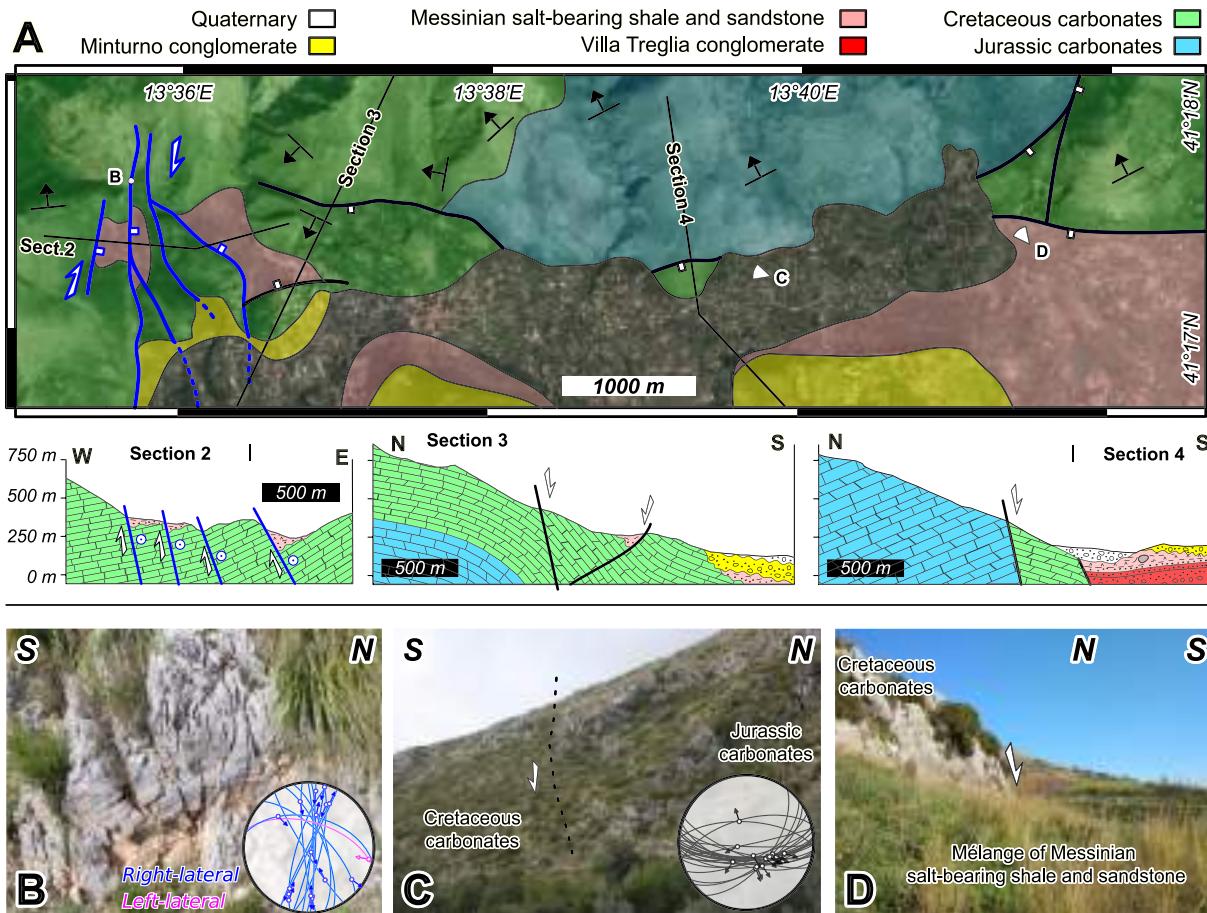
Figure 7. Geology of the northern portion of the Formia Fault and of the Campodivivo Fault. (a) Geological map and cross sections. (b) Photo of a mesoscale N-S striking strike-slip fault and stereoplot of mesoscale faults collected in the surrounding area. (c) Details of the Campodivivo Fault in its central portion with stereoplot of meso-faults data collected in the photographed area. (d) Photo of the eastern portion of the Campodivivo Fault.

same pelagic micrites, fine-grained calcarenites, and rare sandstones of the olistoliths embedded within the Messinian salt-bearing shales and sandstones, pointing to a common source area. No gypsum clasts occur in this unit. A few clasts with a possible shallow-water carbonate platform source have also been observed, as well as chert clasts and rounded granite blocks (Figure 5i). The basal contact of the Villa Treglia conglomerate is not exposed in the studied area, so its total thickness is not yet determined. Also its age is not yet well defined. However, absence of soft-sediment mesostructures and occurrence of brittle normal faults cutting brittle thrust faults (Figure 5l), indicate lithification before the end of compression (i.e., Tortonian-Messinian age). Absence in the Villa Treglia conglomerate of clasts of gypsum that would derive from erosion and re-sedimentation of pre-existing evaporites (as instead observed in the overlying salt-bearing shales and sandstones, Figure 5f), further restricts the possible age for the Villa Treglia conglomerate to the Tortonian-middle Messinan interval. The occurrence of calcarenites and carbonate conglomerate levels with well-rounded clasts of pelagic limestones within the Tortonian-Messinian flysch of the Mt. Massico Ridge (Smeraglia et al., 2019), suggests that the Villa Treglia conglomerate could represent a more proximal facies, lateral equivalent in time, of the same Tortonian-Messinian sequence.

