Marine and Petroleum Geology 163 (2024) 106769

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Tectonic evolution of the Crotone Basin (central Mediterranean): The important role of two strike-slip fault zones

Giacomo Mangano [a,b,*], Massimo Zecchin [b], Dario Civile [b], Salvatore Critelli [a]

[a] Department of Environmental Engineering, University of Calabria, Arcavacata di Rende, CS, 87036, Italy
[b] National Institute of Oceanography and Applied Geophysics – OGS, Sgonico, TS, 34010, Italy

ABSTRACT

The middle Miocene to Quaternary evolution of the Crotone Basin (CB), on the Ionian side of the Calabrian Arc (southern Italy), was strongly controlled by the activity of the NNW- to NW-striking Rossano-San Nicola (RSFZ) and Petilia-Sosti (PSFZ) fault zones. The integration of low frequency 2D seismic reflection profiles, boreholes and geological maps has allowed the discovery of a positive flower structure, which is part of the RSFZ. Such a positive flower structure was responsible for the emplacement of an allochthonous unit in the Late Tortonian and contributed to the onset of gravitational collapse in the Pliocene. Dextral transpressional tectonics related to the RSFZ led to the expulsion of a S-verging thrust controlling the emergence of the northern sector (Cirò area), and the development of an elongated E-W-oriented depocenter in the southern sector of the Crotone Basin (Crotone area), from the Late Tortonian to Late Messinian. In the Late Messinian, the offshore area of the basin turned into a structural high marked by overall exposure conditions, as a consequence of the RSFZ activity. Contractional/transpressional activity also took place at the transition between the Early and Late Pliocene, when the PSFZ governed the superimposition of the Messinian Unit in the Crotone area. Conversely, phases of extensional/transtensional tectonics are inferred to have been occurred along the PSFZ during the Messinian, by the development of a tectonic trough in the south Crotone area. This tectonic regime is also supposed to have persisted during the Early Pliocene and the Pleistocene in the offshore area, where the development of local depocenters took place.

1. Introduction

The stratigraphic architecture of basin fills is crucial to infer large-scale tectonic driving forces responsible for the position and orientation of associated folds and faults, the local domains of extension and shortening, and the timing of the unconformities (Sylvester, 1988). Understanding the deformation phases associated with basinal partitioning is key to interpreting the stratigraphic architecture (Catuneanu et al., 1998; Zecchin et al., 2012, 2013a, 2013b).

The Calabria region in the central Mediterranean is characterized by a complex tectonic history due to regional geodynamic events that markedly influenced the sedimentary evolution of its onshore and offshore basins (Roda, 1964; Van Dijk, 1990; Cella et al., 2004; Massari et al., 2010; Zecchin et al., 2012; Massari and Prosser, 2013; Zecchin et al., 2013a,b; Zecchin et al., 2015; Zecchin et al., 2020; Critelli and Martín-Martín, 2022, 2024; Martín-Martín et al., 2023). Its evolution is closely related to the SE migration of the Calabrian terranes (also known as the Calabrian Arc) since the Middle Miocene onwards, under a setting characterized by the NW-dipping subduction of the Ionian oceanic plate, the associated slab rollback and the Tyrrhenian Sea back-arc extension (Malinverno and Ryan, 1986; Sartori, 1990; Patacca et al., 1990; Gueguen et al., 1998; Critelli, 1993; 2018; Critelli and Martín-Martín, 2022; Martín-Martín et al., 2023) (Fig. 1). The phases of back-arc stretching in the Tyrrhenian Sea were interrupted by quiescence periods in arc migration, which were recorded as episodes of basin uplift and the development of associated unconformities (Zecchin et al., 2012, 2015, 2020; Massari and Prosser, 2013). The SE migration of the Calabrian Arc produced its considerable fragmentation in several blocks bounded by NW- and WNW-trending shear zones (Knott and Turco, 1991; Tortorici et al., 1995; Van Dijk et al., 2000; Mattei et al., 2002; Cifelli et al., 2007; Tansi et al., 2007; Tripodi et al., 2013, 2018) (Fig. 1).

