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Structural architecture and tectonic evolution of the Campania-Lucania arc (Southern Apennines, Italy): Constraints from seismic reflection profiles, well data and structural-geologic analysis

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A R T I C L E I N F O

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A B S T R A C T

This paper sheds light on the structural architecture and tectonic evolution of the Campania-Lucania segment of the Southern Apennines orogen through an integrated analysis of mostly unpublished and partly published (CROP-04 line) seismic reflection profiles, exploratory well logs and geologic-structural relations among the lithostratigraphic units of this region. The pre-orogenic Mesozoic-Neogene carbonate platform, margin-slope and basinal units that compose the upper orogenic level (Apennines fold and thrust belt) were detached from their basement during Miocene thrusting and form a heterogenous multilayer that was thrust above the Apulian foreland platform. The Apulian Platform itself was involved in Pliocene thick-skinned thrusting that controlled the style and localization of Quaternary transtension and extension. The velocity data from sonic logs, the well stratigraphy, and the seismic reflection facies were integrated through an accurate well-to-seismic tie, allowing the building of a specific velocity model for the time-to-depth conversion. We identified different seismic units with distinctive reflections attributes, which were assigned to the lithostratigraphic units logged in the wells. Our analysis documents the stratigraphic-structural arrangement of the thin-skinned thrusts sheets (Liguride Basin, Apennine Platform and Lagonegro-Molise Basin units) that form the Apennines fold and thrust belt. These units show strong lateral thickness changes because of both the original depositional environments and the non-coaxial deformation stages. In contrast, the underlying Apulian Platform is characterized by a regional anticlinorium (~30–50 km wavelength) that, based on our new reconstruction, extends further west than hitherto known. The anticlinorium exhibits shorter-wavelength (<10 km) anticlines limited by N- to NE-verging thrust ramps, whose high dip (~45°) suggests they root in the crystalline basement. Our work provides a sound link between surface and subsurface structural setting and an improvement of the geometry of the Apulian Platform, with important implications for structural and seismotectonic models of the region.

1. Introduction

The Apennines, part of the orogenic system formed during the convergence between the European and African plates (Fig. 1; Faccenna et al., 2001; Malinverno and Ryan, 1986; Royden et al., 1987), represent an outstanding case history where shortening and later extension affected a multi-layer stack with heterogeneous mechanical stratigraphy. In the Southern Apennines, early Neogene *E*- to NE-directed contraction toward the Apulian-Adriatic foreland (Fig. 1b) formed a stack of thin-skinned thrust sheets composed of platform and basin

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stratigraphic successions, which was emplaced above the western part of the Apulian foreland platform. Late Neogene shortening involved the Apulian platform rocks buried under the thin-skinned thrust sheets and led to the growth of a series of foreland-convex arcs (Fig. 1b; Nicolai and Gambini, 2007; Patacca et al., 1990).

We focus on the ~160 km-long Campania-Lucania Arc (hereinafter CLA; Fig. 1b) that bears a twofold scientific interest. During the 1980s and 1990s, the buried Apulian platform has been the target of petroleum exploration; in the same period the deep structure of this sector was investigated as part of the CROP (CROsta Profonda-Deep Crust) project (Fig. 1b; Mazzotti et al., 2000, 2007; Finetti, 2005; Scrocca et al., 2005, 2007), which yielded an updated structural model for the region (Menardi Noguera and Rea, 2000; Mostardini and Merlini, 1986; Nicolai and Gambini, 2007). Notwithstanding, several issues still hinder a full comprehension of the CLA tectonic evolution: 1) the structural arrangement of the thin-skinned thrust belt, which shows abrupt vertical and lateral changes in thickness; 2) the fine imaging of the deformed Apulian Platform at depth, particularly in the western or hinterland part of the Apennines (Fig. 1b); 3) the role of high-angle normal and normal-oblique faults that dismembered the western flank of the orogen during

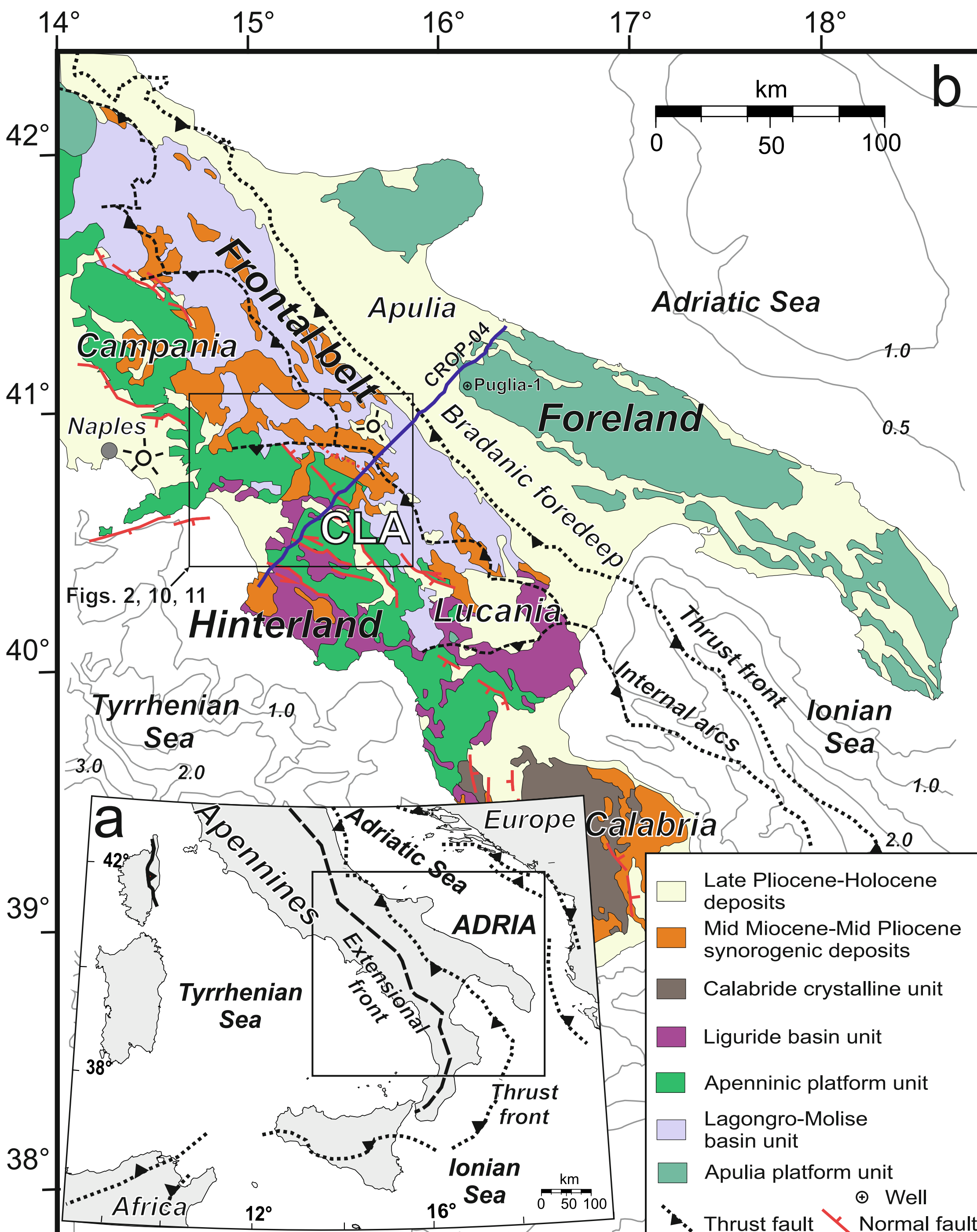


Fig. 1. (a) Geodynamic setting of the central Mediterranean, showing the thrust fronts surrounding Adria and the extensional front of the Apennines. (b) Tectonic map of Southern Italy, showing the thrust front of the Southern Apennines and the front of internal arcs of the Apulian belt. Water depth in km. CLA, Campania-Lucania Arc.

the Late Pliocene-Quaternary (Fig. 1b). The above issues render geometric and kinematic reconstructions of the CLA challenging.

The second scientific interest of the CLA is represented by the seismic hazard assessment of the region, which is affected by moderate to strong seismicity, including the $M_w = 6.9$, 1980 Irpinia-Basilicata earthquake (Fig. 2; Pantosti and Valensise, 1990; Westaway and Jackson, 1987; Westaway, 1993). Therefore, an improved definition of the upper crustal structure can provide valuable insights to understanding the seismotectonic context of this area.

In this paper we present an updated geometric and structural reconstruction of the northern part of the CLA based on i) an accurate appraisal of the geological relations deriving from published and original work in the area, ii) the analysis of seismic reflection profiles (commercial lines and a segment of the CROP-04 line) and iii) well logs interpretation.

The main novelties ensuing from the present work are: 1) a robust link between surface and buried structures beneath this sector of the Apennines; 2) an improvement of the depth and geometry of the top Apulian platform, with the recognition of a hitherto unknown significant structural high; and 3) an integrated model of the crustal geometry with implications for existing tectonic and seismotectonic models.

2. Background setting of the CLA

2.1. Regional framework

The Southern Apennines evolved during the late Paleogene westward-directed subduction of the Tethys oceanic lithosphere underneath the European margin, and its later collision with the western continental margin of Adria (Fig. 1a), a small lithospheric block of North African affinity trapped within the articulated plate boundary between Africa and Europe (Carminati and Doglioni, 2012; Channell et al., 1979; Faccenna et al., 2001; Royden et al., 1987; Van Hinsbergen et al., 2014).

Based on trend, kinematics, and age of tectonic structures, two different structural sectors are distinguished moving from west (hinterland belt) to east (frontal belt) across the orogen (Fig. 1b). Within the hinterland sector, Middle Miocene-Pliocene contractional structures were overprinted by Quaternary normal and normal-oblique faults related to stretching in the Tyrrhenian back-arc basin and orogenic collapse (Brozzetti, 2011; Ferranti and Oldow, 2005; Hippolyte et al., 1994; Monaco et al., 1998; Scrocca et al., 2007). Differently from the hinterland sector, in the frontal belt only contractional and transpressional structures developed from latest Miocene up to early Pleistocene.

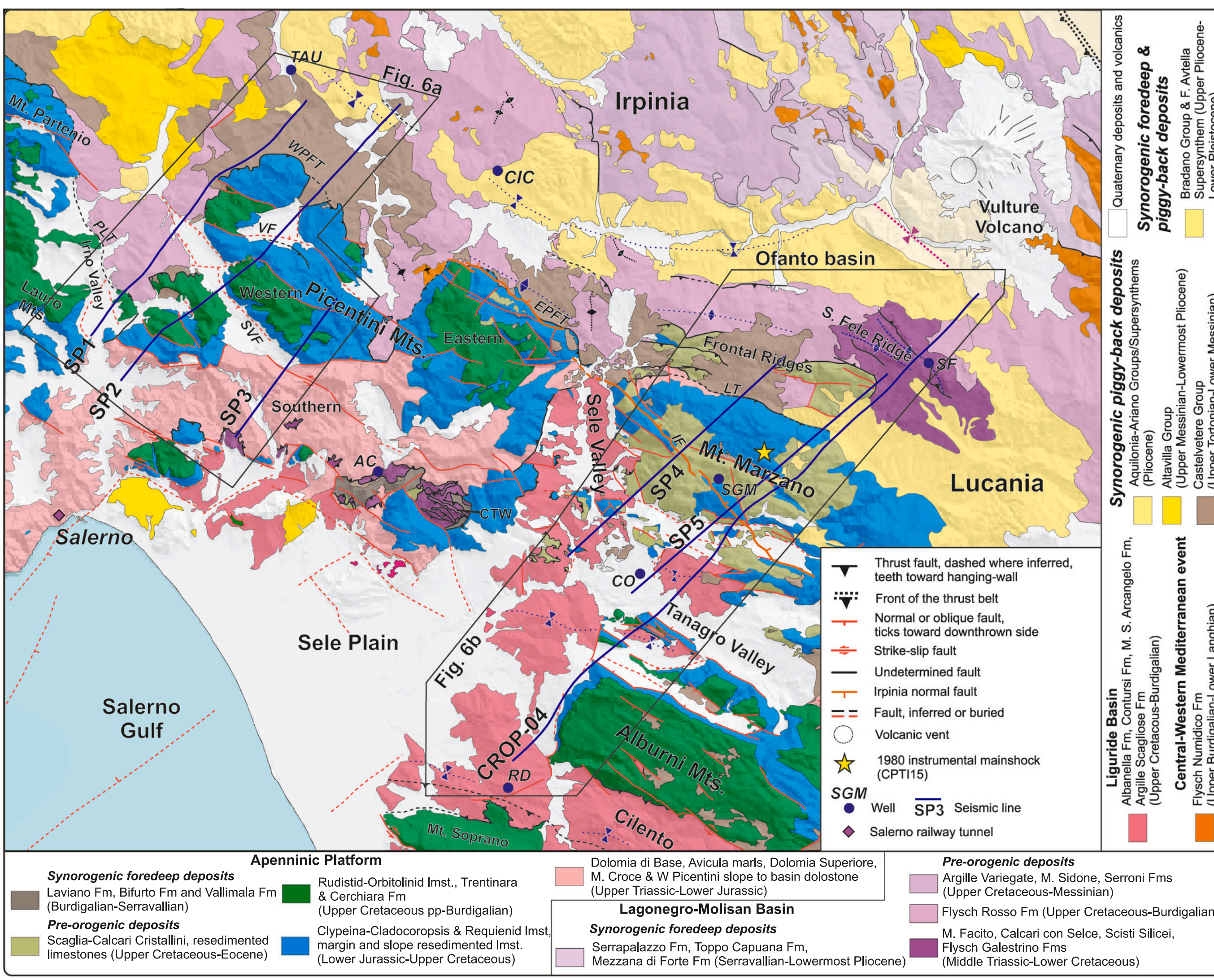


Fig. 2. Geological map of the Campania-Lucania Arc (based on Vitale and Ciarcia, 2018; Bonardi et al., 1988; Cartografia Geologica d'Italia (CARG, 1:50.000 scale) and Carta Geologica d'Italia (CGI, 1:100.000 scale) map sheets). Wells: AC, Acerno; CIC, Ciccone; CO, Contursi; NU, Nusco; RD, Roccadaspide; SGM, S. Gregorio Magno; TAU, Taurasi. Faults: IF, Irpinia fault; LT, Laviano thrust; WPFT, Western Picentini frontal thrust; EPFT, Eastern Picentini frontal thrust; PLT, Partenio-Lauro thrust; SVF, Sabato Valley fault; VF, Volturara fault. CTW, Campagna Tectonic Window.

Further east the Apulian sector of the Adriatic margin represents the foreland of the NE-verging thrust belt (Fig. 1b).

The contractional orogen includes two vertically superposed structural belts (Casero et al., 1988; Menardi Noguera and Rea, 2000; Mostardini and Merlini, 1986; Patacca and Scandone, 2007b). The upper (i.e., Apennine) belt formed in response to Miocene-early Pliocene shortening, which led to the detachment of Mesozoic-Cenozoic sedimentary successions deposited on or near the western Adriatic continental margin from their crystalline basement. The detached successions formed a series of thrust sheets emplaced in-sequence from west to east (Casero et al., 1988; D'Argenio et al., 1975). Estimates of shortening vary by location and tectonic unit, but its aggregate value may reach 200–300 km (Scrocca et al., 2005, 2007). The highest lithotectonic unit is represented by relicts of the Liguride accretionary wedge (Vitale et al., 2019), which includes Mesozoic-Neogene deep basinal rocks off-scraped from the subducted Thetys oceanic crust, and locally ophiolite slices. These rocks crop out in the hinterland and locally in the frontal belt of the Lucania-northern Calabria regions (Fig. 1b). The Liguride rocks structurally overlay Mesozoic-Cenozoic carbonates of the Apenninic Platform, which floors the largest part of the hinterland (Fig. 1b). The Apenninic Platform rocks are in turn imbricated above rocks of the Lagonegro-Molise Basin, which are largely exposed east of the platform rocks and, locally, beneath them within tectonic windows (Figs. 1b, 2). Platform and basinal pre-orogenic successions are paraconformably or unconformably covered by Miocene to Lower Pleistocene siliciclastic and subordinately calciclastic sediments, which were deposited in migrating foredeep and thrust-top basins (Patacca and Scandone, 2007a, 2007b; Vitale and Ciarcia, 2013; Vitale et al., 2019). Synorogenic deposits are less deformed than pre-orogenic rocks and are chiefly exposed in the frontal belt (Fig. 1b). The most recent foredeep is filled by Pliocene-lower Pleistocene deposits (Bradanic foredeep Fig. 1b).

The lower (i.e., Apulian) belt represents the western extension of the Apulian foreland buried under the Apennines and forms a regional-scale anticlinorium consisting of Mesozoic-Tertiary platform rocks and of their crystalline basement (Menardi Noguera and Rea, 2000; Mostardini and Merlini, 1986; Patacca and Scandone, 2007b). Deep well log data in the foreland (e.g. Puglia 1 well, Fig. 1b) document that the Apulian Platform consists, from top to bottom, of a 6 km thick succession of Jurassic-Tertiary shallow-water to margin carbonates, Upper Triassic dolostones, Upper Triassic evaporites and dolostones (Burano Formation), and a minimum ~1 km thick interval of Upper Permian-Lower Triassic epi-metamorphic clastic rocks (Verrucano Formation) of fluvial-deltaic facies (Fig. 3; Channell et al., 1979; D'Argenio and Horvàth, 1984). The total thickness of the Verrucano layer is unconstrained, and a constant thickness of 2 km has been assumed by Boncio et al. (2007) on the basis of DSS data from the Northern Apennines.