4.3. Structure of the Formia Plain

4.3.1. The Formia Fault

This is the ~20 km-long, E-dipping transtensive fault system that bounds the Formia Plain basin to the west (Figures 2 and 4). To the south, it is composed of three main fault segments (Figure 6a). The easternmost fault segment (F1 in Figure 6) is N-S-striking and steeply dipping, and puts in contact NE-dipping strata
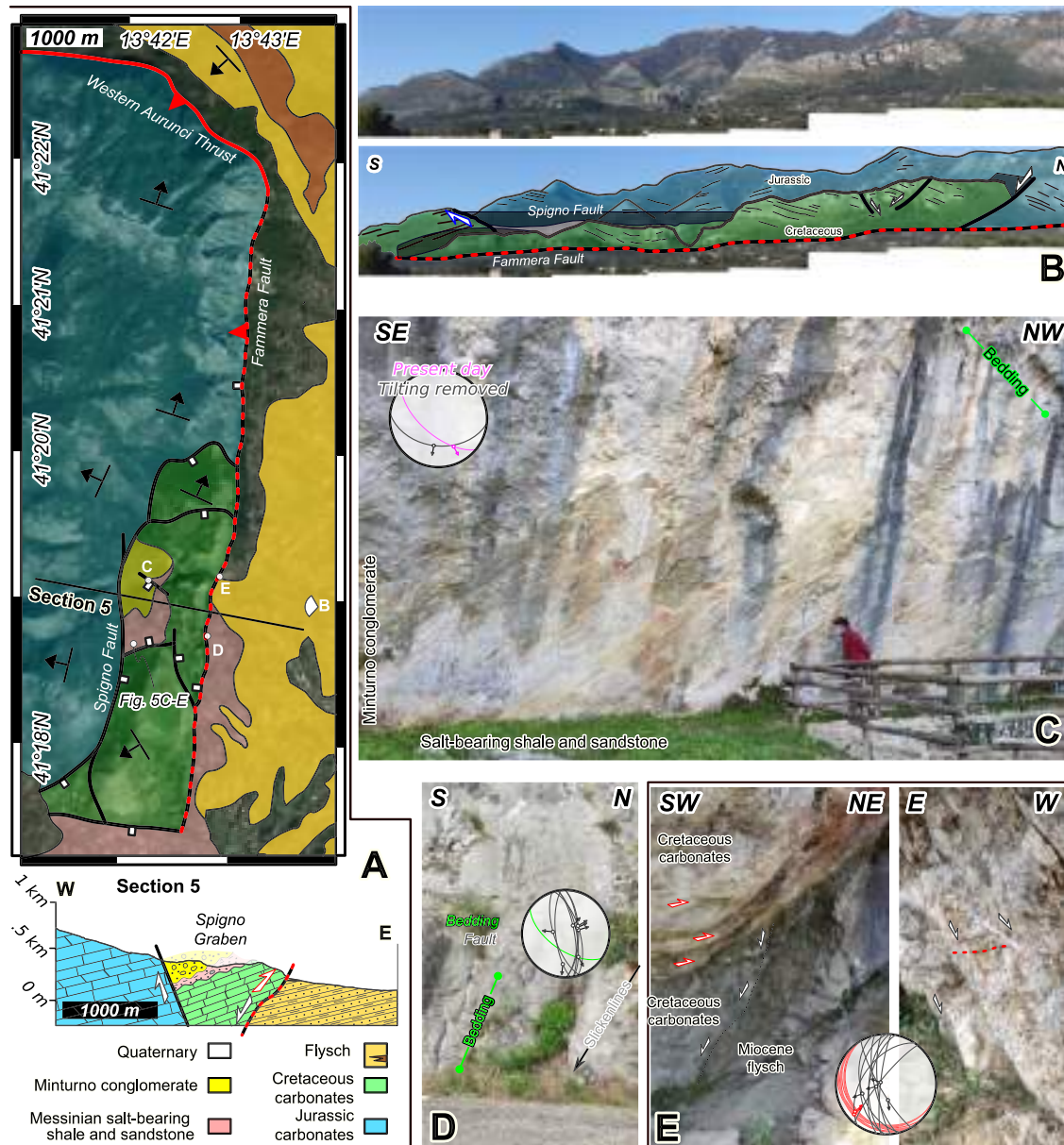
Figure 8. Geology of the Fammera Fault area. (a) Geological map and cross section. (b) Interpreted panoramic photo of the Spigno Graben as seen from the east, representing a natural cross section of the structure. (c) Strike-slip fault mirror in the Minturno conglomerate, with bedding trace indicated in green. Back tilting of strata makes the fault become normal dip-slip. (d) Dip-slip fault in the western damage zone of the Fammera Fault affecting steeply dipping Cretaceous carbonates. (e) Close up views of the Fammera Fault principal displacement zone with plot of structural data, showing low-angle NE-verging thrust cut by high-angle normal faults. Stereographic projections on Schmidt net, lower hemisphere.