The forearc Crotone Basin is located on the Ionian side of the Calabrian Arc at the crucial point of this system. It also experienced the effects of a large-scale gravitational collapse and the emplacement of allochthonous units (the so-called Cariati Nappe in the N sector) (Massari and Prosser, 2013; Minelli et al., 2013; Ceramicola et al., 2014; Muto et al., 2014, 2017; Zecchin et al., 2018; Mangano et al., 2020, 2023a,b). In such a background, the NW-trending (range from N 120°–140°) Rossano-San Nicola (RSFZ) and Petilia Sosti (PSFZ) shear zones played a key role in the evolution the Crotone Basin (Lanzafame and Tortorici, 1981; Tortorici et al., 1995; Van Dijk et al., 2000; Mattei et al., 2002; Cifelli et al., 2007; Tansi et al., 2007; Tripodi et al., 2013,

---

* Corresponding author. Department of Environmental Engineering, University of Calabria, Arcavacata di Rende, CS, 87036, Italy.
E-mail address: giacomo.mangano@unical.it (G. Mangano).

https://doi.org/10.1016/j.marpetgeo.2024.106769
Received 11 January 2024; Received in revised form 19 February 2024; Accepted 21 February 2024

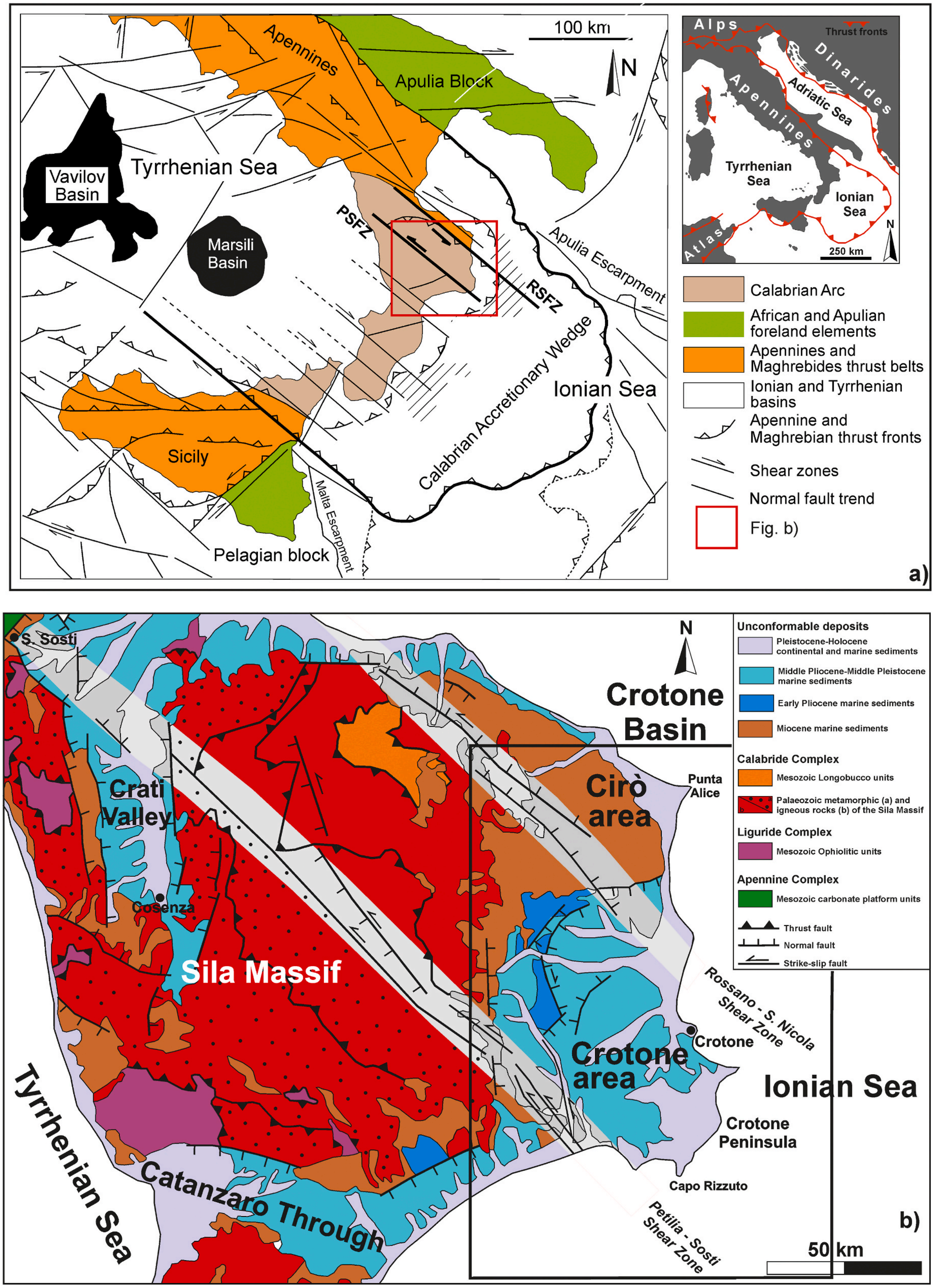

Fig. 1. a) Structural map of the Calabrian Arc, which is comprised between the southern Appenine chain and Maghrebides thrust belt (modified from Van Dijk and Okkes, 1991). The Vavilov and the Marsili back-arc basins are located in the southern Tyrrhenian Sea. The Rossano-San Nicola (RSFZ) and the Petilia Sosti (PSFZ) are highlighted. b) Simplified geological map of the northern sector of the Calabrian Arc including the Crotone Basin. The latter is subdivided in two sectors, the Cirò area and the Crotone area, separated by an E-W-oriented normal fault (modified from Olivetti et al., 2012). The position of the two main shear zones (the Rossano-San Nicola and Petilia Sosti fault zones) affecting this area is also reported together with the major faults. Tectonic features from Van Dijk (1994), Tortorici et al. (1995), Van Dijk et al. (2000), Galli and Scionti (2006), Spina et al. (2007), Massari and Prosser (2013), Zecchin et al. (2020).

2018; Brutto et al., 2016, 2018; Civile et al., 2022) (Fig. 1a and b). Several explanatory models have been formulated so far, but some aspects of structural-stratigraphic frameworks still need to be clarified as the mechanisms that governed the development of the Cirò area and the characterization of the headwall region of the well-known large scale gravitational collapse, the Crotone Megalandslide (Ceramicola et al., 2014; Conforti et al., 2014; Zecchin et al., 2018, 2020; Mangano et al., 2020).