Oil exploration data revealed that the structure of the Apulian belt under the Apennines is made of a series of eastward-convex arcs formed by broad thrust-ramp anticlines (Fig. 1b; "internal arcs" of Nicolai and Gambini, 2007). These arcs developed after the emplacement of the Apennine thrust belt above the flexured Apulian foreland, and their age becomes younger moving from NW to SE (Ascione et al., 2012; Patacca et al., 1990). The buried Apulian arc studied here corresponds to the Central Arc of Nicolai and Gambini (2007), and its growth is thought to

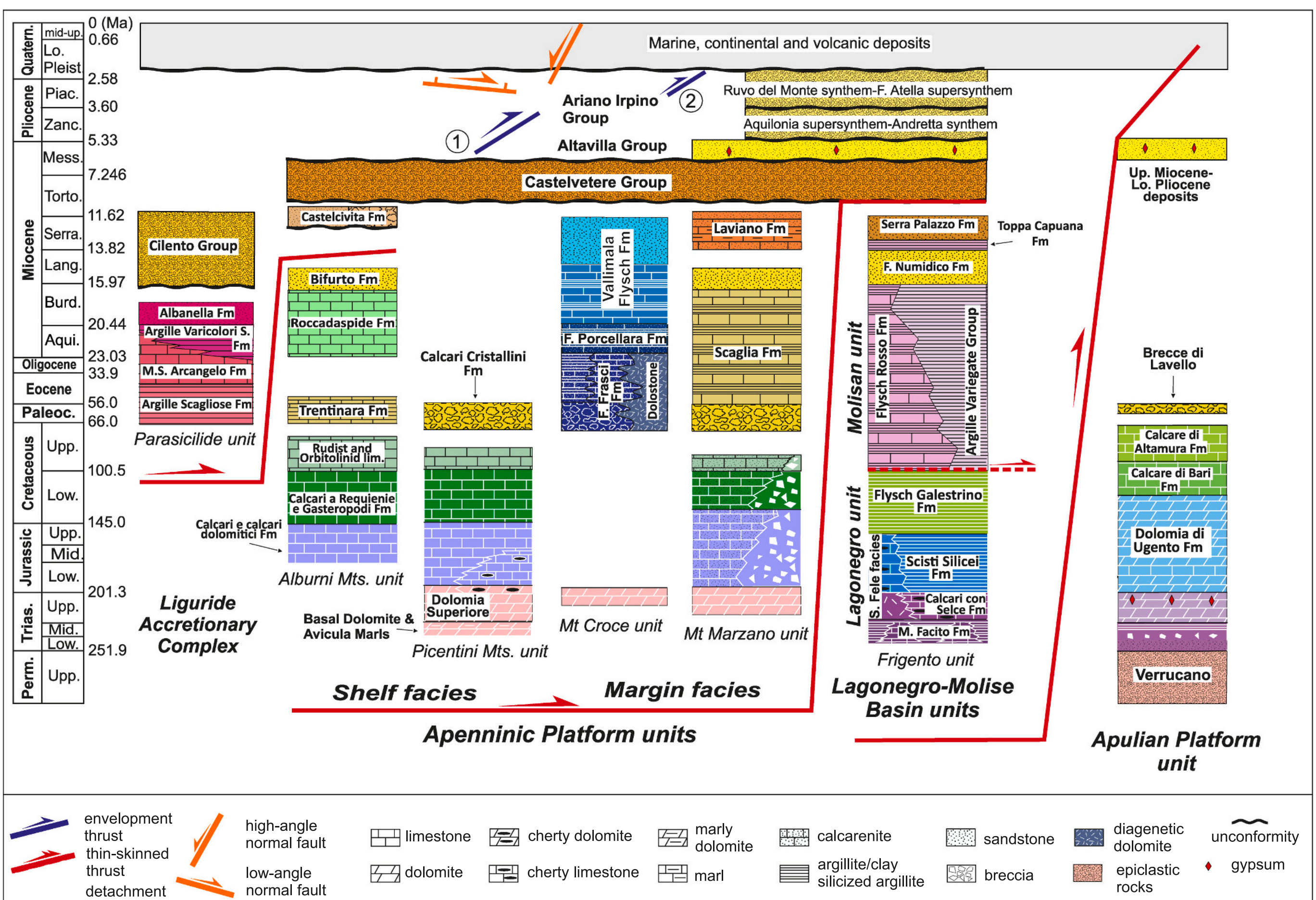


Fig. 3. Schematic stratigraphy of the main litho-tectonic units of the Campania-Lucania Arc (modified from Vitale et al., 2020a). The stratigraphy of the Apulian Platform buried under the CLA is derived from the Puglia 1 well (location in Fig. 1b) and from wells drilled in the CLA. Circled numbers are: 1, Apulian Internal thrust ramps; 2, Apulian external thrust ramps Lo., Lower; Mid., Middle; Up., Upper; Pleistoc., Pleistocene.

have lasted through the Pliocene-early Pleistocene (Mazzoli et al., 2006, 2014). The total shortening experienced by the buried Apulian Platform is debated and estimates range from ~20 up to ~90 km depending on the adopted structural style, whether thick-skinned (Butler et al., 2004; Improta and Corciulo, 2006; Mazzoli et al., 2006, 2014; Shiner et al., 2004; Speranza and Chiappini, 2002) or thin-skinned (Cippitelli, 2007; Patacca and Scandone, 2007a; Scrocca et al., 2007). Although the involvement of the Apulian crystalline basement in contraction is not proven, the steep dip of reverse faults within the sedimentary cover traced in seismic reflection profiles (Shiner et al., 2004) argues for a thick-skinned deformation style (Butler et al., 2004; Mazzoli et al., 2006). It was proposed that thick-skinned contraction inverted previous extensional faults rooted within the crystalline basement, which formed during Neogene forebulge stretching or during the Mesozoic passive margin stage (Shiner et al., 2004; Mazzoli et al., 2006).

The Apulian Platform overlays a deep discontinuity revealed by regional gravity anomalies, wide-angle deep seismic soundings (DSS) and receiver functions (RFs) studies, which outline the existence of a doubling of the Moho beneath the Southern Apennines (Akimbekova et al., 2021, 2023; Cassinis et al., 2003; Di Stefano et al., 2011; Piana Agostinetti and Amato, 2009; Scrocca et al., 2007; Steckler et al., 2008). The Tyrrhenian Moho overlies the W-plunging Adriatic Moho, and its eastern tip broadly coincides with the current extensional front in the Apennines (Fig. 1a; Ferranti et al., 2014).

Orogenic growth was marked by a complex history of tectonic transport that resulted in the superposition of non-coaxial structural fabrics (Ferranti and Oldow, 1999; Hippolyte et al., 1994; Monaco et al., 1998; Vitale et al., 2019). The Liguride and Lagonegro-Molise basinal rocks display an early generation of ~N-S oriented contractional fabrics, consistent with a Miocene eastward tectonic transport. This early fabric is overprinted and dispersed by late Miocene to early Pleistocene structures with ~WNW-ESE to NW-SE strikes which are found in all pre-orogenic rocks and in Miocene-lower Pleistocene synorogenic deposits. Shortening was accompanied by counterclockwise rotations which ranges from ~20° for the Pliocene-Pleistocene deposits up to ~100° for the pre-orogenic Apenninic Platform and Lagonegro successions (Gattacceca and Speranza, 2007).

2.2. *Tectono-stratigraphic outline*

The northern part of the CLA stretches across the Campania and Lucania regions (Fig. 1b) and is characterized by mountain ranges separated by river valleys. To the southwest, the ranges abruptly pass to the Sele Plain-Salerno Gulf basin (Fig. 2), formed on the thinned crust of the eastern margin of the Tyrrhenian Sea.

In the northern CLA, the Liguride rocks are represented by the Parasicilide imbricate (Vitale et al., 2019), which includes an up to ~1 km thick basinal succession of clays, marls and minor limestones and sandstones spanning an uppermost Cretaceous-Burdigalian age (Fig. 3; Table S1). The Parasicilide rocks crop out within the structural lows of the Sele and Tanagro valleys and along the borders of the Sele Plain (Fig. 2).

The Apenninic Platform Unit is found in the Picentini, Marzano and Alburni Mountains (Fig. 2). In the Picentini Mountains, the up to ~5 km thick platform succession includes Upper Triassic intertidal dolostones and limestones, and Jurassic-Upper Cretaceous shelf limestones (Fig. 3; Table S1). Similar shelf facies rocks crop out in the Alburni Mountains where they are represented by a ~ 2 km thick Middle Jurassic-Miocene succession (Fig. 3: Table S1). In the Marzano massif, the Upper Triassic-Lower Cretaceous shelf succession pass laterally and upward to margin-to-slope rocks (Jurassic-Lowr Cretaceous talus breccia and Upper Cretaceous-Paleocene calciturbidites of the Calcari Cristallini Formation, Paleocene-Miocene Scaglia-like and calciturbiditic deposits; Fig. 3). The thickness of the composite shelf- and margin-facies section in the Marzano massif is variable, and it does not exceed a ~ 1.5–2 km (Table S1). A transition from the shelf to the margin-facies is observed in the northern part of the Picentini range as well, where calciturbidites of the Calcari Cristallini Formation overlay the shallow-water Mesozoic succession (Figs. 2, 3).

Platform margin-to-slope deposits also form the structurally distinct Monte Croce Unit, which is imbricated beneath the shallow-water carbonates and the Lagonegro basin rocks in the Campagna tectonic window at the southern border of the Picentini Mountains (Fig. 2; Pappone and Ferranti, 1995; Patacca, 2007; Patacca and Scandone, 2007c, Vitale et al., 2020a). The few hundred meters thick Monte Croce Unit includes Upper Cretaceous-Aquitanian resedimented limestones and argillites, which pass upward to Serravallian turbiditic sandstones (Fig. 3; Table S3). The Middle Miocene section of both shallow-water (Alburni and Picentini units) and margin (M. Croce and locally Marzano units) successions records the progressive flexural sinking of the platform and the formation of an ancient foredeep basin filled by argillites, marls, and calciturbidites (Fig. 3).

The Apenninic Platform Unit is tectonically superposed on Mesozoic-Cenozoic rocks of the Lagonegro-Molise Basin (Scandone, 1972). The composite basinal succession includes two distinct parts, lower and upper, respectively, which are separated by a regional-scale detachment (Fig. 3). The lower section (Lagonegro Unit) is exposed in few tectonic windows on the southern side of the Picentini Mountains (Fig. 2) and is logged in deep wells beneath the platform carbonates. The Lagonegro Unit consists of a Middle Triassic to Lower Cretaceous succession of argillites and limestones, cherty limestones, radiolarites and silicified argillites, and siliceous shales with calcilutite intercalation (Fig. 3). The stratigraphic thickness is uncertain because of the extreme lateral variability of the primary depositional environments and of the intense deformation that affects this unit. Reconstruction of a composite section in Lucania yields estimations ranging between 1400 and 1800 m (Patacca, 2007), and the observed thickness in the CLA is close to the lower bound (Fig. 3; Table S1). The upper section (Molisan Unit) largely outcrops north of the platform carbonate massifs in the Irpinia foothills (Fig. 2) and consists of Upper Cretaceous-Lower Miocene calciturbidites and pelites (Flysch Rosso Formation), which passes upward and laterally to more distal-facies of varicoloured claystones (Argille Variegate Group). Langhian to Serravallian sandstones cover the Molisan succession. The thickness of the unit is variable and increases northward from few tens of meters up to 200 m or higher (Fig. 3; Table S1).

The detachment between the upper and lower sections of the Lagonegro-Molise Basin is localized along the stratigraphic boundary between the Flysch Galestrino Formation and the Flysch Rosso Fm./Argille Variegate Group (Fig. 3). Northeast of the Marzano massif (S. Fele Ridge, Fig. 2), the Lagonegro and Molisan units are still coupled, although they are repeatedly imbricated.

Pre-orogenic platform and basin assemblages are unconformably covered by the Tortonian-Lower Messinian piggy-back basin deposits (immature sandstones, clays, and carbonate olistoliths) of the Castelvetere Flysch Group. In turn, Upper Messinian-Lower Pliocene sandstones, clays and evaporites (Altavilla Group) and Pliocene-Lower Pleistocene clastic deposits of the Ofanto and Ariano Irpino piggy-back basins unconformably cover the older rocks (Figs. 2, 3).

The tectonic evolution of the northern CLA during the middle-late Miocene was characterized by a series of in-sequence thrusts that progressively propagated across the western margin of Adria. As constrained by the age of the foredeep deposits covering the different Apenninic platform successions (Fig. 3), the Parasicilide unit overrode the Apenninic Platform rocks by the end of the Serravallian, and probably did not completely cover the Marzano Unit where the Laviano Formation deposited until the early Tortonian. The stacked Parasicilide and Apenninic Platform thrust sheets were emplaced above the Lagonegro-Molise Basin during the late Serravallian-early Tortonian. The Castelvetere Flysch deposits largely seal the assemblage between the platform and basinal units (Vitale et al., 2020a).

Between latest Messinian and early Pliocene, the whole thrust stack overrode the western Apulian carbonates, as documented by the youngest foredeep deposits drilled on top of the Apulian unit (Ferranti and Oldow, 2005; Patacca and Scandone, 2007b). A tectonic mélange, formed by imbricated rocks of the Lagonegro-Molise Basin and foredeep deposits of the Apulian Platform is locally interleaved between the Apennine units and the Apulian belt and may attain a thickness of up to 1 km (Butler et al., 2004; Shiner et al., 2004; Mazzoli et al., 2006).

During the Pliocene, deep-seated thrusts formed beneath the CLA and caused the re-imbrications of the previously assembled orogenic stack (Patacca and Scandone, 2007b). These younger structures are regarded as envelopment thrusts (Fig. 3; Pappone and Ferranti, 1995; Vitale et al., 2020a, 2020b) because they rooted within the buried Apulian platform at a deeper level than the previous thin-skinned thrusts. The uplift and over-thickening of the tectonic stack were possibly responsible for the development of low-angle normal faults (LANFs) that thinned the Apenninic Platform succession in the southern Picentini Mountains (Ferranti et al., 1996; Ferranti and Oldow, 1999; Vitale et al., 2020a).

The deep-seated thrusts accompanied to development of the CLA in the Irpinia and Lucania regions, which is characterized by a western, *E*-W striking and an eastern, NNW-SSE striking arm, respectively (Figs. 1b, 2, Nicolai and Gambini, 2007).

During the Quaternary, high-angle faults crosscut the pre-existing thrust structures in the hinterland sector (Figs. 2, 3) and controlled the growth of coastal and intermountain basins filled with transitional and continental deposits (Ascione et al., 2013; Brancaccio et al., 1991; Brozzetti, 2011; Ferranti and Oldow, 1999). The master faults that cut across the CLA have WNW–ESE to NNW-SSE strike (Fig. 2) and dip-slip or normal-oblique kinematics (Ascione et al., 1992; Bello et al., 2021; Brozzetti, 2011; Maschio et al., 2005; Lavecchia et al., 2024).

3. Data and methods

A dataset of ~50 commercial seismic reflection profiles (unmigrated and stack), for a total length of ~1000 km (Fig. S1) has been interpreted to constrain the upper crustal geometry of the CLA. Most of the seismic reflection profiles, acquired by the oil and gas industry for exploration purposes during the '80-'90, have been made available for this study by ENI E&P under a confidential agreement. Additional seismic reflection profiles, together with logs of deep boreholes, are publicly available within the Italian repository ViDEPI (ViDEPI Project, 2009–2023).

We analysed and reinterpreted the logs of seven wells in the CLA based on the modern understanding of regional lithostratigraphy. We also considered the Puglia 1 well in the Apulia region to further constrain the structure of the Apulian belt beneath the Apennines.

Prior to the interpretation of the seismic reflection lines, a well-to-seismic tie was performed to match the well stratigraphy (depth domain) with the main reflections (two-way travel time domain, TWT). This operation links the main geological markers to seismic horizons to allow understanding the reflective character of the drilled litho-structural units. The well-to-seismic tie was achieved through the generation of a synthetic seismogram (Castagna et al., 1993) using the Petrel software platform.

Usually, synthetic seismograms are generated by combining sonic and density logs, whose product gives an acoustic impedance contrast. Because the density logs are unavailable, synthetic densities using the Gardner equation were calculated (Gardner et al., 1974; Akimbekova et al., 2024). We generated synthetic seismograms by convolving the seismic wavelet with the acoustic impedance log. Several test are made using different types of wavelet (e.g., a conventional Ricker wavelet), but the best match between synthetic and experimental traces is obtained via a statistical extraction algorithm using five traces surrounding the well, for each seismic profile. To improve this match, a TWT bulk shift was applied manually in the absence of check-shots to reduce some mis-ties, which gave satisfying results considering the regional scale of our analysis.

Beside well data, the seismic profiles interpretation was largely based on information derived from geological and structural maps at various scales. The used cartography includes: i) detailed maps (1:50.000 or lower scale) published in research papers (Ciarcia et al., 2009; Ferranti and Oldow, 1999; Vitale et al., 2020a); ii) the official Geological Map of Italy series at 1:50.000 and 1:100.000 scale and accompanying reports (http://portalesgi.isprambiente.it/en/publications/geological-maps; the maps used in this work are listed in the Reference under the "Servizio Geologico d'Italia" label); and iii) 1:250.000 scale regional syntheses (Carta Geologica dell'Appennino Meridionale: Bonardi et al., 1988; Geological map of Campania Region: Vitale and Ciarcia, 2018). We also based our interpretation on several unpublished mapping projects carried out by us in the area through the years.

From the maps we built geological cross sections along the trace of the interpreted seismic profiles to extrapolate surface information at depth. In addition, the uppermost part of the geological profiles was locally constrained using information from shallow boreholes available from the national database of ISPRA (Servizio Geologico d'Italia, 2017) or from research papers (Celico, 1979). For the deep section, the extrapolation of stratigraphic and thickness data was calibrated using information from industrial wells.

The interpreted seismic profiles were depth-converted using the velocity model obtained combining the sonic log velocity data of the boreholes in the study area and literature data (Improta et al., 2000, 2003; Valoroso et al., 2009; Akimbekova et al., 2024).

4. Results

4.1. Well log analysis

4.1.1. Well logs interpretation

We provide in this section a detailed stratigraphic-structural interpretation of seven wells (Acerno 1, Ciccone 1, Contursi 1, Roccadaspide 1, San Fele 1, San Gregorio Magno 1, and Taurasi 1, Figs. 2 and 4). Wells Contursi 1, Roccadaspide 1, S. Gregorio Magno 1, and S. Fele 1 were previously described by Cippitelli (2007), and more detailed lithostratigraphic and biostratigraphic information of wells Acerno 1, S. Gregorio Magno 1, and S. Fele 1 were provided by Patacca (2007). Only general interpretations exist for well Taurasi 1 (Improta et al., 2003; Servizio Geologico d'Italia, 2009b; Servizio Geologico d'Italia, 2009a). A summary of these wells is provided here, outlining agreements and differences between our and previous interpretations. A detailed description and interpretation of the wells is found in Table S2.

The Acerno 1 well was drilled in the southern part of the Picentini Mountains (Fig. 2). After crossing ~300 m of Upper Triassic dolostones of the Apenninic Platform, the well drills ~200 m of Lagonegro rocks (Calcari con Selce Fm.) and then ~800 m of marginal dolostones and overlying siliciclastic deposits pertaining to the M. Croce Unit. In turn, the M. Croce rocks overlie four imbricates of the Lagonegro-Molise Basin, locally involving a few tens of meters of Middle-Upper Miocene sediments, for a total thickness of >3200 m (Fig. 4). The detached Lagonegro-Molise Basin stack surmounts the Apulian Platform, represented by ~80 m of Messinian evaporites, disconformably overlying Lower Cretaceous shallow-water limestones.

The Ciccone 1 well is located in the western side of the Ofanto basin in Irpinia (Fig. 2). The upper part of the well found 200 m of Pliocene deposits before drilling ~2.2 km of clays and minor sandstones and limestones of the Argille Variegate Group (Molisan basin, Fig. 3). The allochthonous rocks, which form a chaotic complex, rest above 125 m of Lower Pliocene silty clay and limestone breccia that represents the cover of the Apulian Platform. The bottom section of the well is formed by ~200 m of Upper Cretaceous-Paleocene Apulian limestones (Fig. 4).