of the Villa Treglia conglomerate of the western block with the Messinian salt-bearing shales and sandstones of the eastern block (Figure 6b). This exposure also shows progressive variation of the bedding dip from south to north, suggesting a growth-wedge geometry. The fault plane is characterized by a remarkable oblique-slip, right-lateral, component (slickenline pitch 130–140°, Figure 6c), with the fault slickenlines and bedding cut-off lines being not perpendicular to each other. Some fault lenses are sandwiched between the hanging wall and footwall, the main one holding the conformable stratigraphic transition between the Villa Treglia conglomerate and the Messinian salt-bearing shales and sandstones (Figure 6c). The western fault segment (fault F3 in Figure 6a) has the larger stratigraphic offset and it is exposed in the southern portion of the area, where it corresponds to a N-S striking surface coated with a mm- to cm-thick veneer of iron oxides (Figure 6d). This segment is characterized by a right-lateral transtensive kinematics and has

Cretaceous limestones in the footwall and the Messinian salt-bearing shales and sandstones in the hanging wall (Figure 6d). The central F2 fault segment is an antithetic fault of F3. It is placed some tens of meters to the east of the master fault F3, and forms together with it a small transtensive graben. The graben structure is well-exposed toward the north (Figure 6e), where the F2 fault is steeply dipping and has oblique, right-lateral, slickenlines (Figure 6f). The Villa Treglia conglomerate is in the eastern block of the F2 fault, whereas the salt-bearing shales and sandstones crop out in the western block. Toward the north, the Formia Fault is formed by an array of N-S to NNW-SSE-striking and E-dipping faults, as shown in Section 2 of Figure 7a. Despite these faults being arranged in a domino-like system, their kinematics in this area is almost purely strike-slip (slickenline pitch between 0° and 45°), with a right-lateral sense of movement (Figure 7b).

4.3.2. The Campodivivo Fault

This is an E-W-striking and S-dipping extensional fault that extends for at least 10 km from the Formia Fault (west) to the Fammera Fault (east) (Figures 4 and 7a). To the west, Cretaceous limestones are both in the hanging wall and footwall and the limited stratigraphic offset makes it arduous to trace its western tip. Toward the east, the displacement increases. In its central portion, most of the faults' trace is buried below Quaternary slope deposits (Figure 7a), except for a small area in which the fault zone is exposed (Figure 7c). There, the fault has Cretaceous and Jurassic limestones in the hanging wall and footwall, respectively. Mesoscale faults in the damage zone (the principal slip surface is not exposed) are E-W-striking and show normal kinematics (slickenline pitch between 60° and 90°), with both small left-lateral and right-lateral components. Farther east, the Campodivivo Fault bifurcates: the southern branch having the mélange of Messinian salt-bearing shales and sandstones in the hanging wall and Cretaceous carbonates in the footwall (Figure 7d).

4.3.3. The Fammera Fault

The southern branch of the Campodivivo Fault toward the east intersects the southern tip of the N-S-striking Fammera Fault (Figure 8a). As seen in the map of Figure 4, southward of the Fammera Fault, the flysch and the Cretaceous carbonates are exposed to the east, whereas Messinian to Quaternary sediments occur to the west, pointing to the occurrence of a W-dipping normal fault in continuity with the Fammera Fault, and probably arresting onto the E-W-striking Minturno Horst (Figure 4). The northern branch of the Campodivivo Fault northward changes its orientation and joins the W-dipping Spigno Fault (Figure 8a). This latter fault forms one of the four sides of the Spigno graben, a nearly rectangular structure in map, delimited to the east by the Fammera Fault and bounded by E-W striking transverse normal faults to the north and to the south (Figures 8a and 8b). In the central portion of the graben, the Early Pleistocene Minturno conglomerate, the Messinian salt-bearing shales and sandstones, and the Cretaceous carbonates are tilted and dip toward the Spigno Fault, indicating that the fault was still active after the Early Pleistocene. Consistently, the Minturno conglomerate is also affected by tilted extensional faults (Figure 8c).

Concerning the Fammera Fault, mesoscale faults within its damage zone display normal kinematics regardless of the orientation of strata, pointing to a postfolding activity for the fault (Figure 8d). The principal displacement zone of the Fammera Fault is also exposed in a 3-m wide outcrop (Figure 8e), where Cretaceous limestones are on top of the flysch. The site is affected by SW-dipping low-angle reverse faults displaying a top-to-NE sense of movement, with W-dipping high-angle normal faults cutting—thus postdating—the low-angle reverse faults. The main contact itself is W-dipping and pertains to the extensional system: the older or younger character being attributable to a local extensional reactivation of a former thrust structure of regional relevance. The observation that the Fammera Fault northward joins the low angle NW-SE striking western Aurunci thrust (Figure 8a) and does not propagate across the flysch, indicates that its extensional reactivation has occurred only in the southern portion.