The aim of this study is to provide new information on the tectono-stratigraphic evolution of the Crotone Basin and clarify the uncertainties mentioned above. This is achieved through the interpretation of unpublished 2D seismic reflection profiles and exploration wells. An important test of this work is to tie the geometry of the unconformities bounding the stratigraphic sequences to the tectonic evolution of the shear zones and relate them to the geodynamics of the central Mediterranean.

2. Geological setting

The study area is located on the Ionian side of the Calabrian Arc part of the Calabrian Accretionary Wedge, and is locked between two shear zones, which are the RSFZ to the north and PSFZ to the south (Van Dijk, 1991, 1994; Van Dijk and Okkes, 1991; Van Dijk et al., 2000; Civile et al., 2022; Tansi et al., 2007; Critelli and Martín-Martín, 2022; Mangano et al., 2023a) (Fig. 1a and b). The Calabrian Arc form an arcuate independent tectonic block that connects two Neogene orogens, the NW-trending Apennines to the north and the E-trending Maghrebian chain to the southwest (Fig. 1a). The offshore part of the Calabrian Accretionary Wedge is generally interpreted as the result of the rollback of the NW-dipping Ionian slab, which was accompanied by repeated slab tears. This led to a progressive narrowing of the slab under continued NW to NNW Cenozoic convergence between Africa and Eurasia (Malinverno and Ryan, 1986; Dewey et al., 1989; Sartori, 1990; Gueguen et al., 1998; Faccenna et al., 2001, 2004; Rosenbaum and Lister, 2004; Barone et al., 2008; Critelli and Martín-Martín, 2022). The Calabrian Arc migrated towards the SE from the Late Serravallian onwards, after it was separated from the Corsica-Sardinia Block (Bonardi et al., 2001; Critelli and Martín-Martín, 2022; Martín-Martín et al., 2023). The southeastward migration of the Calabrian Arc was periodically interrupted by episodes of collision between the adjacent tectonic plates (Amodio Morelli et al., 1976; Bonardi et al., 2001; Butler et al., 2004; Iannace et al., 2007). Discrete phases of forward arc migration were accompanied by the formation of oceanic sub-basins (Vavilov and Marsili) in the Tyrrhenian Sea and led to prolonged tectonic subsidence in the study area (Zecchin et al., 2020; Campilongo et al., 2022).