The Contursi 1 well was drilled in the Tanagro Valley, a structural low between the Mt. Marzano and the Alburni Mts. (Fig. 2). Below ~100 m of Quaternary deposits, the well drilled through ~900 m of scaly clays with sandstones and mixed siliciclastic-limestone levels of the Parasicilide succession (Figs. 3, 4), which structurally overlies ~500 m of

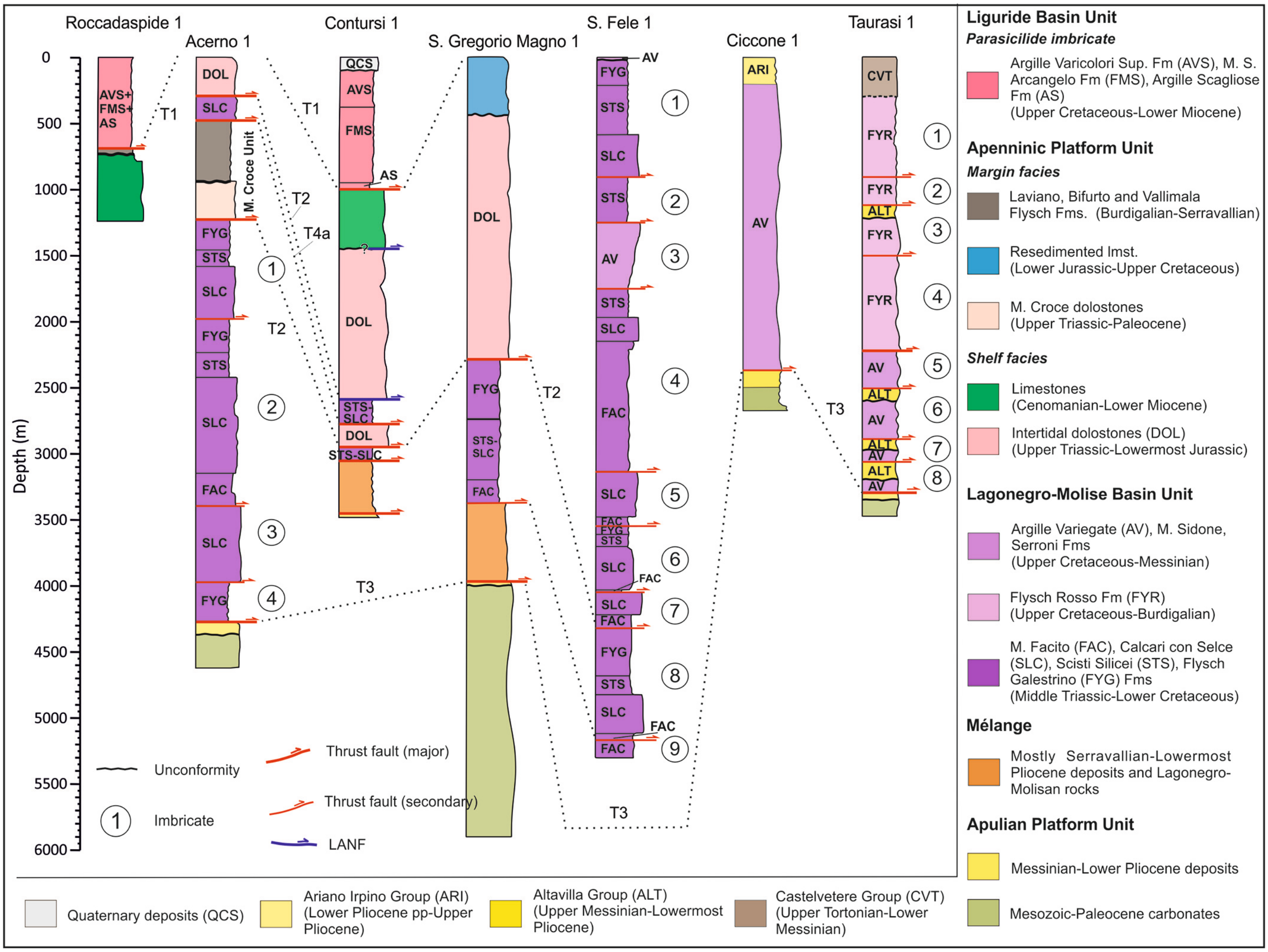


Fig. 4. Logs of the wells analysed in this paper (location in Fig. 2; see Table S2 for a detailed description and interpretation of the well logs). Circled numbers identify individual imbricates within the Lagonegro-Molise Unit.

Cretaceous carbonates and ~ 1.1 km of Upper Triassic intertidal dolomites. According to Ferranti and Oldow (1999) and Cippitelli (2007), the contact between Cretaceous and Triassic sections, characterized by the omission of the Jurassic section, is a low-angle normal fault. Below the Triassic platform rocks, the well encountered ~200 m of undated scaly clays with intercalations of marly limestones and cherty dolomitic limestones that, in agreement with Cippitelli (2007), we interpret as part of the Lagonegro Unit. Resting below this section, the well drilled through ~200 m of Upper Triassic dolomite with occasional layers of dark clays. Whereas Cippitelli (2007) doubtfully considers this interval as part of the Lagonegro succession, we attribute it to the Apenninic Platform (likely the base of the M. Croce Unit, Fig. 3) inverting, as in the Acerno 1 well, the expected structural relation between platform and basin rocks. The following ~500 m of undated section, whose upper part (100 m) is represented by scaly clays with intercalation of marly limestones, is attributed to the Lagonegro Unit. In the remaining part of this section, the above rocks are interleaved with evaporite levels suggesting the presence of a mélange of Lagonegro rocks and Messinian deposits. This interpretation largely agrees with Cippitelli (2007), who refers this ~500 m thick section to a Miocene chaotic complex. The well ended at ~3.5 km in a few meters of Upper Miocene polygenic breccia with evaporite inclusions (Fig. 4).

The Roccadaspide 1 well is located in the southwestern sector of the Alburni Mts. (Fig. 2). The well firstly penetrated ~700 m of Upper Eocene (?)-Aquitanian clays and marls with interbeds of limestones and sandstones of the Parasicilide imbricate. According to Cippitelli (2007), only the uppermost ~100 m belong to the Parasicilide imbricate, whereas the remaining section represents the Middle Miocene Cilento Flysch Group that in outcrop rests unconformably on the Parasicilide rocks (Fig. 3). Below the Parasicilide imbricate, the well drilled through a ~ 50 m thick shaly-silty complex with minor sandstone intercalations to which Cippitelli (2007) assign a Burdigalian age. This section corresponds to the Bifurto Formation, the uppermost stratigraphic level of the Apennine Platform (Fig. 3; Table S2), and in the well it overlies ~500 m of Upper Cretaceous-Lower Eocene platform carbonates (Fig. 4).

The S. Gregorio Magno 1 well was drilled in the southern part of the Marzano massif (Fig. 2). The upper ~2.3 km are represented, following the interpretation of Patacca (2007), by Middle Jurassic-Cretaceous slope carbonates and intertidal Upper Triassic dolomite of the Apenninic Platform Unit. Patacca (2007) attributes the sharp contact between the Middle Jurassic and the Upper Triassic strata to a normal fault that omits the Liassic section, consistent with our interpretation of the Contursi 1 well. The Apennine Platform succession overlies ~1.1 km of Lagonegro rocks, which are followed by ~600 m of additional basinal rocks. The latter section is composed of calcareous sandstones with minor marly clays, pelagic limestones, and includes levels of Upper Triassic cherty limestones of the Lagonegro Unit, and Lower Cretaceous shales of the Molisan Unit. In the log, these basinal deposits were related to the Lower-Middle Miocene Serrapalazzo Fm., the foredeep of the Lagonegro-Molise Basin (Fig. 3). However, Patacca (2007) interpreted the basinal deposits as a Lower Pliocene wildflysch, which includes olistostrome of Lagonegro-Molise basin rocks, deposited on top of the Apulian carbonates, as recognized by several drillings in the subsurface of the Lucania region. We refer the 600 m thick basinal deposits to a tectonic mélange, mostly formed at the expense of Lagonegro rocks incorporated within Miocene and possibly Lower Pliocene deposits, which elsewhere in the southern Apennines form the base of the thin-skinned allochthon (Fig. 4; Butler et al., 2004; Shiner et al., 2004; Mazzoli et al., 2006). The mélange complex overlies ~20 m of Upper Messinian evaporite, which lies disconformably on ~1.9 km of Jurassic-Cretaceous Apulian limestones.

The San Fele 1 well is located at the hinge of the CLA frontal ramp (Fig. 2) and drills through an antiformal stack of Lagonegro-Molise basin rocks for a total thickness of ~5200 m, without reaching the base of this unit. The interpretation of the San Fele 1 well log provided by Patacca (2007) and Cippitelli (2007) shows at least seven repetitions of Lagonegro rocks, with interleaved slice(s) of Paleogene-Miocene Molisan rocks. We defined in the log nine individual Lagonegro-Molise imbricates with uneven thickness, and only two of them (imbricates 4 and 8) preserve a near complete Lagonegro Unit stratigraphy, which in this area is representative of the more proximal part of the basin (San Fele facies, Scandone, 1972; Figs. 3, 4). Following previous interpretations, imbricate 3 is considered as a slice of Paleogene-Neogene Molisan rocks sandwiched between Lagonegro imbricates. Whereas the middle part of imbricate 4 (between 2146 and 2217 well depth) was related in the log and by Cippitelli (2007) to the Molisan Unit as well, Patacca (2007) considers this interval as the M. Facito-Calcari con Selce transition (Lagonegro Unit). The latter interpretation is supported in the present work.

Well Taurasi 1 was drilled in the western Irpinia area (Fig. 2) and penetrated several imbricates of the Molisan Unit and subordinately Miocene deposits until reaching the upper part of the Apulian Platform (Fig. 4). The uppermost 600 m of the log are unrecovered, but they are likely drilled in the Castelvetere Flysch and underlying Flysch Rosso pelites, as indicated by nearby outcrops. Based on the stratigraphic thickness of the Castelvetere Flysch measured in the field (200–300 m: Servizio Geologico d'Italia, 2016a), we assign the upper 300 m of the unrecovered section in the well to this formation, and the remaining 300 m to the Flysch Rosso. The following log section penetrates through silty clays, sandstones, and calcilutites assigned to the Flysch Rosso, which forms two distinct imbricates resting on the Upper Messinian clay and evaporite of the Altavilla Group at ~1.1 km depth. The Miocene deposits cover two additional imbricates of the Flysch Rosso down to a major thrust fault at ~2.25 km depth. The following ~1.1 km thick section drills through the more distal succession of the Molisan basin and includes four thin (from ~200 to ~400 m) imbricates, each made of Argille Variegate and Altavilla deposits. Below the imbricate 8, at a depth of ~3.3 km, the well encountered ~50 m of Messinian-Lower Pliocene mudstone and gypsum (largely age-equivalent to the Altavilla Formation) overlying ~100 m of Upper Cretaceous carbonates of the Apulian Platform (Fig. 4).

4.1.2. Wells to seismic ties

Four wells (San Gregorio Magno 1, Taurasi 1, San Fele 1, Acerno 1) with available sonic logs were used to match the stratigraphic markers with seismic reflections through the creation of synthetic seismograms, and to identify the main seismic horizons. The results show different degrees of well-to-seismic ties (Fig. S2), which range from good (San Gregorio Magno 1 and Taurasi 1 wells) to fairly good (Acerno 1 well), to poor (San Fele 1).

Comparing the generated synthetic versus real seismic traces, we relate the strongest acoustic impedance response in the seismic profiles to the top of the Apulian Platform and overlying Upper Miocene-Lower Pliocene foredeep terrigenous deposits (Fig. S2). Near the top, Apulian carbonates are generally seen as strong to medium-strength, low-frequency reflections in wells San Gregorio Magno 1, Taurasi 1 and Acerno 1.

The Lagonegro-Molise successions encountered in Acerno 1, Taurasi 1, San Gregorio Magno 1 and San Fele 1 wells contain interbeds of clays, sandstones, marls, and pelagic carbonates. These interlayers generate alternating acoustic impedance contrasts within the unit and correspond to semi-continuous, mid- to high-amplitudes seismic reflections.

The sonic log of the Apenninic Platform carbonates was registered only in the San Gregorio Magno 1 well. The base of the unit is readily distinguished by a very strong reflection at 2193 m TVD (0.6 s), which represents a marked contrast generated at the contact between the lower-velocity (4500–5500 m/s) Lagonegro basin rocks and the faster-velocity (5500–6000 m/s) Apenninic platform carbonates.

The final synthetic seismograms were then matched to the seismic lines. The example of Fig. S2 shows the seismic line and the final synthetic seismograms along the Taurasi well, where the top of the Apulian carbonates exhibits a blue, hard and positive reflection on the seismic lines.

It should be noted that some discrepancies could arise because of the variable quality of the digitized logs, not calibrated to a check shot survey, and of the vintage seismic data. Nevertheless, we consider that the tying of the well formation tops to seismic data afforded here is convenient for our regional scale analysis.

4.1.3. Velocity model and depth conversion

The velocity model used for the depth conversion of the interpreted seismic profiles is defined by combining velocities sourced from literature (Improta et al., 2000, 2003; Valoroso et al., 2009; Akimbekova et al., 2024) and velocity logs available from the studied wells. The assigned velocities are reported in Table S3.

We adopt here a heterogeneous 2D velocity model accounting for the structural complexities, thus enabling a more accurate depth conversion of the interpreted profiles (Fig. S3). Our primary input consisted of three interpreted horizons in the time domain (Top Apenninic Platform, Top Lagonegro, Top Apulian), and a fourth one (Base of Apulian platform) reconstructed using the isopach technique, i.e. assuming a constant thickness for the Apulian Platform. The average thickness of the Apulian sediments (top at 1.8 s TWT) was obtained from the Puglia 1 well (Fig. 1b; Table S2) and is interpreted down to about 4 s (TWT) with a wide antiformal geometry. On top of that, we incorporated further complexity by introducing a horizontal velocity change in the northern interpreted lines, assigning 3800 m/s to the shallowest interval, which represents the Molisan Unit.

4.2. Seismic profiles analysis

4.2.1. Seismostratigraphic scheme

We have interpreted the seismic profiles based on seismic facies analysis (Xu and Haq, 2022) calibrated through the well-to-seismic tie, and considering regional (Nicolai and Gambini, 2007) and local (Improta et al., 2000) seismostratigraphic schemes. The analysis led to the identification of nine seismic units characterized by distinctive seismic facies (Fig. 5). The seismic facies were defined using a qualitative approach because the displayed amplitudes were not correctly restored but they were used to enhance the coherent reflections (e.g., on the CROP-04 line). Therefore, the relations with the petrophysical/lithological factors may be not completely reliable (Mazzotti et al., 2007). Because of the complex structural setting and the presence of both detached pre-orogenic units and para-autochthonous synorogenic deposits, many of the identified seismic facies are irregularly stacked and laterally discontinuous.

The uppermost seismic unit corresponds to the siliciclastic deposits of the Castelvetere Flysch (CVT), which is imaged for up to 0.5 s (TWT) in the Irpinia region. The CVT seismic facies is characterized by medium to low amplitude, high-frequency, discontinuous or chaotic reflections (Fig. 5). In the uppermost part, this seismic unit locally includes Pliocene-Quaternary deposits.

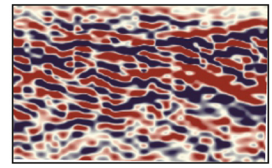
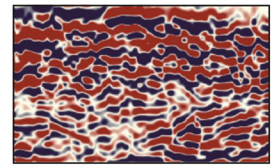
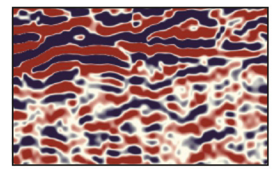
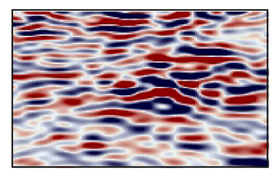
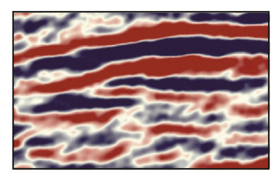
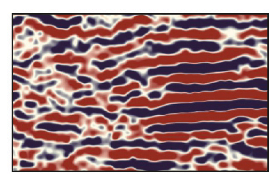
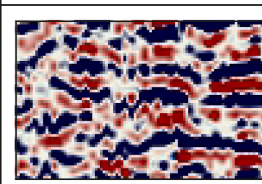
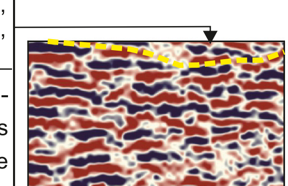
UNIT		LITHOLOGY	GEOMETRY	SEISMIC FACIES
CASTELVETERE (CVT)		Massive to crudely bedded sandstones with intercalation of clays, polygenic conglomerates, calcareous olistoliths and claystone olistostromes. Calcareous conglomerates and breccias at base.	Medium- to low- or very low amplitude, high-frequency, discontinuous or chaotic reflections.	
PARASICILIDE (PSC)		Argillites and claystones, with intercalations of marls, calcilutites and fine sandstones; mid- to coarse sandstones in the upper part.	Medium- to high-amplitude, low-frequency, semi-continouos or chaotic reflections.	
APENNINIC PLATFORM SHELF (APN-S)		Calcilutites and calcarenites, passing downward to dolostones and dolomitic limestones; locally marls.	High-amplitude, low-frequency, continuous reflections becoming low-amplitude and discontinuous to chaotic downward.	
APENNINIC PLATFORM MARGIN (APN-M)		Carbonatic conglomerates and breccias with local marls and clays intercalations, passing downaward to dolostones and dolomitic limestones.	Medium-amplitude, high to medium-frequency, semi-continuous reflections becoming discontinuous to chaotic downward.	
MOLISAN (MOL)		Argillites, claystones and marls with intercalations and heteropic passage to calciturbidites; sandstones in the upper part.	High-amplitude, very low-frequency and continuous reflections alternated with low-amplitude discontinuous, and chaotic to complex-layered reflections.	
LAGONEGRO (LAG)		Argillites, calcilutites, and sandstones with massive limestone inclusions, passing upward to cherty limestones, to radiolarites and silicified argillites, to siliceous shales with pelite intercalations.	Medium- to high amplitude, high- frequency and continuous reflections; toward the NE reflections become progressively low amplitude and chaotic to complex-layered.	
TECTONIC MELANGE (MLG)		Mélange of sandstones, breccia limestones, evaporites and clays.	Low- to medium amplitude, discontinuous and complex-layered or chaotic reflections.	
APULIAN	(FMP)	Clays, silts, conglomerates and evaporites.	Low-medium amplitude, medium frequency, semicontinuous.	
	(APL)	Calcilutites and calcarenites, passing downward to dolostones and dolomitic limestones, and to evaporites.	High-amplitude, low-frequency continuous reflections, that become low-amplitude, semi-continuous to discontinuous downward (lower part).	

Fig. 5. Chart of the seismic units and correlation with the main lithotectonic units of the Campania-Lucania Arc.

The seismic unit corresponding to the Parasicilide Unit (PSC) is imaged to a limited extent for a few tens of ms (TWT) in the southern part of the Marzano massif and in Tanagro Valley. The PSC unit is generally characterized by semi-transparent or chaotic facies related to the high clay content (Argille Scagliose and Argille Varicolori Superiori formations). Some sparse and laterally discontinuous, moderate to high amplitude reflections within this unit may correspond to the sandstones and marly limestones levels of the M. S. Arcangelo Fm. (Figs. 3, 5).

The Apenninic Platform Unit (APN), which is found in the first ~1 s (TWT) of most of the seismic profiles, is here divided in two seismic sub-units, the shelf (APN-S) and the margin (APN-M) respectively, according to their lithological differentiation (Fig. 3). The APN-S sub-unit corresponds to the Alburni and Picentini inner platform successions (Fig. 3), and is characterized by continuous, high- to moderate-amplitude and low-frequency reflections in the upper part. The APN-M sub-unit corresponds to the Mt. Croce and Marzano successions (Fig. 3) and is characterized by lateral transitions from high- to low-frequency reflections, probably due to the irregular contacts between slope mudstones and massive resedimented carbonates, respectively. Downward, reflections become more discontinuous and show a lower amplitude and higher frequency; they are associated with the Upper Triassic tidal dolomites common to both the shelf and margin domains of the platform (Fig. 3).