5. Discussion

5.1. Miocene Fold-and-Thrust Belt Evolution

A long-lasting issue in the literature addressing the tectonic evolution of the central Apennines is the degree of allochthony and the origin of the chaotic sediments bearing blocks of pelagic rocks (e.g., Cardello et al., 2021; Centamore et al., 2010; Ogniben, 1969; Sani et al., 2004). The amount of shortening that can be
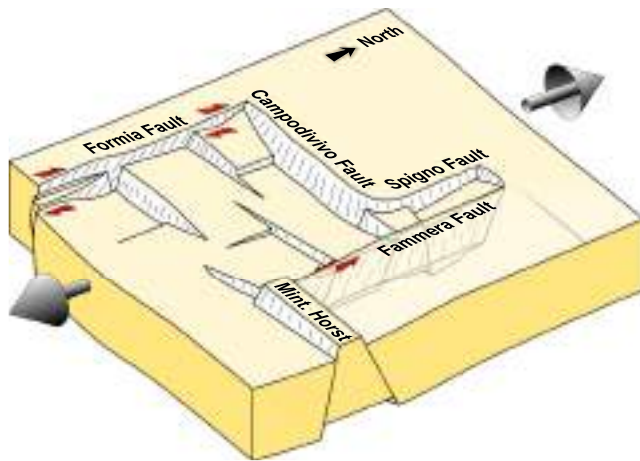
Figure 9. Scheme illustrating the Plio-Quaternary extensional system in the Formia Plain.

reconstructed for this part of the Apennines strongly depends on their interpretation. Our work allowed us to put order in the Miocene stratigraphy of the study area. In particular, we show that the pelagic rocks reported in the area are exotic olistoliths (i.e., olistoliths of rocks not exposed in the local sedimentary succession, but similar to those reported in the Mara 1 well) embedded within Messinian sands and shales (Figures 5a and 5b). This interpretation is based on a correlation with similar exotic olistoliths of Cretaceous-Paleocene pelagic limestones embedded within the Tortonian-Messinian flysch deposits exposed in the eastern Aurunci Mt. and in the Massico Ridge (Bergomi et al., 1969; Di Girolamo et al., 2000; Sgrosso, 1974; Smeraglia et al., 2019). It is thus not necessary to interpret them as klippen of a tectonic nappe made by the deep-water sedimentary cover of Tethys ocean, as previously proposed (e.g., Sani et al., 2004). We stress that the Villa Treglia conglomerate, which paraconformably underlies the salt-bearing shales and sandstone, includes well-rounded clasts of these pelagic limestones. The conglomerates and calcarenites of the Villa Treglia conglomerate could be correlated to the ∼900 m thick conglomeratic unit overlying the flysch in the offshore Mara 1 well (Figure 3), and to lenses of calcarenite and heterolytic conglomerate occurring within the flysch in the Massico Ridge (Sgrosso, 1974; Smeraglia et al., 2019). Thus, we suggest the Villa Treglia conglomerate was deposited in an upper Tortonian to lower Messinian fan delta, interfingered within the Tortonian-Messinian flysch. However, since the relationships between these conglomerates and the flysch are to be fully defined, as an alternative, their deposition in a piggy back basin cannot be excluded (as suggested by the possible growth-wedge observed at its top; Figure 6b). The emerged belt delivering the material for the fan delta and the olistoliths, was placed in a more internal (western) position with respect to their accumulation area, that is, it was placed in the present-day offshore, to the SW of the Formia Plain.

Another main question concerning the fold-and-thrust belt evolution is the nature of the N-S striking Fammera Fault. A far-traveled nature for the Volsci Range frontal thrust, with a hanging wall flat on footwall flat relationship, has been proposed by many authors (e.g., Centamore et al., 2007; Naso & Tallini, 1993). In this hanging wall flat on footwall flat interpretation, the Fammera Fault should be a subhorizontal to gentle-dipping fault, which is clearly not consistent with its straight geometry, pointing instead to a steeply dipping oblique ramp geometry (oblique ramps being common structures in thrust systems; e.g., Apotria, 1995; Wilkerson et al., 2002), limiting the displacement of the Volsci Range in the study area to less than a few tens of kilometers.

5.2. The Plio-Quaternary Extensional System

The major fault systems active during the Plio-Quaternary extension (i.e., the Formia Fault, the Campodivivo Fault, and the extensionally reactivated portion of the Fammera Fault) are E-W and N-S striking and form the classic pattern of perpendicular fault sets developing during extension. The E-W striking boundary faults of the Minturno Horst can be also framed in this pattern (Figure 4). The slightly left-lateral transtensive behavior of the extensional Fammera Fault, the normal kinematics of the faults bounding the Spigno Graben, and the right-lateral transtensive kinematics of the Formia Fault, can be framed within a Plio-Quaternary tectonic setting of the area, controlled by a general N-S extension that also produced S-dipping dip-slip faults: the Campodivivo Fault, the southern boundary fault of the Minturno Horst, and the northern boundary faults of the Spigno Graben (Figure 9). These faults are connected via N-S striking faults (Formia, Spigno, and Fammera faults) that mimic the geometry of transfer faults (e.g., Morley et al., 1990). The opposite strike-slip components along the Fammera and Formia faults are fully in agreement with our interpretation, in which the Formia Plain is in essence the S-verging hanging wall of the Campodivivo Fault, the Formia and the extensional Fammera faults being the transfer faults bounding it.