The evolution of the Crotone Basin was controlled by tectonic activity along the PSFZ and the RSFZ (Critelli, 1999; Critelli et al., 2014; Bonardi et al., 2001; Zecchin et al., 2012; Massari and Prosser, 2013; Zecchin et al., 2015, 2020; Civile et al., 2022; Mangano et al., 2022a,b; Criniti et al., 2023) (Fig. 1a and b). The early stages of basin evolution were accompanied by subsidence and accumulation of continental conglomerate deposits on the so-called Serravallian Unconformity (SU), also known as the basal unconformity (Zecchin et al., 2020), and by basin-shoulder uplift that generated the regional-scale Tortonian Unconformity (TU) (Zecchin et al., 2020 and references therein). During the Tortonian time, a phase of transpressional tectonics led to the development of NW-trending structures responsible for the emplacement of the Cariati Nappe, an Oligocene to Tortonian tectono-stratigraphic unit located in the northern part of the Crotone Basin (Muto et al., 2014, 2017) (Fig. 2, A-A' geological transect). Later, the Crotone Basin recorded the effects of the Messinian Salinity Crisis and alternating episodes of transtension and transpression (Borrelli et al., 2021, 2022; Zecchin et al., 2013a, 2013b, 2020). The considerable sea-level drop recorded during the Messinian event, in the order of several hundred of meters, was accompanied by transpressional tectonics and led to the exposure of the basin. This phase was marked by the development of the well-known Intra-Messinian (IMU) and Upper Messinian (UMU) unconformities (Zecchin et al., 2020; Borrelli et al., 2021, 2022). The IMU is associated with a stratigraphic hiatus spanning from ~5.60 to 5.55 Ma and formed during the main Mediterranean