We subdivide the Lagonegro-Molise Basin Unit in two seismic units, corresponding to the Molisan (upper) and Lagonegro (lower) units (Fig. 3). The Molisan seismic unit (MOL) is imaged in the western Irpinia area for over 1 s (TWT). The unit is characterized by discontinuous, often chaotic reflections, which are related either to the prevailing clay lithology of the Molisan succession or in part to Miocene pelites imbricated within the Molisan deposits as documented by Taurasi 1 well. The chaotic facies passes laterally to high-amplitude, low-frequency, and continuous reflections (Fig. 5), which are attributed to the limestone layers of the Flysch Rosso and/or to tectonic intercalations of evaporite layers of the Altavilla Group (Taurasi 1 well, Fig. 4).

The Lagonegro seismic unit (LAG) has variable thickness, which typically increases northward from 0.6 to 0.8 s to 1.5 s (TWT). The maximum thickness is over 2 s (TWT) in the Irpinia area. The seismic facies of the LAG unit below the Picentini and Marzano ranges generally displays mid-high amplitude, very high-frequency, and rather continuous reflections. However, this seismic facies locally passes to low-continuity reflections with medium-low amplitude and with complex-layered, often chaotic geometry. In the Irpinia area, the LAG unit displays some high-amplitude, low-frequency reflections as well. As documented by the San Fele 1 well and by outcropping successions in the San Fele ridge, these latter reflections may correspond to the massive dolomites and to the thickly bedded cherty limestones that represent the proximal facies of the Calcari con Selce and Scisti Silicei formations, respectively (San Fele facies, Fig. 3; Scandone, 1972).

Along the southern profiles (SP4, SP5 and CROP-04) we assign a group of seismic reflections to the tectonic mélange (MLG) mainly based on the well data. The MLG facies shows reflections characteristics like those of the MOL facies but is more chaotic and complex-layered and shows a larger low-amplitude content. The seismic characters likely reflect the extent of tectonic disruption and the interleaving of Mesozoic-Cenozoic rocks of the Lagonegro-Molise basin within Upper Miocene and Pliocene sandstones, pelites and evaporites, as documented by Contursi 1 and S. Gregorio Magno 1 wells (Figs. 4, 5).

The deepest seismic unit corresponds to the Apulian Platform, which is encountered in all the seismic profiles. The unit is subdivided in two sub-units, labelled FMP (upper) and APL (lower). FMP displays variable seismic characters, ranging from low to medium amplitude, medium-frequency reflections with semi-continuous geometry (Fig. 5). This seismic facies is attributed to drilled Messinian evaporites and/or Lower Pliocene clays sandstones and locally conglomerates, which represents the foredeep cover of the buried platform (Fig. 3). The continuity of FMP is imaged with difficulty because of the limited resolution of seismic data and relatively low thickness, but it seems to have a variable lateral extent.

The underlying seismic facies (APL) exhibits high-amplitude, low-frequency, continuous reflections in the upper part. Reflections rapidly decrease in amplitude and degree of continuity moving downward. The APL facies is attributed to the Mesozoic carbonate succession of the Apulian platform. The top of the platform corresponds to a marked increase in amplitude and decrease in the frequency of reflections, along with a sharp change in reflections geometry from layered-parallel above to parabolic below. This feature probably occurs because of the deposition of the foredeep deposits (unit FMP) above an irregularly shaped, faulted carbonate bedrock.

4.2.2. Seismic profiles interpretation

Three profiles (SP1 to SP3) cross the Picentini Mountains in the western part of the CLA. Profiles SP4 and SP5 lie in the eastern part of the arc across Mt. Marzano. The fifth and easternmost profile is a portion of the CROP-04 line, which extends from the Alburni to the San Fele ridge across the Tanagro valley and Mt. Marzano. Detailed geological maps were used to build the geological sections along the trace of the profiles (Fig. 6a, b). Geological units in the sections are labelled according to Fig. 6a and b, and seismic units identified in the seismic profiles are labelled following the scheme of Fig. 5.

The major thrusts traced in the seismic profiles are numbered following an order that considers the timing of nucleation and the present structural position (from the older to the younger and from the upper to the lower; Fig. 7). T1 is the sole thrust of the Parasicilide imbricate, T2 represents the overthrust of the Apenninic Platform above the Lagonegro-Molise basin and is characterized by two main splays, T2a and T2b. T3 is the basal tectonic contact of the Lagonegro-Molise Basin above the Apulian Platform. The thrusts affecting the Apulian Platform are labelled with T4a-f and grouped in two sets, internal and external, respectively. Each T4 thrust has specific letters (i.e., T4a) designating their position from the hinterland toward the foreland. In the following description, the distances are referred to the SW end of each line.

4.2.2.1. Profiles SP1, SP2 and SP3. These profiles traverse the western Picentini Mountains (Figs. 6a, 8a to 8c) with a length that varies from ~14 km (SP3) to ~30 km (SP1 and SP2). The structurally highest Apenninic Platform thrust sheet reaches a thickness of up to 1.4 s (TWT). The thrust sheet is composed of shallow-water successions (seismic unit APN-S), as constrained by field data. The projection of the Acerno 1 well in profile SP3, although quite distant (12 km), suggests that margin-slope facies deposits of Mt. Croce stratigraphic unit (seismic unit APN-M) may be present in the western part of the profile (km 0–1) resting structurally beneath a thin (~200 m) slice of Lagonegro rocks which in turn underlie the shelf succession of unit APN-S (Figs. 4, 8c).

Based on field constraints, we interpret the Lagonegro slice as floored by a thrust and limited above by a low-angle normal fault (Fig. 8c). Likewise, a low-angle normal fault is traced in the Apenninic shelf succession, where it juxtaposes Cretaceous over Triassic rocks (profile SP2, km 3; profile SP3, km 7).

The Apenninic Platform thrust sheet has a hanging-wall flat geometry and ramps across the MOL Unit at the northern border of the Picentini Mountains, where it is associated to a frontal anticline (profile SP2, km 20–24). In profile SP1, which runs across the foothills immediately west of the Picentini Mountains, the frontal ramp is traced underneath the MOL and CVT units between km 4–6 (Fig. 8a). In map view, the trace of the frontal ramp is curvilinear and steps back west of the mountain range (Figs. 2). The ramp in profile SP2 represents the Western Picentini Frontal Thrust (WPFT), which continues to the east as the Eastern Picentini frontal thrust (EPFT) and at the Marzano Massif as the Laviano thrust (LT) (Fig. 2). The less advanced ramp in profile SP1 is part of a different segment of the thrust front, which borders the eastern

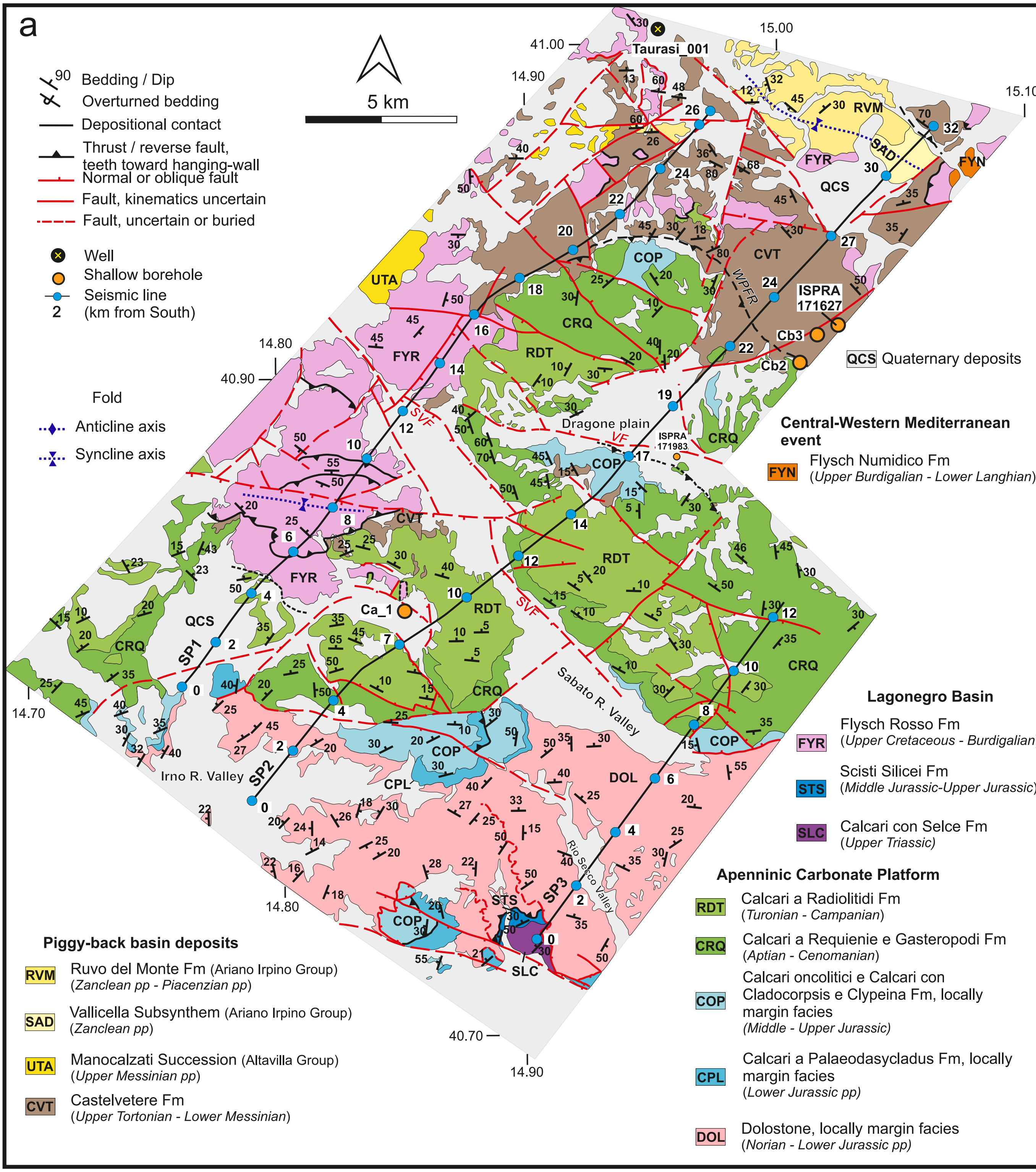


Fig. 6. Detailed geological maps of the western and eastern sectors of the Campania-Lucania Arc: a) Picentini Mountains sector, mostly based on Geological Map of Italy 1:50.000 scale - sheets 432 Benevento, 449 Avellino, 450 S. Angelo de' Lombardi, 467 Salerno (Servizio Geologico d'Italia, 2009a, 2009b, 2016b, 2016c); b) Marzano-Alburni sector, mostly based on Geological Map of Italy 1:100.000 scale - sheets 186 S. Angelo de' Lombardi, 187 Melfi, 198 Eboli (Servizio Geologico d'Italia, 1970b, 1970c, 1970d) and on Geological Map of Italy 1:50.000 scale - sheets 486 Eboli, 451 Melfi (Servizio Geologico d'Italia, 2010, 2016a).

side of the Partenio and Lauro mountains (Partenio-Lauro Thrust, PLT, Fig. 2). It is not established whether the two thrust segments (PLT and WPFT) are connected by a transfer fault or by a diffuse system of relay ramps.

In profile SP2, the frontal ramp of T2 appears sealed by the Castelvetere Flysch. However, the shallow boreholes Cb1-Cb2 and Cb3 document a different thickness and elevation of the Castelvetere Flysch in the hanging-wall and in the footwall of the thrust ramp (geological

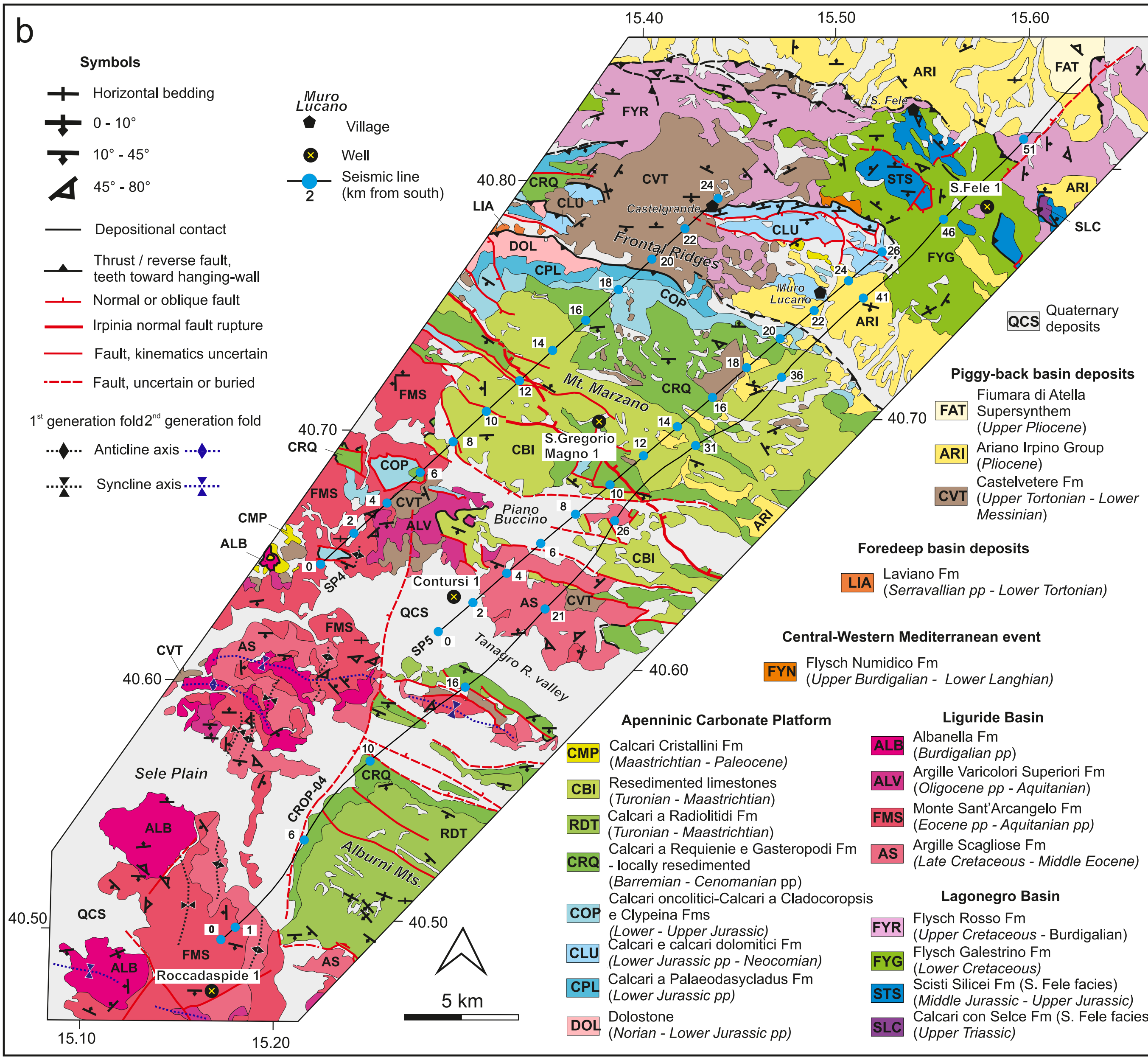


Fig. 6. (*continued*).

section in Fig. 8b). This suggests that the fault may have been active also during or after deposition of the flysch.

A thrust within the Apenninic Platform unit whose upper tip is imaged at km 17 in profile SP2 could be interpreted as a splay thrust (T2b) connected to the T2 basal surface (Fig. 8b). The Castelvetere Flysch is found extensively in the footwall of this fault north of the Dragone Plain basin, and only in small patches in its hanging-wall at the southern flank of the basin (Fig. 6a). Like for the frontal ramp of T2, the different thickness and elevation of the flysch in the hanging-wall and footwall of T2b (geological section in Fig. 8b), suggests that T2b could have been active also during or after the flysch was deposited. However, some unknown amount of throw could be due to slip on the Volturara normal fault (Fig. 6a) during the Quaternary.

The LAG Unit underneath the Apenninic thrust sheet has a thickness of 0.8–1 s (TWT) and, based on truncation of reflectors and calibration of profile SP3 by the Acerno 1 well, is subdivided into three imbricates stacked on low-dipping thrusts (Figs. 4, 8a to 8c). A NE-dipping detachment between the LAG and MOL units is traced in the central part of profiles SP1 and SP2 and limits the northward tapering of the LAG Unit (Fig. 8a, b). This detachment corresponds to the regional detachment between the two stratigraphic sections mapped elsewhere in the southern Apennines (Figs. 3).

In profiles SP1 and SP2, the MOL Unit forms a stack of multiple imbricates and duplexes with a total thickness > 2 s (TWT). Major thrusts bounding the imbricates are imaged based on abrupt seismic facies changes and reflectors truncation, with secondary fault splays limiting individual horses within duplexes. Most of these thrusts are bended, suggesting they were deformed after their development. The faults traced in the seismic profiles show a correlation with the thrusts that bound individual imbricates in the Taurasi 1 well. Based on the well log, we infer that the upper half of the imbricated stack is composed of the Flysch Rosso, while the lower half includes imbricates of the Argille Variegate (MOL-FYR and MOL-AV, respectively, in Fig. 8a, b). Overall, the thickness of individual imbricates, which can be regarded as the maximum thickness of an unbroken stratigraphic succession, does not exceed 0.3 s (TWT).

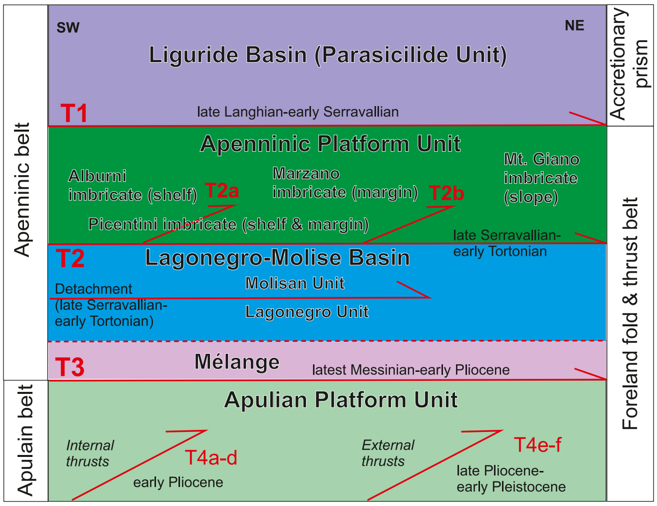


Fig. 7. Tectonic units and thrust hierarchy and nomenclature in the Campania-Lucania Arc.

Both the LAG and MOL units rest on the APL Unit along thrust T3 at depths between 1.5 and 2 s (TWT). A thin (~0.1 s TWT) interval of low-amplitude, semicontinuous reflectors (FMP) is found in the uppermost part of the APL unit just below T3 and is correlated to the Upper Miocene-Lower Pliocene foredeep deposits covering the Apulian carbonates in the Taurasi 1 and Acerno 1 wells (Figs. 8a to 8c). Slight thickness changes observed in the FMP unit suggest the existence of local unconformities that separate the Miocene-Pliocene deposits from underlying carbonates.

The APL Unit is characterized by wide (~6–10 km wavelength), NE-verging anticlines that are mirrored by folds affecting the overlying LAG, MOL and APN thrust sheets. The anticlines are limited on their forelimb side by high-angle thrusts (T4b to T4e-f) that mostly flatten out within the LAG and MOL units. Some of these thrusts are projected to within the Taurasi 1 well, and those who emanate from thrust T4e-f toward the bottom of the well do not appear folded pointing to their relative younger age.