Concerning the timing of extension, the deposition of the Pleistocene Minturno conglomerate reveals (a) an extensive arrival of clasts supplied from the Jurassic and Cretaceous shallow-water carbonates exposed in the western Aurunci Mts. and (b) the disappearance of clasts supplied by the pelagic source of the Villa

Treglia conglomerate. This source switch indicates that the belt made of pelagic Mesozoic domain (found in the Mara 1 well) was already drowned during the Pleistocene and that the Aurunci Mts. were already exhumed. Mixing and disruption of strata of the salt-bearing sandstone and shale to form a sedimentary mélange embedding pelagic olistoliths occurred during Pliocene time, indicating that the "pelagic" belt drowned during the Pliocene (i.e., it was still emerged and supplying olistoliths during the formation of this mélange). Some authors support a Messinian age for the onset of extension in the Formia Plain (e.g., Cipollari & Cosentino, 1991) and in the neighboring Garigliano Plain (e.g., Cipollari et al., 1999; Cosentino et al., 2006). We cannot rule out that limited local extension could have occurred in late Messinian times, however, our source-to-sink approach indicates that the main activation of the extensional system occurred not earlier than the Pliocene.

Concerning the end of extension, faulting and tilting of the Minturno conglomerate within the Spigno graben (Figures 8a and 8c) indicate that extensional tectonics lasted at least until the end of the Early Pleistocene.

5.3. Reconstructing the Western Portion of the Jurassic Rifted Margin of the Apenninic Platform

As previously mentioned, in the central Apennines, the Early Jurassic rifting caused the development of N-S and E-W elongated horst and graben structures, where persistent carbonate platforms and pelagic basins developed during the Middle Jurassic to Cretaceous post-rift period (Bosellini, 2004; Cardello & Doglioni, 2015; Cosentino et al., 2010; D'Argenio et al., 1975; Ogniben, 1969; Patacca & Scandone, 2007; Santantonio & Carminati, 2011). In the northern area of the central Apennines, the rim of the carbonate platform is characterized by two N-S striking segments (Figure 10a), one of them being the Olevano-Antrodoco Fault (an extensional fault developed upon rifting and reactivated as a transpressive fault during shortening; e.g., Castellarin et al., 1978; Tavani & Cifelli, 2010). On its western side, the platform margin is right-stepped south of the Rocca di Cave village (Carbone et al., 1971), as constrained by the Cretaceous platform margin facies found in the Artena area (Praturlon & Sirna, 1976) and the slope/pelagic basin facies found in many wells of the Pontina plain (e.g., Tre Cancelli-1 and Fogliano-1; Figure 10a) and forming the substratum of the Albani Hills volcanic district (Funiciello & Parotto, 1978). Another E-W trending step occurs in the southern part of the N-S segment bounding the carbonate platform to the east, in the Matese Mts. (Calabrò et al., 2003). Although the Matese and Rocca di Cave steps are not aligned, it is worth noting that the Rocca di Cave area is in the hanging wall of the Olevano-Antrodoco Fault, which in its southern portion re-deforms the NW nose of the Volsci Range (Tavani & Cifelli, 2010). The Matese Mts. are instead in the footwall of the Volsci Range. Accordingly, by removing about 20 km of NE translation for the Volsci Range (Curzi, Billi, et al., 2020), and a similar value for the southern portion of the Olevano-Antrodoco fault (Tavani & Cifelli, 2010), the Rocca di Cave exposure should be shifted nearly 40 km to the SW with respect to the Matese Mts. (blue dashed line in Figure 10a). This produces the alignment of the two E-W trending segments, to form a single structure against which the major N-S trending Jurassic lineaments arrest. This configuration retraces a transfer zone (e.g., Morley et al., 1990), which is also paralleling the southern boundary of the carbonate platform, as defined by the limit between shallow-water facies of the Volsci Range and the pelagic basin/slope facies found in the Mara-1 well (Figure 3). Here, the southern E-W striking boundary of the platform is also interpreted as a transfer fault, across which the N-S striking segment of the carbonate platform limit is shifted about 100 km.