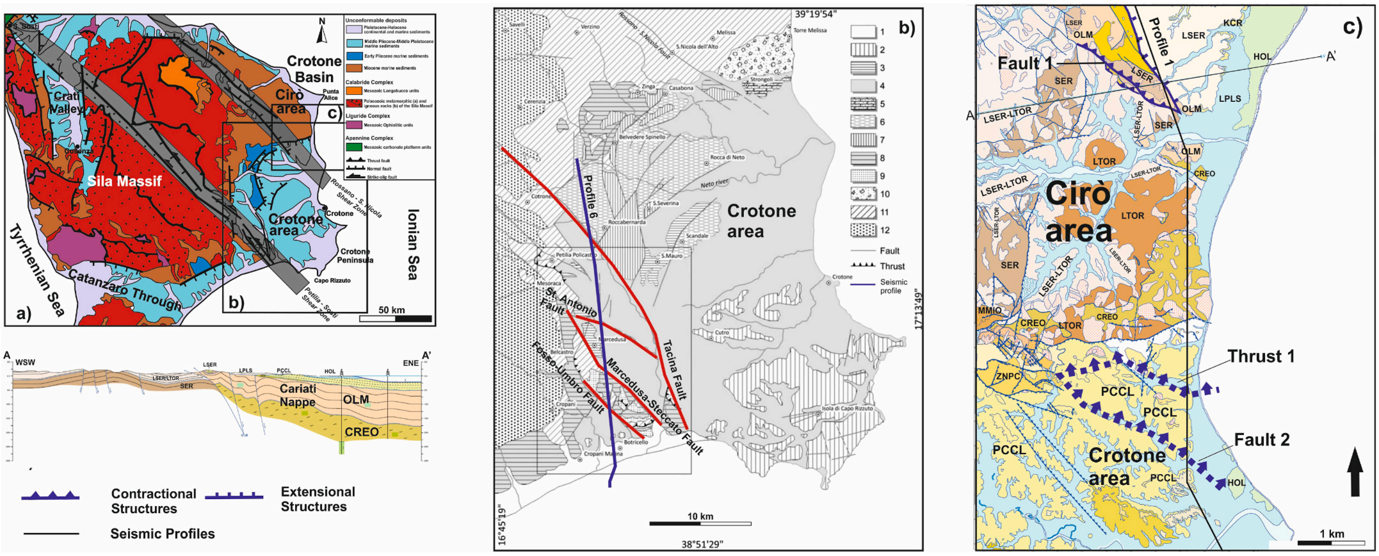

Fig. 2. a) Simplified geologic map of the northern sector of the Calabrian Arc showing the main fault zones, namely the Rossano-San Nicola and Petilia Sosti (see caption Fig. 1 for more details). b) Schematic geological map of the Crotone area (modified from Massari and Prosser, 2013) illustrating the main fault lineaments constituting the PSFZ, which are the Tacina, the Sant'Antonio, the Marcedusa-Steccato and the Fosso-Umbro faults. The location of the seismic Profile 6 is also displayed. c) Foglio Cirò 562 (modified from Critelli et al., 2014) illustrating the orientation of *Fault 1, Fault 2* and *Thrust* 1 that controlled the superimposition of the Cariati Nappe and the exhumation of Cirò area. A-A′ geological transect showing the Cariati Nappe. An E-W-oriented extensional fault separates the Cirò and the Crotone areas. Abbreviations: ACV-OLM: Early Oligocene – Late Miocene; ADC-ZNPC: Zanclean-Early Piacenzian; AV-CREO: Cretaceous – Eocene; CMD-LPLS: Late Pleistocene; KCR-PCCL: Piacenzian-Calabrian; LSER/LTOR: Late Serravallian – Late Tortonian; LSER: Late Serravallian; LTOR: Late Tortonian; MMIO: Middle Miocene; SER: Serravallian. 1. Recent coastal deposits; 2. Marine Terrace (Pleistocene); 3. Fluvial Terraces (Middle-Late Pleistocene); 4. Lamone Formation (Middle Pleistocene); 5. Arenaria di Strongoli (Gelasian); 6. Cutro Clay (Zanclean); 7. Zinga Group (Zanclean); 8. Cavalieri Marl and Timpone dei Giudei (Zanclean); 9. Carvane Group (Late Messinian); 10. Argille Scagliose (Middle Messinian); 11. Late Serravallian – Messinian; 12. Crystalline basement.

base-level drop (Clauzon et al., 1996, 2005; Butler et al., 1999; Krijgsman et al., 1999; Roveri et al., 2001, 2014; Hilgen et al., 2007; Zecchin et al., 2013a). The sudden base-level drop also induced isostatic/flexural rebound processes (DeCelles and Cavazza, 1995; Krijgsman et al., 1999; Hilgen et al., 2007; Barone et al., 2008; Govers et al., 2009; Massari and Prosser, 2013; Muto et al., 2014). In contrast, the UMU is inferred to be linked to incipient collision and temporary coupling of the NE part of the Calabrian Arc with the Apulian microplate around 5.42 Ma (Massari and