In the Irpinia area, the deep structure of the Apulian Unit corresponds at surface to folds that involve synorogenic deposits of the Castelvetere Flysch and Ariano Irpino group (e. g. Taurasi syncline, Fig. 8a, b), suggesting that syncline growth postdates the Early Pliocene.

High-angle faults with a normal component of slip are imaged beneath the intramountain basins filled up by Quaternary alluvial deposits with maximum thickness of ~100 m (Fig. 8a, b). These faults cut the thrust structures with an offset limited to <0.1 s TWT, but for most of them their seismic signature and displacement are not clearly resolved.

4.2.2.2. Profiles SP4 and SP5. The two profiles cross the high valley of the Sele River between ~0–8 km, then the Marzano massif between ~8–20 km and finally a belt of narrow ridges (the Frontal Ridges) elongated parallel to and north of the Marzano for the remaining ~5–7 km (Figs. 2, 6).

In the southwest, Parasicilide rocks that outcrop or are buried beneath the Quaternary alluvial cover of the Sele Valley are detached and emplaced along thrust T1 above the Apenninic Platform, as constrained by outcrops and by calibration thrugh the Contursi 1 well. Both outcrop bedding data and the curvature of reflectors document that the Parasicilide rocks are tightly folded and are locally imbricated by thrusts splaying from T1. However, the near complete Parasicilide section recovered by the Contursi 1 well suggests that the stratigraphy of the thrust sheet is almost preserved at least in the western part of the profiles (Figs. 4, 8d, e). The eastward decrease in thickness of the PSC Unit in both seismic profiles is interpreted as due to a ramp-flat geometry of T1.

The Apenninic Platform thrust sheet extends across the whole profiles' length and emerges in the Marzano massif and at the Frontal Ridges. The thrust sheet is formed by Jurassic-Cretaceous shelf, margin and margin-to-slope facies rocks resting, locally with multiple unconformities, on Upper Triassic-Jurassic intertidal dolomites (APN-M Unit), as documented by outcrops and by the S. Gregorio Magno 1 and Contursi 1 wells (Figs. 4, 6b). The thrust sheet attains an average thickness of 0.8–1 s (TWT), less than in the Picentini Mountains in the west, where platform shelf facies rocks are present throughout the seismic section (Figs. 8a to 8c). In the Marzano range, the APN-M sheet forms a hanging-wall flat above thrust T2, which ramps at the northeast end of both profiles. The leading edge of the thrust sheet is characterized by a triangle zone whose roof backthrust carries the Lagonegro and Molisan rocks above the margin to slope carbonates (Fig. 8d, e). The Castelvetere Flysch appears only slightly involved in the triangle zone.

The APN-M thrust sheet is internally shortened across the Laviano thrust, which brings platform to margin carbonates of Mt. Marzano, which are included here in the Marzano imbricate, above margin-to-slope carbonates of the Frontal Ridges that form the Mt. Giano imbricate (Figs. 6b, 8c, d). The Laviano thrust is interpreted as the outcropping ramp of thrust T2b that likely emanate from T2. The horizontal shortening associated with the Laviano thrust appears limited to few km. The seismic image nicely depicts the hanging-wall ramp testified by the outcrops at the front of the massif (see the geological sections in Fig. 8d, e). The footwall carbonates form 1 km-wavelength anticlines, interpreted as propagation-folds of secondary blind thrust splays (e.g., Vitale et al., 2020a) that are imaged beneath T2b. The Castelvetere Flysch deposits that cover the footwall carbonates are also involved in folding and thrusting, albeit to a more limited extent relative to the pre-orogenic rocks.

The Apenninic imbricates rest on Mesozoic Lagonegro rocks (LAG Unit) that overlay a mélange of undistinguished Miocene and Molisan rocks (MLG Unit), drilled in the S. Gregorio Magno 1 and Contursi 1 wells (Figs. 4, 8d, e). The LAG Unit increases in thickness moving from west to east from ~0.4 to up to 1.8–2.3 s (TWT). Like in the profiles across the Picentini Mountains, this thickness increase is related to the internal imbrication of the basinal rocks beneath and ahead of the Frontal Ridges. Beneath Mt. Marzano, the S. Gregorio Magno 1 well documents the existence of only one, almost stratigraphically complete, Lagonegro thrust sheet, which has an ~0.5 s (TWT) thickness. Although the S. Gregorio 1 well does not record the occurrence of Molisan rocks, it is likely that the thick reflectors package to the northeast of the well involves slices of Molisan rocks as documented by the S. Fele 1 well. The mélange beneath the LAG Unit is imaged based on calibration from the Contursi 1 and S. Gregorio Magno 1 wells and attains a thickness of 0.3–0.5 s (TWT).

At the western end of the profiles, the Contursi 1 well shows that LAG and the overlying APN-M units are duplicated by a thrust fault that in the seismic profiles ramps through the stratigraphic layering (T4a). Like in the Acerno 1 well and in the interpreted Picentini Mountains profiles, T4a cuts across the low-dipping thrust T2 and duplicates the structural section, carrying a thin (~200 m) slice of Lagonegro rocks on Upper Triassic dolostones of the Apenninic Platform (Fig. 4). Thrust T4a possibly roots within the Apulian unit as the parallel thrusts northeast of it (Fig. 8d, e).

The Miocene polygenic breccia with evaporite inclusions drilled at the bottom of the Contursi 1 well is assigned to the MLG Unit, which lies, along thrust T3, above the FMP unit, the synorogenic cover of the Apulian carbonates. The bottom of the well is inferred to reach few tens of ms above T3. Moving to the east, the FMP seismic unit is imaged above the Apulian carbonates relying on the calibration from the S. Gregorio Magno 1 well.

Like in the eastern profiles, the Apulian carbonates (APL) are characterized by large-wavelength anticlines bounded by high-angle thrusts on their forelimb. The major culmination of the APL Unit and of the overlying imbricate stack is centred at ~12–15 km distance beneath Mt. Marzano, where its forelimb is bounded by thrusts T4d1, T4d2 and

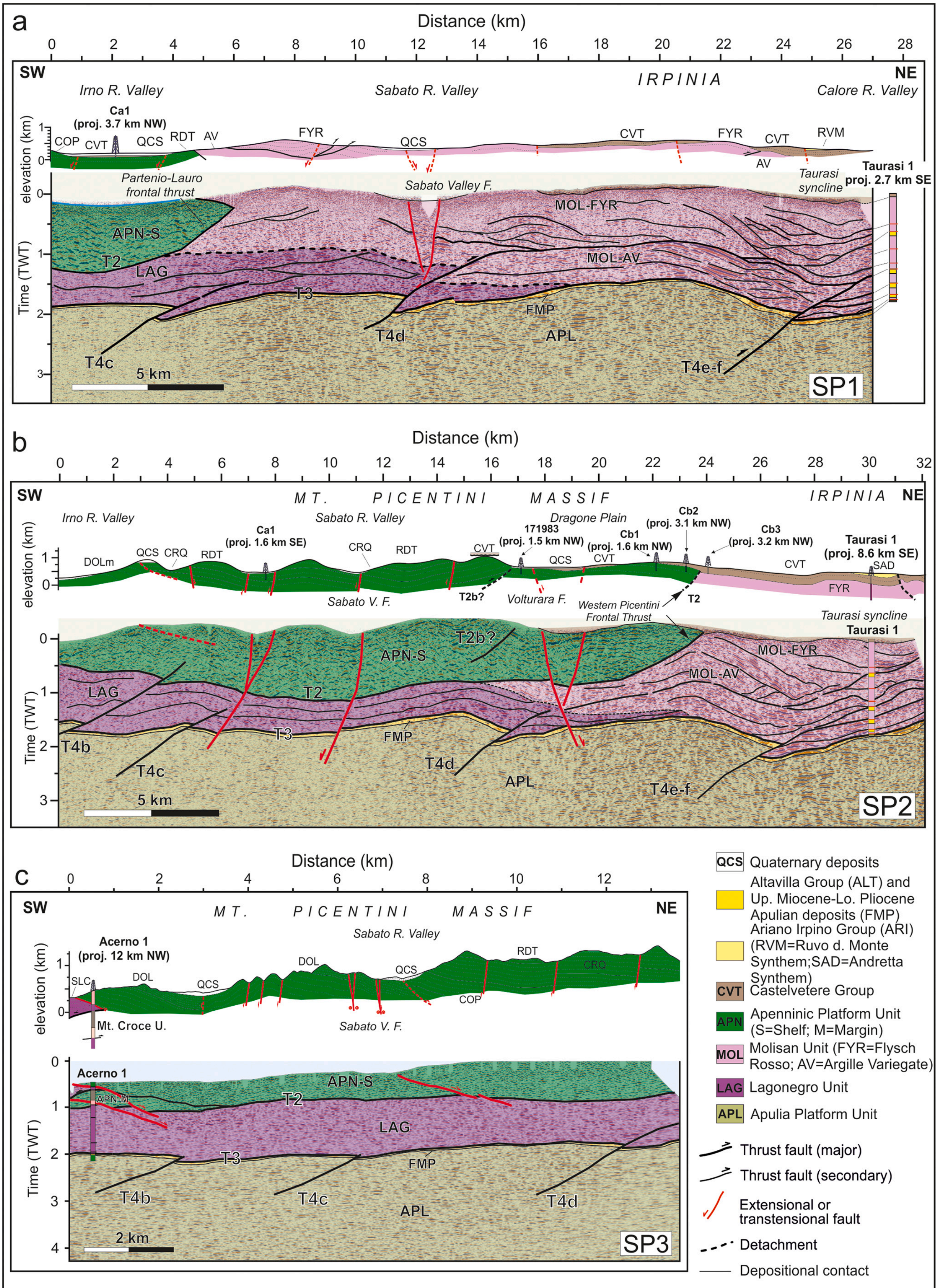

a
Distance (km)
SW
NE
Irno R. Valley
Sabato R. Valley
IRPINIA
Calore R. Valley
Ca1
(proj. 3.7 km NW)
COP
CVT
QCS
RDT
AV
FYR
QCS
CVT
FYR
CVT
RVM
AV
elevation (km)
Partenio-Lauro
frontal thrust
Sabato Valley F.
Taurasi
syncline
Taurasi 1
proj. 2.7 km SE
MOL-FYR
APN-S
T2
LAG
MOL-AV
T3
FMP
T4d
APL
T4c
T4e-f
5 km
Time (TWT)
SP1
b
Distance (km)
SW
MT. PICENTINI MASSIF
IRPINIA
NE
Irno R. Valley
Sabato R. Valley
Dragone Plain
Ca1
(proj. 1.6 km SE)
171983
(proj. 1.5 km NW)
Cb1
(proj. 1.6 km NW)
Cb2
(proj. 3.1 km NW)
Cb3
(proj. 3.2 km NW)
Taurasi 1
(proj. 8.6 km SE)
DOLm
QCS
CRQ
RDT
CRQ
RDT
CVT
QCS
CVT
CVT
SAD
FYR
Sabato V. F.
T2b?
Volturara F.
Western Picentini
Frontal Thrust
T2
Taurasi syncline
Taurasi 1
APN-S
T2b?
MOL-FYR
MOL-AV
LAG
T2
T3
FMP
T4b
T4c
T4d
APL
T4e-f
5 km
SP2
c
Distance (km)
SW
MT. PICENTINI MASSIF
NE
Sabato R. Valley
Acerno 1
(proj. 12 km NW)
SLC
DOL
QCS
DOL
QCS
RDT
CRQ
COP
Mt. Croce U.
Sabato V. F.
Acerno 1
APN-M
APN-S
T2
LAG
T3
FMP
T4b
T4c
APL
T4d
2 km
SP3
QCS Quaternary deposits
Altavilla Group (ALT) and Up. Miocene-Lo. Pliocene Apulian deposits (FMP)
Ariano Irpino Group (ARI) (RVM=Ruvo d. Monte Synthem;SAD=Andretta Synthem)
CVT Castelvetere Group
APN Apenninic Platform Unit (S=Shelf; M=Margin)
MOL Molisan Unit (FYR=Flysch Rosso; AV=Argille Variegate)
LAG Lagonegro Unit
APL Apulia Platform Unit
Thrust fault (major)
Thrust fault (secondary)
Extensional or transtensional fault
Detachment
Depositional contact

Fig. 8. Interpreted TWT seismic profiles, showing on top the geological section: a) line SP1; b) line SP2; c) line SP3; d) line SP4; e) line SP5; f) line CROP-04. Stratigraphic units (see Figs. 6a & 6b for additional information): QCS, Quaternary; RVM, Upper Pliocene; SAD, Lower; Pliocene; ARI, Pliocene; CVT, Castelvetere Flysch (Upper Miocene). Apenninic Platform unit: DBS, Upper Triassic-Lower Jurassic; CLP, Lower Jurassic; CLU; Upper Jurassic; COP, Middle-Upper Jurassic; CRQ, Lower Cretaceous; RDT, Upper Cretaceous (shelf); CBI, Upper Cretaceous (margin). Lagonegro-Molise Basin: LAG, Lagonegro Basin unit; FYG, Flysch Galestrino Formation (Lower Cretaceous); Molisan Unit: FYR, Flysch Rosso Formation (Upper Cretaceous-Paleogene); AV, Argille Variegate Formation (Upper Cretaceous-Miocene). Liguride Basin (Parasicilide unit) (Upper Cretaceous-Miocene): AS, Argille Scagliose Formation; AVF, Argille Varicolori Formation FMS, Monte S. Arcangelo Formation. For the label of seismic unit, see Fig. 5. MOL-FYR, Molisan Unit mostly composed of Flysch Rosso Fm; MOL-AV, Molisan Unit mostly composed of Argille Variegate Fm.

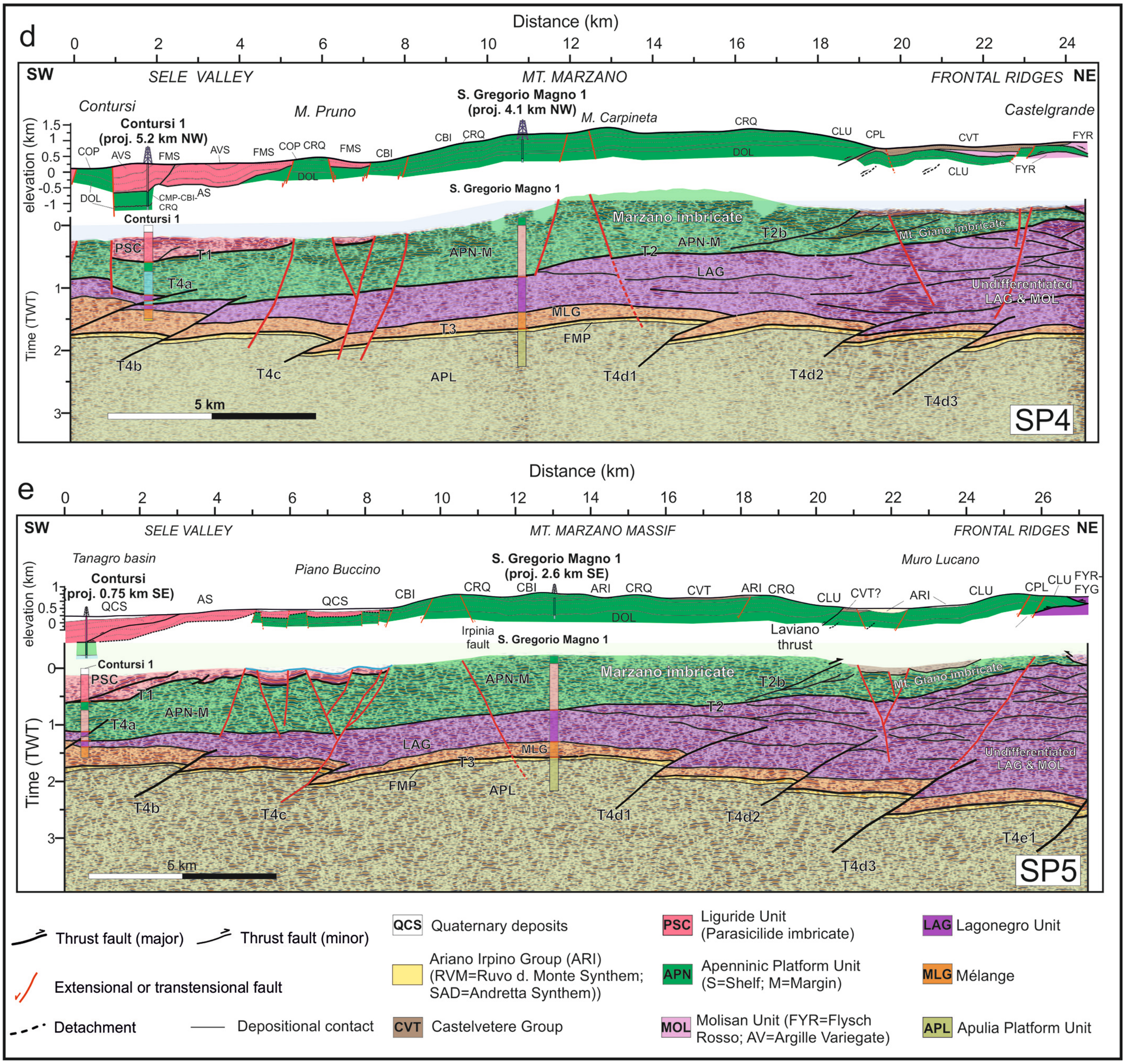


Fig. 8. (*continued*).

T4d3. These thrusts displace thrust T3 and flatten out within the LAG-MOL units. Minor Apulian highs are found between the S. Gregorio Magno 1 and the Contursi 1 wells.

High-angle faults with a normal component displace the Apennine thrust belt with an offset limited to 0.5 s (TWT). The high-angle faults show both SW and NE dip and control the growth of intramountain basins like the Piano di Buccino basin, which is filled by Quaternary deposits. These faults occasionally up-throw the Apenninic Platform rocks in the Contursi and Mt. Pruno structural blocks. In the seismic profiles, most of these faults can be traced down to 2 s (TWT). Whereas some of the normal faults cut across the top Apulian platform, others appear detached along the T4 thrusts.