In line with recent advances on the reconstruction of rifted margins (e.g., Lavier & Manatschal, 2006; Sapin et al., 2021; Whitmarsh et al., 2001), the archetypal domains of magma-poor hyperextended rifted margins have been recognized in the Jurassic rifted margin of this area (Tavani et al., 2021), with the carbonate platform corresponding to the poorly stretched proximal domain and the surrounding deep-water basins forming the necking domain and, in their deeper portion, even the hyperextended domain. We thus propose that the segmentation of the carbonate platform by E-W striking transfer faults can be interpreted as the segmentation of the Jurassic rift system. Accordingly, shift in the carbonate platform across transfer faults implies shift of the necking and hyperextended domains (and thus of the Liguride domain formed by the hyperextended and oceanic domains of the rift), thus these faults being the continental continuation of Tethysian oceanic transform faults. Noteworthy, an along-strike gap in the Liguride domain occurs in the
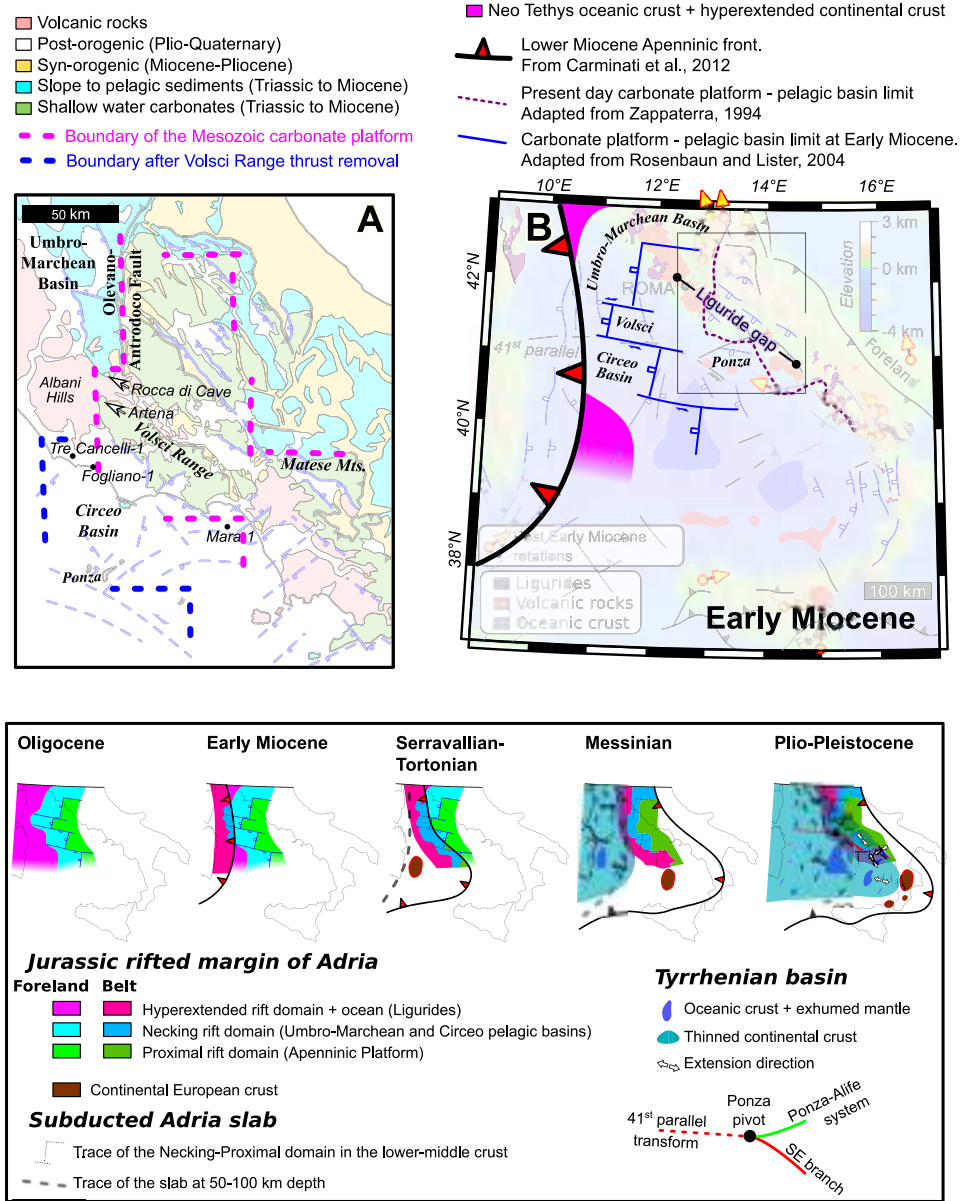
Figure 10. Regional framework of the Ponza-Formia-Alife oblique system. (a) Geological map of Figure 1d with overly of the boundary between the shallow-water carbonate platform and pelagic basin domains and inferred position of the basement Jurassic transfer fault. (b) Reconstruction of the foreland area of the Apennines at early Miocene, with the western portion of the carbonate platform-pelagic basin limit shown. (c) Simplified scheme showing the evolution of the Apennines Belt-Tyrrhenian back-arc basin. See text for details.