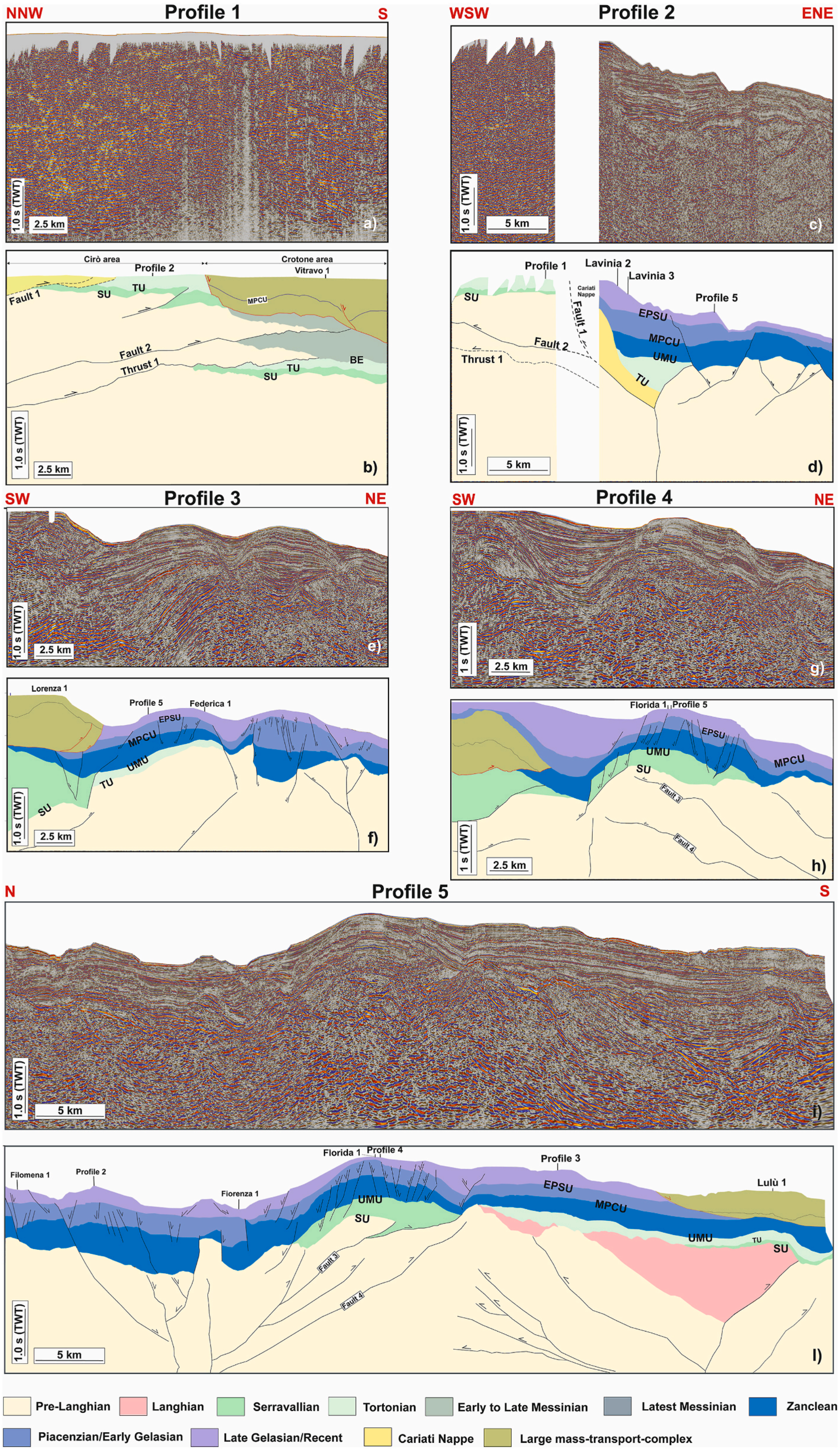

Fig. 3. Uninterpreted and interpreted seismic profiles 1 to 5 a) to l) showing the main seismic-stratigraphic units separated by unconformities. Black-colored segments indicate faults. Abbreviations: SU – Serravallian Unconformity; TU – Tortonian Unconformity; UMU – Upper Messinian Unconformity; MPCU – Middle Pliocene Unconformity; EPSU – Early Pleistocene Unconformity. See Fig. 5 for their locations. Seismic data have been provided by ENI Natural Resources.

Prosser, 2013).

In the Early Pliocene (Zanclean), the Crotone Basin experienced widespread subsidence associated with the onset of ocean spreading in the Vavilov sub-basin in the Tyrrhenian Sea. This event, which started at ca. 4.2 Ma, coincides with the onset of slope instability in the Crotone Basin (Feraud, 1990; Massari and Prosser, 2013; Zecchin et al., 2018, 2020; Mangano et al., 2020, 2021, 2022b,2023b). A second Pliocene tectonic episode took place at the Zanclean-Piacenzian boundary and was associated with transpressive movements along the NW-trending shear zones. It led to a general uplift of the Crotone Basin, resulting in the formation of the Mid-Pliocene Unconformity (MPCU; Zecchin et al., 2004a; 2012, 2015). This transpressive episode was responsible for the onset of the Crotone Megalandslide (Minelli et al., 2013; Zecchin et al., 2018; Mangano et al., 2020, 2021, 2022b, 2023a).