4.2.2.3. Profile CROP-04. The analysed 54 km long segment of the CROP-04 profile stretches close by and parallel to lines SP4 and SP5, from the Cilento area to the San Fele Ridge, passing by the western flank of the Alburni Mountains, the Tanagro Valley, and the Marzano massif

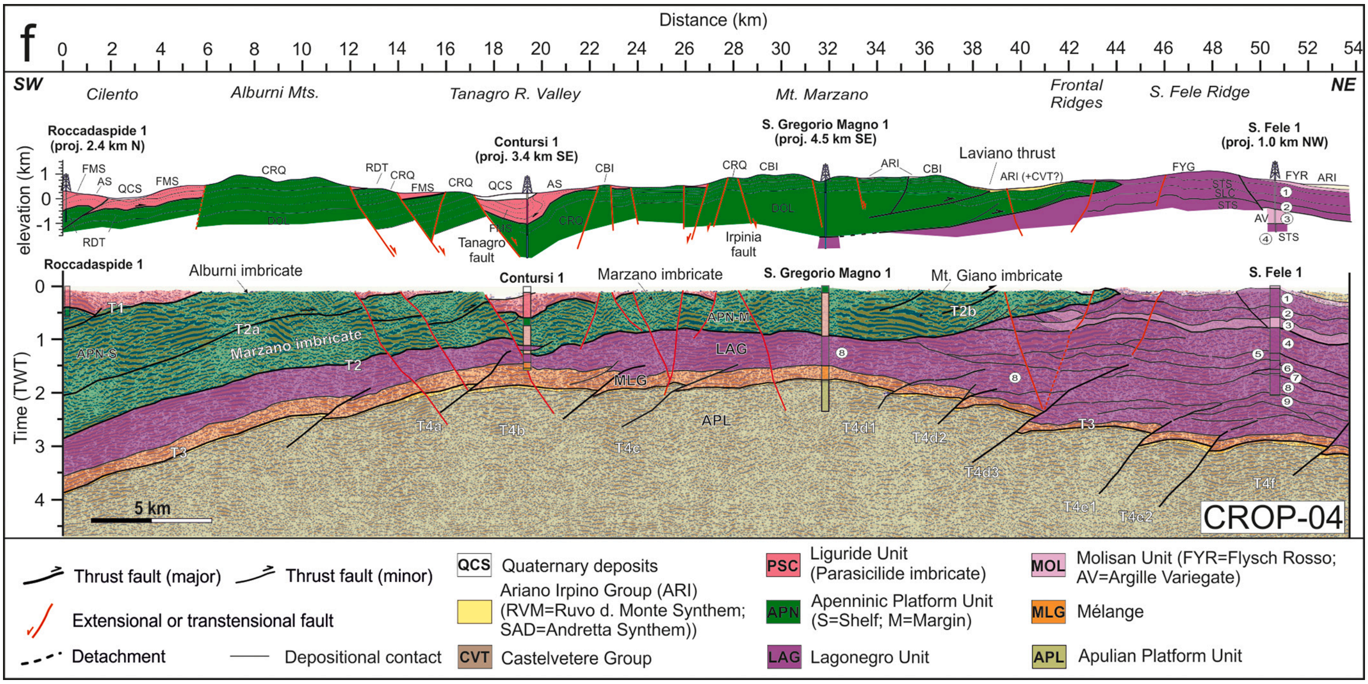


Fig. 8. (*continued*).

(Figs. 2, 6b, 8f).

The PSC Unit is imaged in the southwestern and in the central parts of the profile and its continuity is disrupted by high-angle reverse and normal faults. As recorded by the Roccadaspide 1 and Contursi 1 wells, the unit attains a thickness of 0.7–0.9 km (~0.5 s TWT). Both in outcrop and in the seismic profile, the Parasicilide rocks are characterized by pervasive, short-wavelength (~1 km) folds. The PSC Unit overthrusts the Apenninic Platform carbonates along T1, which ramps above the carbonates east of the Contursi 1 well (Fig. 8f).

The thickness of the Apenninic carbonates decreases from ~2 s (TWT) west of the Alburni Mountains, to an average of 0.7–0.8 s TWT in the Marzano massif. The larger thickness in the southwest is related to a duplication of the Apenninic Platform across thrust T2a, which is regarded as a buried splay of the basal thrust (T2) of the Apenninic thrust sheet. Thrust T2a carries the inner platform succession (seismic unit APN-S) that outcrop in the Alburni massif above the platform margin succession, which is found at Mt. Marzano (unit APN-M). The hanging-wall and footwall units are here referred to as the Alburni and Marzano imbricates, respectively (Fig. 8f). The thrust T2a has a flat geometry in the southwest part of the profile and ramps beneath the Alburni massif. The leading edge of T2a is imaged just west of the Contursi 1 well, whose log shows a reduced inner platform facies possibly related to the transition toward the margin facies cropping out at the Mt. Marzano.

As observed in the profiles SP4 and SP5, additional thickening within the Apenninic carbonates is observed across the Laviano thrust, which carries the Mt. Marzano margin facies (Marzano imbricate) above the margin-to-slope facies of the Frontal Ridges (Mt. Giano imbricate). As observed in the parallel profiles, the Laviano thrust represents the emerging ramp of T2b, a splay that emanates from the basal thrust T2 beneath the southern side of Mt. Marzano and shows a flat-ramp geometry. A series of narrow (~1 km) wavelength folds clearly affect the margin-slope carbonates of the Mt. Giano imbricate and have a lower amplitude and larger wavelength in the marginal carbonates of the Marzano imbricate.

Thrust T2 ramps beneath the northern flank of Mt. Marzano and its leading edge is located at the Frontal Ridges, where it is represented by a triangle zone with local backthrust of the Lagonegro-Molisan rocks (Flysch Galestrino and Flysch Rosso formations) above the margin-slope carbonates of the Mt. Giano imbricate (Fig. 8f).

The LAG Unit is imaged continuously beneath T2, and like in profiles SP4 and SP5, its thickness dramatically increases moving to the northeast. Beneath Mt. Marzano, the continuity of seismic reflectors and the calibration from the S. Gregorio 1 well shows that the LAG Unit forms a single imbricate with a thickness of 0.6–0.7 s (TWT). The imbricate lies almost horizontal and its top is at around 1 s (TWT). Oppositely, beneath the Tanagro R. Valley, the LAG Unit is locally duplicated by thrust ramp T4a that pinches a slice of Apenninic Platform carbonates in between the Lagonegro rocks, as suggested by Contursi 1 well. Southwest of Contursi 1 well, reflectors of the LAG Unit dip steeply to the west and the top of the unit is identified at 2.8 s (TWT) at the end of the profile.

The thickness of the LAG units increases in correspondence of the frontal ramp of T2 starting from ~35–40 km and reaches up to 2.5 s (TWT) at the S. Fele Ridge, where it is composed of several imbricates as documented by the S. Fele 1 well (Fig. 4). The well log shows the presence of eight individual imbricates of Lagonegro and one of Molisan rocks, and additional imbricates are imaged at higher depths in the seismic profile. The imbricates are limited by low-dipping thrusts generally parallel to reflectors, which have been folded and locally disrupted by reverse faults emanating from the Apulian Platform. Duplex structures at various scales can be identified within several imbricates. We show a possible correlation of imbricate 8 of S. Fele 1 well with the Lagonegro rocks found in the S. Gregorio Magno 1 well (Fig. 8f), because both drilled intervals show the complete Lagonegro stratigraphy from the M. Facito to the Flysch Galestrino formations and are of comparable thickness (Fig. 3, Table S2). The Molisan imbricate drilled by the S. Fele 1 well has been traced south toward Mt. Marzano and appears structurally thickened beneath the Mt. Giano imbricate. We are aware, however, that additional Molisan rocks may be included in the antiformal stack moving away from the S. Fele 1 well.

Like in profiles SP4 and SP5, the MLG Unit is imaged beneath the LAG Unit based on Contursi 1 and S. Gregorio 1 well logs. Distinction between MLG and LAG units is approximate in the CROP-04 line as well.

The APL Unit and overlying FMP synorogenic cover beneath thrust T3 form a regional-scale anticlinorium that post-dates displacement along T3 and folds the overlying APN, LAG and MLG units. The anticlinorium culminates at 1.5 s TWT with a wavelength slightly larger than the ~54 km length of the interpreted portion of the profile. The anticlinorium is cut by southwest dipping thrusts that that are tracked down to 3 s (TWT) and generally flatten out within the MLG or LAG units. The more external thrusts (T4d2 to T4f) could be responsible for amplification of the Lagonegro antiformal stack beneath the S. Fele Ridge (Fig. 8f).

Sets of SW- and NE-dipping high-angle normal faults are located just above the Apulian culmination. The normal faults are interpreted also considering the improved CROP-04 images provided by Ercoli et al. (2023), based on data pre-conditioning and seismic attribute analysis. Major NE-dipping normal faults dissect the northeastern flank of the Alburni massif and include the Tanagro fault that controls growth of a Pliocene-Quaternary basin. The normal faults are imaged in the seismic line across all the tectonic units down to 2.5 s (TWT) (Fig. 8f).

5. Discussion

5.1. The structure of the Apennine fold-and-thrust belt

The analysis of the seismic reflection profiles, corroborated by well data and by an extensive appraisal of surface geological relations, provides new insights into the crustal structure of the Apennines orogen, as illustrated by the depth-conversion of interpreted seismic profiles SP2, SP4, and CROP-04 (Figs. 9a to 9c). We discuss in this section the main results for the Apennine fold-thrust belt, which forms the upper level of the orogen, proceeding from the upper to the lower tectonic unit. Results for the buried Apulian belt are discussed in the following section.

The Parasicilide Unit, mostly preserved in fault-bounded depressions, shows a folded internal structure both at the outcrop and the seismic scale. The folds reported in geological maps (Fig. 6a, b), show 1 km wavelength or less, a tight, and locally recumbent geometry, and are fairly correlated to those imaged in the seismic profiles (Fig. 9b, c). Notwithstanding the intense folding, our maximum thickness estimate (900 m) for the Parasicilide succession from the seismic profiles agrees with outcrop data (800–900 m, Servizio Geologico d'Italia, 2016a) and with the 700–900 m thick successions drilled by the Roccadaspide 1 and Contursi 1 wells (Fig. 4). The intense folding coupled with a relative limited structural thickness is consistent with the interpretation of the Parasicilide imbricate as a remnant of the Liguride accretionary prism, thrusted over the continental margin of Adria as a relatively thin sheet (Vitale et al., 2019).

In the northern CLA, the Apenninic Platform Unit forms a regional thrust sheet >50 km wide, which is emplaced above the Lagonegro Unit along thrust T2. The basal detachment has a flat geometry beneath most of the thrust sheet and ramps at the front of the Picentini and Marzano ranges. At least two main thrust splays (T2a and T2b) subdivide the thrust sheet into three distinct imbricates. T2b splays off the basal

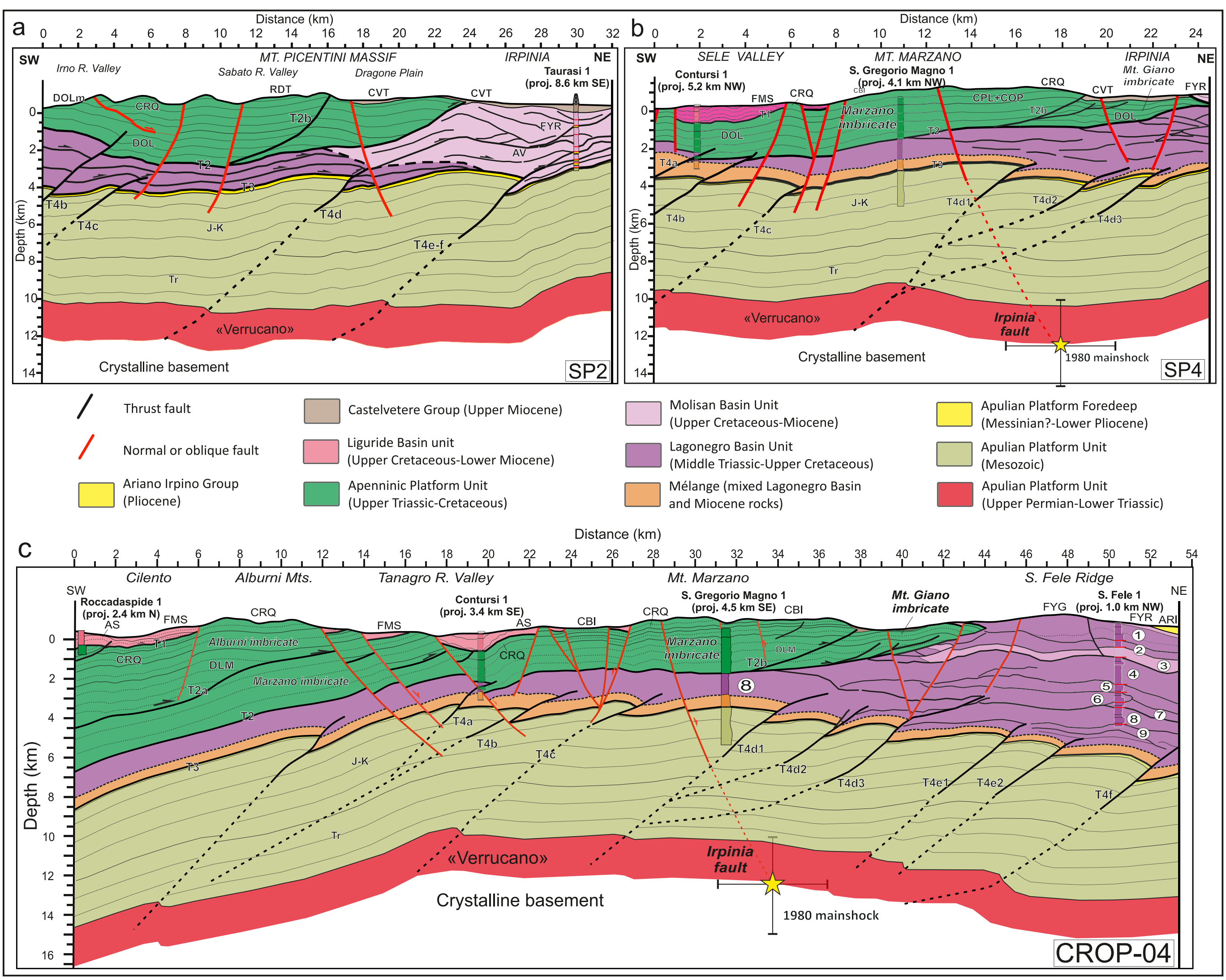


Fig. 9. Geological interpretation of depth-converted seismic profiles SP2 (a), SP4 (b) and CROP-04 (c).

detachment in the central part of the Picentini and Marzano ranges and has a listric (Fig. 9a) or flat-ramp (Fig. 9b, c) geometry depending on location. T2a has a flat-ramp geometry as well, and likely branches from T2 south of the interpreted part of the CROP-04 profile. Additional minor splays are found in the footwall of T2b north of Mt. Marzano and are characterized by fault-propagation folds in the relatively thinner margin-to-slope carbonates of the Mt. Giano imbricate of the Frontal Ridges (Fig. 9b, c).

The lateral changes in sedimentary facies of the Apenninic carbonates within different imbricates of the thrust sheet are reflected in variable thickness estimates from the interpreted seismic profiles. Our depth conversion yield thicknesses of up to ~3 km for the main shelf succession in the western Picentini Mountains (Fig. 9a). This value is in reasonable agreement with existing estimates based on surface geological data (Table S1). The Geological Map of Italy 1:100.000 scale - sheet 467 Salerno and 468 Eboli (Servizio Geologico d'Italia, 2009a, 2016a) report thickness of the platform succession in the southwestern and eastern Picentini Mountains of 3400–5300 m and 2900 m, respectively. The larger range of the former estimate is related to the presence, in the southwestern Picentini Mountains, of a thick interval of Upper Triassic dolostones (Fig. 3), which is barely intersected by the seismic sections. Therefore, our 3 km estimate for this unit is representative of the Uppermost Triassic-Cretaceous shelf (locally margin) succession found in the northern and eastern sectors of the massif and is also consistent with previous assessments at a regional scale (D'Argenio and Alvarez, 1980).

The thickness of the Apenninic platform in the Alburni Mountains in the southern part of the CROP-04 profile is ~5 km (Fig. 9c). However, we consider this value an overestimate of the original stratigraphic thickness because of tectonic thickening. Specifically, we surmise that the splay T2a accommodates thrusting of the Alburni shelf facies (Alburni imbricate) above the Marzano margin facies (Marzano imbricate). The frontal ramp of T2a is located under the northern flank of the Alburni range and juxtaposes the Alburni imbricate, with horizons forming a hanging-wall monocline, above the Marzano imbricate, which is characterized by a footwall ramp (Fig. 9c). By considering such internal imbrication, the thickness of the shelf succession is ~3 km, in agreement with the estimate for the Picentini Mountains. So far, only Berardi et al. (1996), based on field data, and Cippitelli (2007), on the ground of the CROP-04 seismic line interpretation, recognized the existence of tectonic doubling of the Apenninic Platform beneath the Alburni. In other works, the thickness of the shelf succession may have been overestimated (e.g., 6 km by Nicolai and Gambini, 2007).

We found a maximum thickness slightly <2.5 km for the margin succession that floors the Marzano massif (Fig. 9b, c). This value is larger than the maximum estimates from the Geological Map of Italy 1:50.000 scale - sheet 468 Eboli (Servizio Geologico d'Italia, 2016a) and from the regional work of Patacca and Scandone (2007a), which are 1800 and 1300 m, respectively. Notwithstanding, our estimate is constrained by the S. Gregorio Magno 1 well (2280 m, Fig. 4), and it is in good agreement with the thickness computed for the buried extension of the margin facies underneath the Alburni massif in the CROP-04 profile (Marzano imbricate; Fig. 9c). The discrepancy between field and seismic images estimates could result from incomplete exposures recorded by geological maps and/or from thickening in the Triassic dolomites in the lower part of the Marzano succession.

The thickness estimated from seismic reflection data for the margin-to-slope succession (Mt. Giano imbricate) in the Frontal Ridges reaches 1–1.5 km. However, deep wells are not available to calibrate this estimate. The fact that the Mt. Giano imbricate is relatively thin when compared to the shelf succession of the Picentini Mountains likely favoured the local back-thrusting of the Lagonegro-Molisan units above the Frontal Ridges carbonates (Fig. 8d, e). It is likely that margin-to-slope facies rocks, akin to those found in the Frontal Ridges, are present in the subsurface north of the eastern Picentini block as well, where a triangle zone is shown in the interpreted seismic profiles of Mostardini and Merlini (1986). Conversely, the thicker shelf succession exposed in the western Picentini may have prompted the formation of a ramp anticline (Fig. 8a, b).

We extrapolate the existence of the Mt. Giano imbricate in front of M. Marzano also in the CROP-04 profile (km 38–44, Fig. 9c), which runs only ~1 km east of profile SP5 (Fig. 2). Our reconstruction is based on the proximity (only ~400 m to the west) of the Mt. Giano carbonates outcropping in the Frontal Ridges (Fig. 6b) and follows previous interpretations of the CROP-04 profile (Cippitelli, 2007; Mazzotti et al., 2000, 2007; Patacca and Scandone, 2007a, 2007b, 2007c; Scrocca et al., 2005, 2007). For a different interpretation, where the Apenninic carbonates are limited to the northern front of the Marzano massif, see Ascione et al., 2013; Amoroso et al., 2014).

The Lagonegro-Molise basinal unit forms a structurally complex allochthonous sheet that is relatively thin (1–1.5 km) beneath the Apenninic Platform in the south. However, the Lagonegro-Molisan allochthon thickens dramatically in the Irpinia area in the north due to multiple imbrications, as documented by the S. Fele 1 and Taurasi 1 wells (Fig. 4; Patacca, 2007) and by the seismic images. The basinal rocks underneath the Apenninic Platform in the Picentini and Marzano Mountain ranges are made of the Lagonegro Unit. Conversely, the antiformal stack in the Irpinia area is made of Molisan rocks in the west and of Lagonegro rocks with minor imbricated Molisan rocks in the east (north of the Marzano massif). In the east, the base of the basinal allochthon is formed by a mélange of complexly imbricated rocks of the Lagonegro-Molise Unit and Miocene synorogenic deposits, which were drilled by the S. Gregorio Magno 1 and Contursi 1 wells. In the Irpinia area to the west, individual Molisan imbricates can be distinguished in the mélange as documented by the Taurasi 1 well (Fig. 4). Apart from Molisan and their Miocene cover, the mélange likely formed in part at the expenses of the Apulian foredeep deposits (Cippitelli, 2007; Patacca and Scandone, 2007a, 2007b, 2007c).