central Apennines (Figure 10b). Remnants of the Tethys oceanic crust and of its sedimentary cover occupy the upper portion of the tectonic pile in both the northern and southern Apennines (Figures 1b and 10b). In the central Apennines, the topmost portion of the tectonic pile is instead occupied by thrust sheets deforming Mesozoic pelagic basin/slope domains, as exposed in the Circeo Mt. (e.g., Accordi, 1966) (Figure 1d) and found in the Mara 1 well (Figure 3), which were supplying pelagic clasts delivered into the foredeep during the Miocene. Despite the uncertainties associated with the restoration, an overlay of the reconstructed rift system onto the early Miocene setting of the Apennines belt (Figure 10b) shows that the Liguride gap points to a salient-like geometry of the Jurassic rifted margin segmented by E-W striking Jurassic transfer faults.
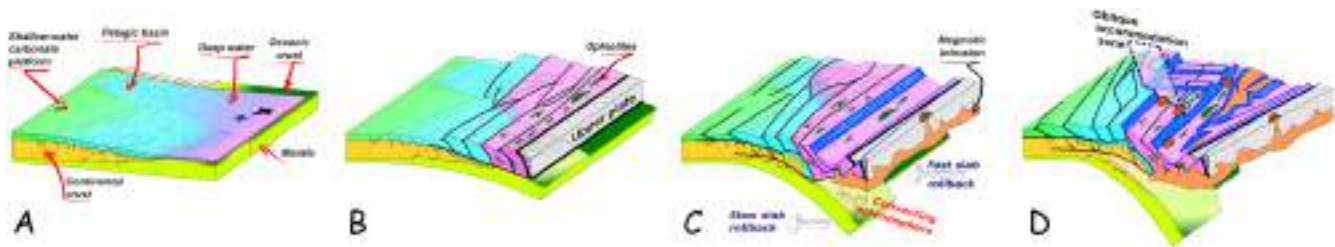
Figure 11. Scheme showing the progressive evolution of a segmented rifted margin during convergence and differential rollback. (a) Pre-orogenic rifted margin architecture. (b) Early convergence stage, with accretion of the sedimentary cover of the distal portion of the rifted margin. (c) The northern portion of the margin enters the hard collision stage while the southern one is still in the subduction/soft collision stage. Slab rollback starts causing the development of an initially almost cylindrical back arc basin. (d) Faster rollback in the southern portion of the slab cause faster migration of the extensional front and overall arching of the back arc basin margin, whose connection with the northern portion of the basin margin is ensured by the development of an E-W accommodation zone, which is vertically above the inherited Mesozoic transform zone.

This reconstruction evidences how the along-strike variability in the architecture of the Apennine fold-and-thrust belt is strongly influenced by the segmentation of the inherited rift. Such an observation is in line with many other foreland thrust and fold belts, in which the along-strike variation in structural style of thrust systems relates with the rift-related variability of the tectono-stratigraphic architecture of the lower plate, such as the Pyrenees (e.g., Lescoutre et al., 2021; Muñoz et al., 2013), Taiwan (e.g., Mouthereau et al., 1999), the Po plain (e.g., Turrini et al., 2016), and the Zagros (Sepehr & Cosgrove, 2005; Tavani et al., 2020).

5.4. Arching the Adria Slab and the Tyrrhenian Basin

We have shown that the central portion of the roughly E-W oriented Ponza-Alife accommodation zone is characterized by the N-S oriented Plio-Pleistocene extension, developed coevally with oceanic crust production in the Tyrrhenian back-arc basin. This N-S extension domain locates in an area across which the Plio-Quaternary regional extension direction permutates, shifting from NE-SW to NW-SE (Figure 1c). The transition between these domains of mutual perpendicular extension direction occurs through an area in which faults are oriented mostly E-W, such as those bounding to the north of the Gaeta Basin (seismic lines of Figure 3), and those exposed in the Formia Plain (Figure 4). These E-W striking structures are oblique to the main trend of the Plio-Quaternary extensional system of the Apenninic margin and are parallel and perpendicular to the E-W and N-S striking Early Jurassic extensional faults exposed in the central Apennines (e.g., Cardello & Doglioni, 2015; Castellarin et al., 1978; Fabbi, 2015; Pierantoni et al., 2013; Storti et al., 2018), many of which are exposed a few tens of kilometers to the NE, in the Matese Mts (Calabrò et al., 2003), where they show evidence of Quaternary extensional reactivation (Valente et al., 2019). At a larger scale of observation, the Ponza-Alife accommodation zone locates in the upper plate of the orogenic system, vertically above a discontinuity in the downgoing Adria slab that has ensured the faster E-ward rollback of its southern portion with respect to the northern portion. Such a discontinuity is typically modeled as a lithospheric tear fault (e.g., Rosenbaum & Lister, 2004) and the reason for such a differential rollback is attributed to the oceanic and continental nature of the lithosphere to the south and to the north, respectively, as inherited from the Triassic-Jurassic rifting (e.g., Doglioni, 1991; Faccenna et al., 1997; Malinverno & Ryan, 1986). Our paleogeographic reconstruction supports the occurrence of such a juxtaposition of different crustal types, which we attribute with unprecedented detail to the occurrence of transfer zones across which the Mesozoic rift domains were left stepping (Figure 10b).