The thickness of the basinal antiformal stack increases from west (~3.5 km in the Taurasi 1 well area; Fig. 9a) to east (up to ~6 km, including the basal mélange, beneath the S. Fele Ridge; Fig. 9c). The growth of the antiformal stack appears connected to off-scraping of slices of the basinal succession caused by the advancing Apenninic Platform sheet along T2. This process acted mostly at the stratigraphic boundary between the Flysch Galestrino and the Flysch Rosso Fm./Argille Variegate Group (Fig. 3), as recognized by several authors (Casero et al., 1988; Scrocca et al., 2005, 2007). Although the LAG and MOL seismic units are relatively well distinguished (Fig. 5), the exact position of the detachment between the two units in seismic sections is only hypothesized (dashed line in Figs. 8a, b and 9a). The limited resolution at increasing depths and the complex imbrication history of these rocks (e. g. Scrocca et al., 2007) did not allow to resolve the detachment accurately.

The Lagonegro rocks outcropping at the S. Fele Ridge have long been related to a proximal facies of the Lagonegro Basin (S. Fele facies; Scandone, 1972); rocks akin to those found in outcrop are reported in the S. Fele 1 well log at various depths (e. g. Dolomia di S. Fele; Table S2; Patacca, 2007). The Lagonegro succession logged in the S. Gregorio Magno 1 well is also made of proximal basin rocks (Patacca, 2007). The published stratigraphic similarity between the two wells supports our spatial correlation between imbricate 8 in the S. Fele 1 well and the Lagonegro succession drilled by the S. Gregorio Magno 1 well (Fig. 9c).

Our depth-converted sections yields a ~ 1.5 km thickness of the Lagonegro Unit in the central-northern Picentini Mountains, a value that is doubled in the southern part of the massif due to internal shortening as recorded by the Acerno 1 well log (Fig. 9a). The 1.5 km estimate is larger than the ~700 m value provided by the Geological Map of Italy 1:50.000 scale - sheet 467 Salerno (Servizio Geologico d'Italia, 2009a), which is based on incomplete outcrops of Lagonegro rocks exposed in the tectonic windows of the southern part of the massif. However, it agrees with the ~1.6 km thickness of imbricate 2, which preserves the complete Lagonegro stratigraphy, within the Acerno 1 well (Fig. 4). The original thickness of the Lagonegro Unit constrained by the S. Gregorio Magno 1 well is ~1.1 km beneath Mt. Marzano (Fig. 9b).

In the southwestern part of the CROP-04 profile, the west-dipping high-frequency reflections assigned to the Lagonegro Unit beneath the Alburni massif do not show appreciable internal deformation and their depth-converted thickness approaches ~1.5 km (Fig. 9c), in broad agreement with estimates from beneath the Marzano and Picentini Mountains. Assignment of the high-frequency reflections beneath the Alburni to the Lagonegro Unit is based on the similar seismofacies and on the spatial continuity with reflectors proven to be Lagonegro rocks by Contursi 1 and S. Gregorio Magno 1 wells (Fig. 4). This interpretation follows most of the previous literature (Patacca and Scandone, 2007b; Scrocca et al., 2005, 2007), although Cippitelli (2007) suggested that they may represent a Permo-Triassic substratum of the Apenninic Platform.

Summarizing, our 1–1.5 km thickness values for the Lagonegro succession beneath the Picentini and Marzano mountains are consistent with published estimates based on exposed stratigraphic sections (~1.15 km for the S. Fele facies: Passeri et al., 2005; ~1.35 km minimum: Patacca and Scandone, 2007a, 2007b, 2007c) and on crustal isostasy considerations (~1 km; D'Argenio and Alvarez, 1980).

The structure of the Molisan Unit is extremely complex and estimations of sedimentary thickness range between few 10s to 100 s meters (Servizio Geologico d'Italia, 2016a, 2016b, 2016c). Our broad assessment of a stratigraphic thickness of ~500–600 m based on reconstruction of the antiformal stack and constraints from the Taurasi 1 well (Fig. 9a) is consistent with the field observations (600 m) reported in the Geological Map of Italy 1:50.000 scale - sheet 450 S. Angelo dei Lombardi (Servizio Geologico d'Italia, 2016c). This estimate is complicated by the original variability in sedimentary facies and thickness (Fig. 3; Table S1) and must be considered as a maximum value.

5.2. The structure of the buried Apulian belt

The seismic profiles presented in this work confirm that the Apulian belt forms a wide regional anticlinorium offset by N*E*-verging reverse faults, as recognized by several studies (Casero et al., 1988; Menardi Noguera and Rea, 2000; Mostardini and Merlini, 1986; Nicolai and Gambini, 2007). Whereas the analysed section of the CROP-04 profile crosses almost the entire anticlinorium, the commercial seismic profiles display only its culmination and forelimb.

The Apulian culmination in the CROP-04 profile is located between Contursi 1 and S. Gregorio Magno 1 wells and its forelimb slopes down moving north to S. Fele 1 well (Fig. 9c). Our estimation of the depth of the Apulian culmination (~3–4 km) between Contursi 1 and S. Gregorio Magno 1 wells broadly agrees with previous depth-converted interpretations of the CROP-04 profile (Cippitelli, 2007; Scrocca et al., 2005, 2007; Ascione et al., 2013), and with the position of the Vp isovelocity lines defined as the top Apulian carbonates in the Vp tomographic models of the CROP-04 line (Amoroso et al., 2014; Improta et al., 2014).

On the other hand, different reconstructions exist for the top of the Apulian carbonates in the forelimb of the anticlinorium. In our interpretation, the carbonates top slopes down from ~4 to ~6 km moving from S. Gregorio Magno 1 to S. Fele 1 wells (Fig. 9c), in agreement with Scrocca et al. (2005, 2007). Alternatively, other studies place the maximum depth of the Apulian top beneath the Frontal Ridges at 7 km (Cippitelli, 2007), 8 km (Ascione et al., 2013; Amoroso et al., 2014), or 9 km (Improta et al., 2014). In the published Vp velocity models (Amoroso et al., 2014; Improta et al., 2014), the isovelocity lines which are thought to represent the carbonates top beneath the Frontal Ridges form a 10 km wide syncline, separated from the Apulian culmination (Contursi 1-S. Gregorio Magno 1 structure) by a main, thick-skinned ramp, which spatially coincides with our thrust T4d3. Instead, in our interpretation (as well as in Scrocca et al., 2005, 2007), the forelimb of the Apulian culmination is offset by a set of more closely spaced reverse faults accommodating an upthrow of ~1 km each on average. According to our reconstruction, the highest depth of the Apulian Platform (~7 km) occurs in a more eastern position in the hanging-wall of thrust T4f. The discrepancy with the above authors likely results from the different resolution between Vp models and seismic interpretation.

Results of our analysis have been merged with the published map of Nicolai and Gambini (2007) to build a new depth contour map of the top of the Apulian Platform (Fig. 10). The novel reconstruction fills a gap within the published map and allows to obtain a continuous structural contour map of the platform beneath the CLA. The newly contoured part of the map (sector B in Fig. 10) was reconstructed by kriging the depth converted horizons into a slightly smoothed surface. Contour lines were traced every 200 m, and the surface is shown continuous across the main faults that affect the Apulian Unit. In most cases, vertical displacements on these faults are in the range of the structure contour map resolution (200 m).

The map compiled by Nicolai and Gambini (2007) and the novel reconstructions of the top Apulian Platform are partially overlapping, and some minor inconsistencies were found along the boundaries. Slight elevation differences in the northern part of sector B (Fig. 10) have been corrected by modifying the structure contour lines and then reconstructing again the entire mapped surface. These minor differences are due to the non-homogeneous distribution of the seismic reflection profiles and to possibly different velocity models adopted for the depth conversion. Indeed, the workflow parameters and details of the velocity model used for the structure contour map of Nicolai and Gambini (2007) are not available. All the elevation differences bear an error < 10% that is considered acceptable given the lithological variations of the allochthonous units resting above the Apulian Platform.

The new structure contour map shows the progressive deepening of the mapped horizon toward the SSW and a broad high beneath the Picentini Mountains (area B), which parallels the already known highs beneath the Alburni, Marzano and Frontal Ridges (Fig. 10). The high in area B shows two culminations separated by a N*E*-SW trending low. The low projects southward along the northern termination of the Salerno Gulf basin, and likely reflects offset across the northern continuation of the faults controlling the growth of the offshore basin (Figs. 2, 10).

The traces of the T4 thrust ramps were correlated between the western and the eastern profiles. Because of the inhomogeneous distribution of the seismic profiles, the thrusts are represented with a continuous trace when they are controlled by the interpreted subsurface data. Otherwise, they are shown with dashed lines. The points used to build the fault traces do not represent the upper tip lines of the fault, rather they have been picked on each profile where the thrusts cut the top Apulian carbonates midway between hanging-wall and footwall.

Although the accuracy of the correlation between the thrust ramps detected in the western and eastern profiles may be hampered by the gap in data between the two sectors, our reconstruction, following in the eastern sector the structural pattern mapped by Nicolai and Gambini (2007), shows that the ramps have a WNW-ESE strike. The ramps are not uniformly distributed, rather they appear grouped in two sets, which we label internal and external, respectively (Figs. 7, 10). The internal set is formed by sub-parallel thrusts T4a to T4d that have a spacing of 2 to 6 km and form a ~ 20 km wide array distributed on the culmination of the Apulian anticlinorium (Figs. 9c, 10). In the western sector, they appear more widely spaced (~10 km) and are less in number because several splays of T4d are present in the east and merge along strike moving to the west (Fig. 10). The vertical throw of the top Apulian carbonates accommodated by individual thrusts of this set ranges between ~200–400 m on average.

The depth converted sections document that the faults are characterized by a high dip-angle (~45° on average), consistent with the value shown for the Apulian thrusts in the CROP-04 line by most previous authors (Cippitelli, 2007; Scrocca et al. (2007). As suggested by several studies (Butler et al., 2004; Shiner et al., 2004; Mazzoli et al., 2006; Improta and Corciulo, 2006), the steep dip of faults cutting through the Apulian anticlinorium agrees with a thick-skinned deformation style for

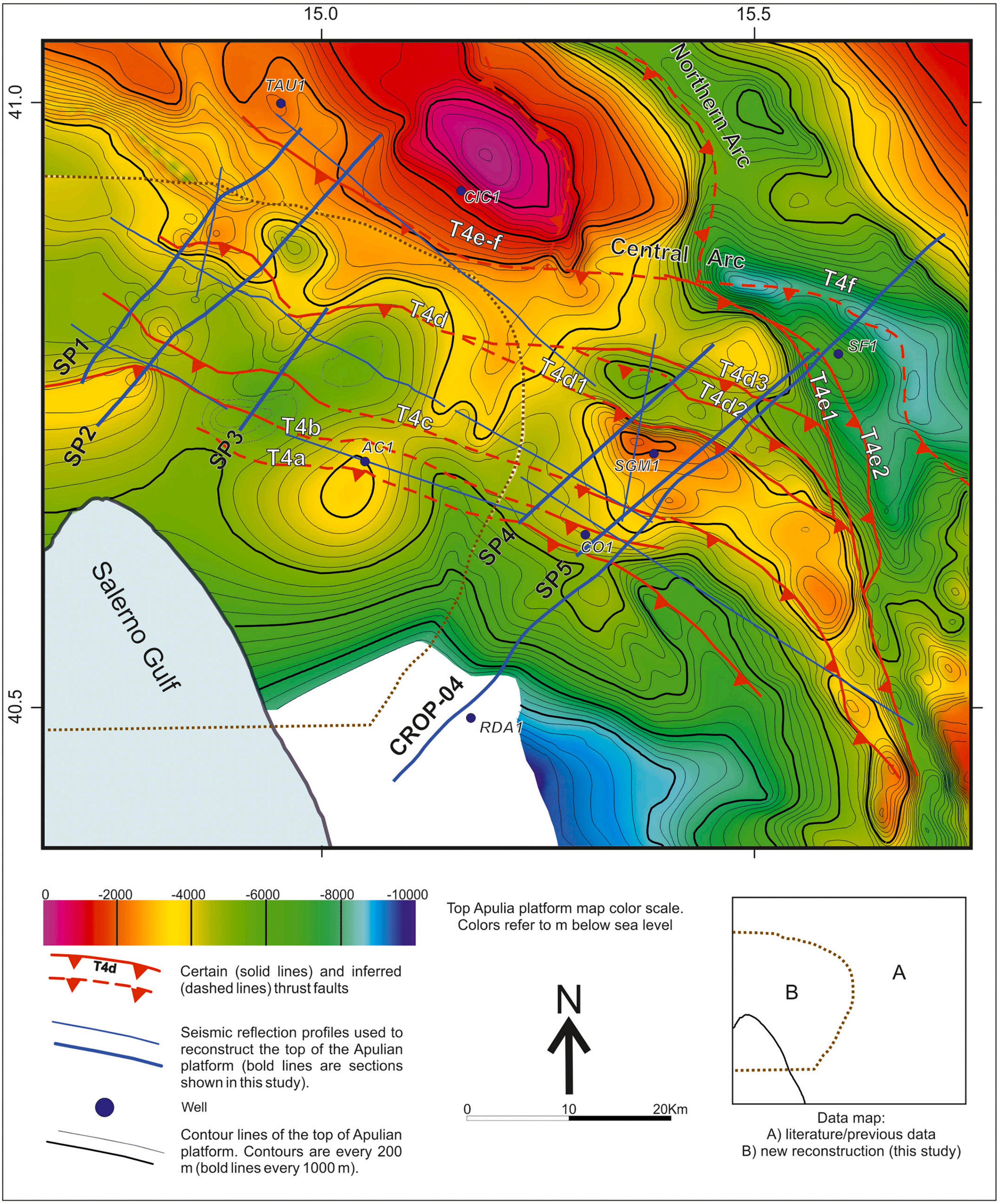


Fig. 10. Structure contour map of the top Apulian carbonates in the CLA. The map is the merge of pre-existing data (Nicolai and Gambini, 2007) and new interpreted seismic reflection profiles. The brown line represents the boundary between sectors where pre-exiting data were available (area A in the picture) and where new data have been interpreted (area B). The wells used to constrain the interpretation are labelled according to Fig. 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the Apulian belt.

In Figs. 9a to 9c, thrusts T4 are projected downward (dashed lines) through the Apulian sedimentary cover until the Verrucano layer. Upon propagating above the Apulian Platform carbonates, these ramps cut through the previously formed thin-skinned structures and thus they are considered as envelopment thrusts sensu Bally et al. (1966) (see also Pappone and Ferranti, 1995; Vitale et al., 2020b).

The comparable structural relations that are found in the Acerno 1 and Contursi 1 wells bear implications for the geometry of the most internal thrust, T4a. In the upper part of the Acerno 1 well, an imbricate of Lagonegro rocks is sandwiched between the Picentini Mountains shelf carbonates and the M. Croce margin-to-slope carbonates, which are both part of the Apenninic Platform (Figs. 3, 4; Patacca, 2007). The complex structure highlighted by the well, with reversal of the original structural relations, where the Apenninic Platform is regionally thrust over the Lagonegro rocks on T2, is likewise exposed in the Campagna tectonic window nearby the Acerno 1 well (Fig. 2; Patacca, 2007; Vitale et al., 2020a). The basal fault of the uppermost Lagonegro imbricate in the Acerno 1 well at a depth of ~0.5 km could be interpreted as merging into the regional detachments T2 or T3, and thus be part of the thin-skin structures of the Apenninic thrust belt (Patacca, 2007). Alternatively, as suggested here, it can be considered the shallow tip of a thrust ramp rooted in the Apulian belt (thrust T4a).

The low-angle normal fault that bound upwards the Lagonegro imbricate and offset its basal thrust in profile SP3 is exposed nearby the Acerno 1 well (Fig. 8c) and is part of a regionally recognized system of extensional structures (Oldow et al., 1993; Ferranti et al., 1996; Ferranti and Oldow, 1999; Bucci et al., 2014; Novellino et al., 2015) whose age, although not well constrained, is assigned to the Pliocene (Fig. 3). On this basis, we suggest that thinning of the upper part of the orogenic stack in the southern Picentini Mountains could have been triggered by thrust uplift along internal thrusts T4a to T4c (Fig. 8c).

A broadly similar structure emerges in our interpretation of the deeper part of the Contursi 1 well, where the fault that carries a slice of Lagonegro rocks on top of Triassic dolomite at a depth of ~2.8 km (Fig. 4) is interpreted as the thick-skinned thrust T4a (Figs. 8e, f, 9b). Above this thrust, a low-angle normal fault has been proposed to represent the contact between Cretaceous and Upper Triassic carbonates at a depth of ~1.5 km (Cippitelli, 2007; Ferranti and Oldow, 1999), although we did not trace the LANF in the seismic profiles.

In the proposed scenario, the extent of envelopment thrusting accommodated by T4a, and possibly other Apulian thrust ramps in the hinterland sector of the CLA is not restricted to the Acerno 1 well-Campagna tectonic window area (Patacca, 2007), but it may have a larger width (Fig. 10). The fact that the enveloping imbricate of Lagonegro rocks reaches a shallower tip in the west (Acerno 1 well) compared to the east (Contursi 1 well, Fig. 4) could be attributed to a segmented geometry of T4a. The more substantial uplift accommodated in the west by internal thrust ramps T4 is documented by the shallow structural level achieved by Lagonegro rocks, both cropping out in the tectonic windows of the Southern Picentini Mountains and encountered by a railway tunnel near Salerno town below the Apenninic carbonates (Fig. 2; D'Argenio et al., 1987).

The external thrusts T4e-T4f represent the front of the Apulian Central Arc (Fig. 10). In the west, these thrusts have a WNW-ESE strike like the internal thrusts, but moving to the east they progressively swing to an NNW-SSE strike and envelop the internal thrusts. The vertical offsets of the Apulian top across the external thrusts appear larger (~800–1000 m) than on the internal thrusts, particularly for T4f (Fig. 9c).

According to Nicolai and Gambini (2007), the *E*-W trending segment of the frontal ramp of the Central Arc coincides with our thrust T4d (including the segments T4d1, T4d2 and T4d3 in the east). Instead, we propose that the frontal ramp is formed by thrust T4f in the eastern sector, which in the west merges with thrust T4e and with internal ramps of the Northern (Campano-Molisan) Arc mapped by Nicolai and Gambini (2007) (Fig. 10).

Considering the limited throw of thrusts T4 relative to the wavelength of the Apulian anticlinorium and their position in both the back- and forelimb of the anticlinorium, they clearly cannot be responsible for the growth of the regional fold. On the opposite, we consider the T4 thrusts as structures pre-dating or accompanying as secondary structures the bending of the Apulian crust. Formation of the anticlinorium is possibly related to impingement of the newly formed Tyrrhenian Moho above the W-plunging Adriatic Moho beneath the Apennines (Akimbekova et al., 2021; Menardi Noguera and Rea, 2000; Steckler et al., 2008). In this scenario, the observations that the major normal faults are nested at the top of the anticlinorium (Fig. 9c), suggest that also the extension may be related to crustal bending and encroachment of the Tyrrhenian mantle into the western Adria lithosphere.

5.3. Remarks on the tectonic evolution of the CLA

The sequential stages of the CLA tectonic evolution are tracked by different synorogenic deposits, which help to date thrust nucleation and motion, by the growth of structural fabrics with dissimilar trends during individual tectonic stages, and by substantial vertical-axis rotations recorded by paleomagnetic studies. We provide here, based on our crustal model and on existing structural and paleomagnetic data, a reconstruction of the timing, geometry and kinematics of the main deformation steps that led to the building of the CLA (Fig. 11).

Several generations of macrofolds are distinguished. The pre-orogenic units, and particularly the Parasicilide imbricate, show at least two sets of folds. The older set trends from N-S to NNE-SSW and is attributed to the middle-(late?) Miocene. The younger set has a WNW-ESE to NW-SE trend and is developed in Upper Miocene-Lower Pliocene synorogenic deposits as well. An additional macrofold set with a NW-SE trend is found in Upper Pliocene-Lower Pleistocene deposits of the eastern Ofanto syncline (OS2, Fig. 11). The sense of tectonic transport in different units is consistent with the trace of different generations of macrofolds. The Liguride and Lagonegro units, and to a lesser extent the Apenninic Platform, experienced an older shortening toward the ESE. This early shortening was superposed by a second contractional transport toward the N to NNE, which affects the Upper Miocene-Pliocene deposits as well. Moving to the frontal belt, the contractional transport of the Upper Pliocene-Lower Pleistocene deposits swings toward the ENE. These transports refer to the present-day coordinates.

The uppermost and older thin-skinned thrust T1 is aged between late Langhian and early Serravallian and accommodated the emplacement of the Parasicilide imbricate, which is part of the Liguride accretionary prism, above the western sector of the Apenninic Platform (Fig. 7; Vitale and Ciarcia, 2013; Vitale et al., 2019). The eastern seismic profiles (SP4, SP5 and CROP-04) show that T1 has a flat trajectory that ramps up along the southwestern flank of Mt. Marzano (Fig. 9b, c), in agreement with data from geological maps. Although outcrops of the Parasicilide rocks are highly fragmented and mostly buried below Quaternary basins, the Parasicilide allochthon likely extended above the Picentini and Alburni Mountains, and the leading edge of T1 was probably located in the southwestern sector of the Marzano massif and east of the Alburni Mountains (Fig. 11). In support of this reconstruction, we recall that the Parasicilide thrust sheet never reached the northern flank of the Marzano massif, where the Laviano formation continued to deposit until early Tortonian (Fig. 3), when the activity of T1 had already ceased (Vitale et al., 2020a). We relate the first fold fabrics in the Parasicilide rocks, which has an average ~ NNE-SSW trend, to emplacement of the Liguride prism above the Apenninic Platform, suggesting that T1 had a broad E-SE vergence in present-day coordinates (Fig. 11).

The emplacement of the Apenninic Platform above the Lagonegro-Molise Basin domain along T2 occurred between latest Serravallian and late Tortonian (Fig. 7). Deformation reached the southern Picentini sector after the Serravallian deposition of the Vallimala Flysch Formation on the Mt. Croce margin domain, and the northern Marzano sector

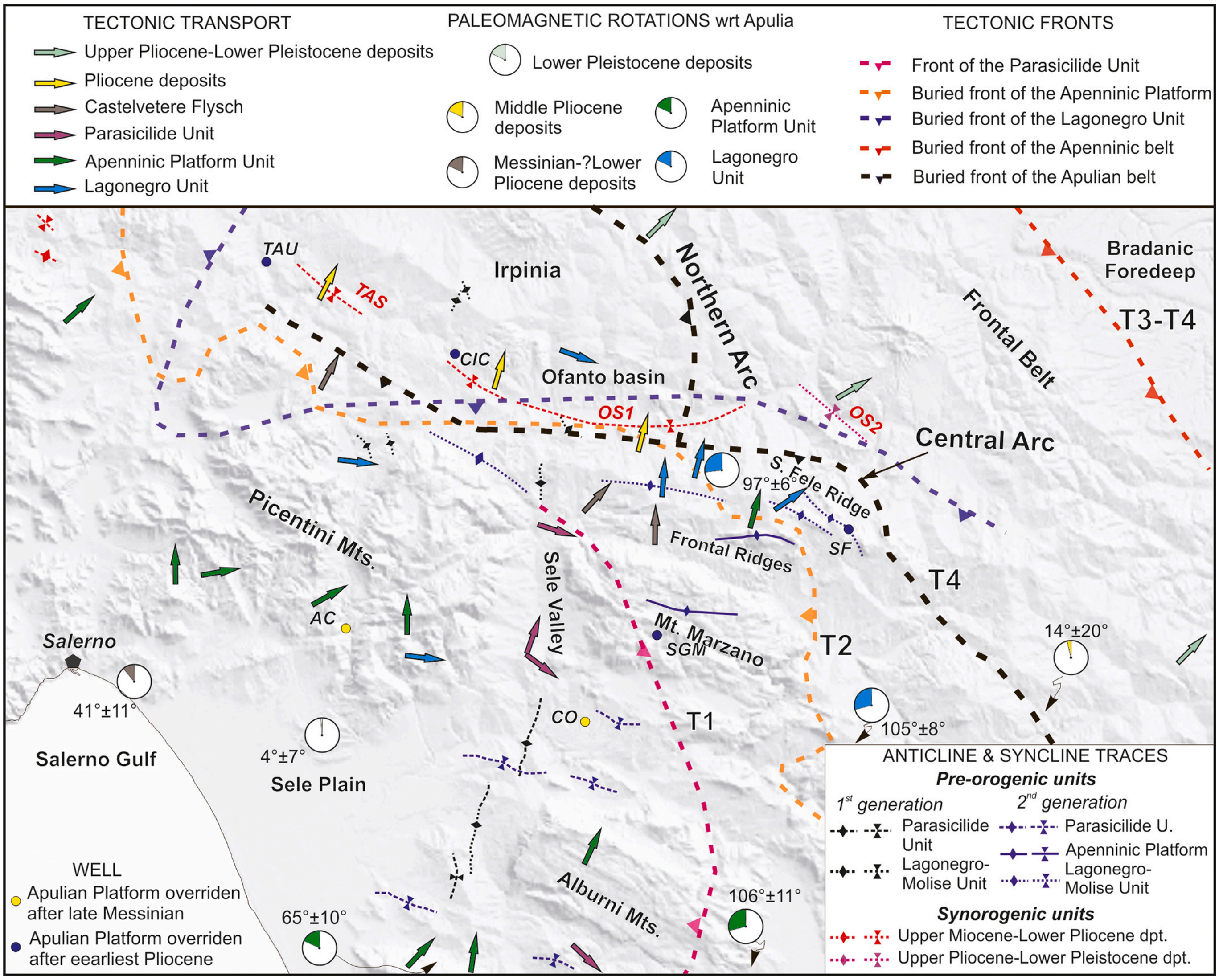


Fig. 11. Integrated surface and sub-surface structural map of the CLA. The figure shows: i) the position of the leading edges of the allochthonous units of the Apenninic thrust belt and of the front of the Apulian arcs based on Nicolai and Gambini (2007) and on results of this study; ii) the macroscale folds; iii) the sense of tectonic transport (arrows) determined for individual allochthonous sheets (Hippolyte et al., 1994; Berardi et al., 1996; Ferranti and Oldow, 1999; Vitale and Ciarcia, 2013; Vitale et al., 2020a); and iv) the amount of vertical-axis rotation in different units documented by paleomagnetic measurements (Gattacceca and Speranza, 2007). Abbreviations of wells as in Fig. 2. Folds: TAS, Taurasi syncline; OS-1, Ofanto syncline 1; OS-2, Ofanto syncline 2.

after early Tortonian deposition of the Laviano Formation (Fig. 3). Within the Apenninic thrust sheet, the internal imbrication along thrusts T2a and T2b, also occurred during this stage, because these splay thrusts do not appear to cut across the basal detachment T2. A further, more internal splay thrust, documented in the CROP 04-line south of the portion of the seismic profile analysed here (Cippitelli, 2007; Patacca and Scandone, 2007a, 2007b, 2007c), duplicates the shelf succession between the Mt. Soprano and Mt. Alburni (Fig. 2). The detachment between the Lagonegro and Molisan units probably occurred during this stage (Fig. 7), allowing thrusting of the Apenninic Platform directly above the Lagonegro Unit stripped of its Molisan cover. Motion of T2 was largely sealed by late Tortonian-early Messinian deposition of the Castelvetere Flysch on both the platform and basinal successions (Fig. 3).

The sense of motion during the activity of T2 is not precisely established, but the existence of an early generation of NNW-SSE to NNE-SSW trending structures within the Lagonegro-Molise units would suggest a broad eastward transport in present-day coordinates (Fig. 11; e. g. Vitale et al., 2020a). Alternatively, the sense of transport along T2 could have been toward the NNE in present-day coordinates, as suggested by the widespread occurrence of WNW-ESE trending fold traces in the Apenninic Platform, in the overlying Parasicilide sheet, and in the Lagonegro units (Fig. 11). In this latter view, the earlier NNW-SSE trending folds in the Lagonegro rocks would have occurred during the earlier phase, perhaps in response to an incipient foreland deformation. Thrusting of the Apenninic Platform above an already folded Lagonegro Unit has been documented in Lucania within the SE arm of the CLA (Mazzoli et al., 2001).

Between latest Messinian and early Pliocene, the stacked Parasicilide, Apenninic and Lagonegro-Molisan units overrode the more internal sectors of the Apulian Platform along T3 (Fig. 7). Emplacement was favoured by the interposition of an up to 1 km thick mélange, formed at the expenses of Miocene-Lower Pliocene foredeep deposits of the footwall platform and incompetent rocks of the Lagonegro-Molise succession (Fig. 9b, c). Although there are no surface constraints on the sense of motion on T3, the broad alignment of wells with a similar age of synorogenic deposits covering the inner Apulian domain provides qualitative kinematics clues (Fig. 11). Indeed, Messinian evaporites were drilled by the Acerno 1 well on top of the Apulian Platform, and coeval evaporites are included in the mélange at the base of Contursi 1 well few hundred of meters above the platform (Fig. 4). These occurrences suggest that the detached stack was just south of the two wells by the late Messinian. Because the two wells are aligned WNW-ESE (Fig. 11), this agrees with a broad NNE displacement sense for T3 in present-day coordinates. Further north, the Taurasi 1 and Ciccone 1 wells, which are aligned in a similar direction, have penetrated Lowermost Pliocene rocks on top of the Apulian carbonates. This finding documents that the thrust belt had moved ~25 km to the NNE on T3 from the Acerno 1-Contursi 1 trend to the Taurasi 1-Ciccone 1 trend during the early Pliocene (Ferranti and Oldow, 2005). The displacement sense for T3 inferred from subsurface data would agree with the NNE tectonic transport determined by structural studies in Pliocene deposits (Fig. 11).

Starting from the early Pliocene, the Apulian Anticlinorium formed beneath the CLA and was preceded or accompanied by motion on thrusts T4 (Fig. 7). The age of the anticlinorium is not precisely constrained, but it must postdate emplacement of the Apennine thrust stack along T3, which is folded and offset by thrust ramps of T4. Because T3 was active in the hinterland part of the arc during the earliest Pliocene, when the thin-skinned allochthonous sheets were thrust over the Apulian Platform at the Acerno 1-Contursi 1 trend, folding of the Apulian rocks and the activity of internal thrusts T4a-d must have started at least during the later early Pliocene. Possibly, motion on thrusts T4a to T4d reactivated the external part of T3, which, during the same time interval, carried the thin-skinned thrust stack over the Apulian Platform at Taurasi 1 and Ciccone 1 wells. In the internal part of the arc, the tectonic duplication documented by the Acerno 1 and Contursi 1 wells could have occurred because of the activation of a splay of T3 (e. g. Patacca, 2007), or because of displacement along a more internal thrust ramp T4 respect to those mapped in this study.

As outlined before, the displacement sense at this stage was broadly to NNE, as suggested by the trend of the syncline formed in Lower Pliocene deposits in the central part of the Ofanto basin (OS1, Fig. 11). The displacement along the T4 ramps suggested by seismic profile interpretation is consistent with the inferred transport direction for T3. Because the Castelvetere Flysch is partly involved in folding and thrusting across the Laviano thrust and at the Frontal Ridges (Fig. 9b, c), it is likely that thrusts T4a-d reactivated, or breached through the northern part of the T2 thrust system as well (e. g. Vitale et al., 2020b).

Summarizing, it is possible that displacement on specific T4 thrust ramps reactivated sequentially more external portion of previous thrusts, particularly T3. This mechanism probably led to growth of the antiformal stack of Molisan units in Irpinia, where the occurrence of imbricates of Molisan rocks and Upper Messinian evaporites in the Taurasi 1 well documents that the stack grew after the Messinian at the expenses of the already detached Molisan units (Fig. 8b). Thrusts in the antiformal stack that were formed earlier (e.g. those connected to T3 or to the internal T4 ramps) appear refolded by the external T4 ramps.

In map view, the foremost T4e-f thrust ramps appear to envelope the older Apulian thrusts (Fig. 10), supporting the inference of their younger age. We associate activity of the T4e-f thrusts to deposition of younger (Uppermost Pliocene-Lower Pleistocene) sediments in the more recent syncline formed at the eastern part of the Ofanto basin (OS2, Fig. 11; Casciello et al., 2013; Giannandrea et al., 2014). During this stage, displacement was directed toward the NE as indicated by the axis of the second-stage Ofanto *syn*-depositional syncline and by structural studies in Uppermost Pliocene-Lower Pleistocene deposits. Because the latest displacement of the frontal thrust belt on the western flank of the Bradanic foredeep (Fig. 1b) occurred during the late Pliocene-early Pleistocene (Patacca and Scandone, 2007a; Ferranti and Oldow, 2005), the coeval deformation in the Apulian Platform beneath the CLA must have been transferred to the front of the Apennines reactivating the leading edge of T3 (thrust T3-T4, Fig. 11).

Paleomagnetic measurements in different pre-orogenic and syn-orogenic successions (Gattacceca and Speranza, 2007) provide insights into the timing of counterclockwise (CCW) vertical-axis rotation and of the pre-rotation geometry and kinematics of deformation fronts in the CLA. Successions of the Apenninic Platform and of the Lagonegro units in the CLA are affected by a comparable amount of rotation with respect to the Apulian foreland, which ranges from 65° in Cilento (internal part of the CLA) to ~100° in a N-S trending alignment between S. Fele Ridge and the Alburni Mountains, within the eastern arm and at the apex of the CLA (Fig. 11). A site in Messinian-(Lower Pliocene?) deposits near Salerno has rotated ~40° CCW, and a nearby Lower Pleistocene site yields no appreciable rotation. Finally, Middle Pliocene deposits immediately to the east of the Central Arc have rotated ~15° CCW.

The observation that the Apenninic Platform and the Lagonegro units have a similar magnitude of CCW rotation suggests that they were already stacked before rotation. Subtracting a post-early Pliocene rotation of ~40° that we assume appropriate for the entire northern arm of the CLA, a maximum CCW rotation of 60° has likely occurred during late Messinian-early Pliocene motion along T3. In the proposed scenario, the transport of previous thrust fronts and associated folds must be restored to the south (T1) and to the east-southeast (T2). When rotation ceased, the Apennine belt above T3 must have been moving toward the ENE.

Paleomagnetic data suggest that formation of the Apulian Central Arc during late Pliocene-early Pleistocene has twisted the previous fabrics and thrust fronts of ~40° CCW in the Picentini and Marzano Mountains, where the western arm of the arc trends E-W. By contrast, rocks in the eastern arm of the arc have rotated less (15° CCW).

The effects of Quaternary high-angle normal faults on the thrust structures are significant mainly in the large basins formed on the hinterland margin of the orogen (Salerno Gulf-Sele Plain) and in the western intermontane basins (Sele and Tanagro valleys) of the CLA. Geophysical and field data document that active extensional faults are presently concentrated along the axial part of the belt (Pantosti and Valensise, 1990; Rovida et al., 2022; Bello et al., 2021), but they are not readily imaged in seismic profiles. The hypocentral depth of the mainshock of the Mw = 6.9, 1980 earthquake has been located between 10 and 15 km depth (Westaway and Jackson, 1987; Westaway, 1993). Our depth-converted sections suggest the rupture nucleated below the Apulian sedimentary cover, within the Permo-Triassic Verrucano layer or in the uppermost part of the crystalline basement (Fig. 9b, c).

6. Conclusions

This study presents an integrated reconstruction of the surface and subsurface structure of a critical sector of the Southern Apennines orogen. Our results support previous reconstructions that propose a net distinction between an upper and a lower thrust belt. The upper orogenic level (Apennine fold and thrust belt) is characterized by stacking of relatively thin-skinned allochthonous units on low-angle thrust detachments. Growth of the fold-and-thrust belt was favoured by the regional mechanical stratigraphy of the western continental margin of Adria, where the occurrence of contiguous platform and basinal lithostratigraphic assemblages favoured the detachment and piling of long-ranging thrust sheets. Within the Lagonegro-Molisan basinal units, detachments operated at several levels and led to the growth of a huge (up to ~6 km) antiformal stack made of thin-skinned imbricates. The Apenninic Platform was preserved as a relatively coherent allochthonous sheet. However, its integrity was interrupted by thrusts splays emanating from its basal detachment, which led to the formation of three (or more) imbricates whose northeast-decreasing thickness is related to a different late Mesozoic stratigraphy, namely the transition from shelf to margin and to slope domains. In addition to a novel image of the subsurface structure, we provide here an independent estimation of the thickness of subsurface lithostratigraphic units, which were only constrained so far by outcrop reconstructions and well point-data.

In contrast, the lower orogenic level (Apulian belt) is characterized by a regional-scale anticlinorium featuring high-angle, deep-seated and probably thick-skinned (basement-involving) thrust ramps that slightly pre-date or accompany as secondary structure the growth of the regional fold. We relate the growth of the anticlinorium to large-scale bending of the crust occurred during the Pliocene, when thicker and narrower sectors of the Adria block were involved in contraction. Uplift of a significant section of the previously underthrust Apulian crust beneath the Apennines was followed by its fragmentation caused by systems of dominantly WNW-ESE striking high-angle strike-slip and normal faults. However, results of this study suggest that previously undetected Apulian highs are still present in the inner parts of the CLA, very close to the foundered coastal sector facing the stretched Tyrrhenian back-arc basin. The normal faults are still active today in the culmination of the Apulian belt and root at the contact between the Apulian crystalline and sedimentary crust, as testified by the 1980 Mw 6.9 earthquake.

By integrating our results with kinematics and paleomagnetic data from previous studies, we provide an assessment of the position and kinematics of thrust fronts during various stages of the middle Miocene-early Pleistocene orogenic evolution. Thanks to the availability of original subsurface data, the new information supplied here may help testing existing models for the Southern Apennines and contribute to seismic hazard assessment of a highly seismogenic region. It can be considered also as a reference study to extend the used approach to other orogens characterized by tectonic belts stacked at different levels and with variable structural styles.

CRediT authorship contribution statement

Luigi Ferranti: Writing – review & editing, Writing – original draft, Supervision, Investigation, Conceptualization. **Filippo Carboni:** Writing – review & editing, Visualization, Methodology, Investigation, Data curation. **Assel Akimbekova:** Writing – review & editing, Software, Methodology, Investigation, Data curation. **Maurizio Ercoli:** Writing – review & editing, Validation, Methodology, Investigation. **Simone Bello:** Writing – review & editing, Validation. **Francesco Brozzetti:** Writing – review & editing, Validation. **Alberto Bacchiani:** Visualization, Investigation, Data curation. **Giovanni Toscani:** Writing – review & editing, Supervision, Project administration, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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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.2024.230313.

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