The above illustrated features and our findings in the area can be framed into the simple model shown in Figure 10c and schematically reconstructed in 3D in Figure 11. The pre-orogenic architecture of the south-western margin of Adria exposed in the central Apennines is characterized by a segmented Jurassic rift (Figures 10c and 11a). Since the Oligo-Miocene, the Meso-Cenozoic sedimentary cover of this rifted margin has been detached from its Paleozoic basement and has been accreted into the Apennine belt (Figures 10c and 11b). The major extensional and transfer faults of the Jurassic rift have been decapitated during this thin-skinned stage (Tavani et al., 2021), and their roots have been subducted. Obliquity between the rifted margin and the belt caused the central Apennines to enter the collisional stage earlier than the southern Apennines (Figures 10c and 11c), where faster south-east rollback and overall slab arching occurred.

Opening of the Tyrrhenian back-arc basin occurred since the Miocene, with an E-ward migration of the extensional wave (e.g., Jolivet et al., 2021), and led to hyperextension, mantle exhumation (Prada et al., 2014) and, since the Messinian, oceanic crust production in the southern Tyrrhenian sub-basin. During the Pliocene, progressive rollback and slab arching in the southern Apennines led to the further widening of the southern Tyrrhenian sub-basin with respect to the northern one (Figures 10c and 11d). This produced the increased counter-clockwise rotation of the southern Apennines arc with respect to the central Apennines (Figures 1b and 10b) and the progressive stretching of the western margin of the southern Tyrrhenian sub-basin, causing the along-margin NW-SE directed extension (Casciello et al., 2006; Knott & Turco, 1991) (Figure 11d). A pivotal point in this Plio-Pleistocene frame is the Ponza area, where the supposed 41st parallel fault (Spadini & Wezel, 1994) should split in its two branches. The NE branch is the Ponza-Alife accommodation zone described in this work. It is an extensional system oblique to the main trend of extensional structures of the margin (reactivating in many inherited E-W and N-S striking Jurassic faults), which kinematically decouples the margin of the northern Tyrrhenian sub-basin (undergoing NE-SW extension) from the margin of the central/southern Tyrrhenian sub-basin (undergoing NW-SE extension). The SE branch of the 41st parallel is a left-lateral transfer fault system (Conti et al., 2017), which ensures coeval WNW-ESE stretching in the southern Tyrrhenian sub-basin and arching, counter-clockwise rotation and along-strike stretching in its eastern Apenninic margin (Figure 10c). These two fault systems in the upper plate joins at the vertical projection of the diffuse tearing system in the downgoing plate, which corresponds to the inherited Jurassic transform formerly bounding to the north the Circeo Basin. Given the above illustrated framework, the 41st parallel fault west of the Ponza pivot point is a kinematically unnecessary feature.

In conclusion, the accommodation zone introduced in this work is an example of twofold inheritance: (a) the accommodation zone developed obliquely to the regional stretching direction because of the occurrence of a diffuse network of inherited faults; (b) the accommodation zone developed at that specific site because of the reactivation of an inherited Tethysian transform fault in the downgoing plate.

6. Conclusions

The Plio-Quaternary Ponza-Formia-Alife oblique system accommodates the segmentation of extensional basins in the Apenninic margin of the Tyrrhenian back-arc basin. Interpretation of offshore vintage seismic lines in the Gaeta Basin with structural and stratigraphic observations from the Formia Plain and the Aurunci Mts., allowed us to unravel the evolution of this oblique system. In particular, we infer that this accommodation zone has its root in an inherited crustal scale transfer fault, which segmented the Jurassic rift system of Adria. After its decapitation and accretion during Miocene thrusting, lateral juxtaposition of different crustal domains is preserved in the lower plate and drove the faster rollback of the southern portion of the subducted slab. This caused, in turn, increased back-arc extension in the southern Tyrrhenian basin, along with arching of its eastern margin and the onset of an along-strike stretching domain. This domain is kinematically separated from the adjacent areas of the back arc basin via the Ponza-Alife accommodation zone, which is in essence the upper plate effect of lower plate reworking of an inherited transform.

Data Availability Statement

Seismic sections in Figure 3 are available at https://www.videpi.com/. Line T1: https://www.videpi.com/videpi/sismica/dettaglio.asp?codice=E-101SR. Line T2: https://www.videpi.com/videpi/sismica/dettaglio.asp?codice=E-109. Line T3: https://www.videpi.com/videpi/sismica/dettaglio.asp?codice=E-186. Line T4: https://www.videpi.com/videpi/sismica/dettaglio.asp?codice=E-188. Line T5: https://www.videpi.com/videpi/sismica/dettaglio.asp?codice=E-190. Line T6: https://www.videpi.com/videpi/sismica/dettaglio.asp?codice=E-192. Fault and bedding data shown in the stereoplots can be found at https://doi.org/10.26022/IEDA/111890.

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