Following the Late Pliocene (Piacenzian) tectonic subsidence concomitant with ocean spreading in the Vavilov Basin, the Crotone Basin recorded another transpressional event in the Gelasian, which led to the formation of the so-called Early Pleistocene Unconformity - EPSU (Zecchin et al., 2012, 2015). A phase of rapid tectonic subsidence and basin collapse occurred during the Late Gelasian in parallel with the opening of the Marsili sub-basin in the Tyrrhenian Sea at 2.3–2.1 Ma (Zecchin et al., 2012, 2015). Later in the 'mid' Pleistocene, the Calabrian Arc was affected by transpressional tectonics at ~1.2–1.1 Ma, as recorded by the well-known Mid-Pleistocene unconformity (MPSU; Zecchin et al., 2020). Following this phase, the Crotone Basin underwent rapid uplift at the order of ~1 mm/yr, as documented by the formation of marine terraces along the coast (Gliozzi, 1987; Zecchin et al., 2004b; 2011).

Following Zecchin et al. (2020), in this study we adopted a wider meaning for the Crotone Basin, which is composed of three areas: the Crotone area to the south, the Cirò area to the north and the offshore area (Fig. 1b). The Crotone and the Cirò areas, separated by an E-W-oriented extensional fault (Fig. 1b), evolved together until the Late Tortonian/Early Messinian and then developed in a different way (Zecchin et al., 2020).

3. Data and methods

A dataset consisting of 2D seismic reflection profiles and wells (Figs. 3–5), provided by ENI National Resources (the main Italian energy company), integrated with information from field geology studies were used in this work. The interpretation of seismic data is based on the recognition of key reflectors (generally corresponding to lithological changes and/or unconformities) bounding seismic units characterized by different seismic facies and/or configuration patterns, reflector terminations, depth (TWT) and thickness of the units. Regional unconformities were identified on seismic reflection profiles and calibrated on the basis of well stratigraphy information and literature data.

4. Results

4.1. The Serravallian to Pleistocene unconformities and their distribution along the Crotone Basin

4.1.1. Serravallian Unconformity

The Serravallian Unconformity (SU) was locally recognized in both the onshore and offshore sectors of the Crotone Basin and corresponds to the base of the Serravallian San Nicola Formation (Zecchin et al., 2020; Arcuri et al., 2023). On the basis of correlations between seismic lines and wells (Figs. 3–5), this unconformity is associated with a medium-to high-amplitude reflector found between ca. 0.3 s (TWT) and ca. 3 s (TWT) in seismic profiles. This reflector is deformed by various transpressional faults that dip to the N, SW and NE depending on the location, and form structural highs and lows (Fig. 3h, l, 4 d).

The SU truncates the reflectors of the underlying units, while the overlying reflectors show onlap and downlap terminations with it. In the Cirò area, the SU was uplifted by the activity of the tectonic structure named: *Thrust 1* and *Fault 2* (see Fig. 3b–d).

4.1.2. Tortonian Unconformity

The Tortonian Unconformity (TU) was locally interpreted in the offshore sector of the basin and in the Cirò area, and constitutes the base of the Tortonian Unit (Zecchin et al., 2020). Based on the correlation between seismic profiles and wells, it was found between ca. 1.3 s (TWT) and ca. 2.9 s (TWT), and is associated with a medium-to high amplitude reflector (Fig. 3b,d, f, l, 4 d, 5), In the offshore sector, the TU has been identified in two positive flower structures associated with the activity of the RSFZ (Mangano et al., 2023a); while in the flower structure located to the S, the TU shows an antiformal geometry (Fig. 3l), in the northern sector the TU dips abruptly towards the W and represents the backlimb of the Cariati Nappe, which is onlapped by the Tortonian deposits (Fig. 3d).

4.1.3. Base of Evaporites

The Base of Evaporites (BE) has been identified in the Crotone area and in the S offshore sector. It is associated with the base of the Messinian Unit. Based on the available wells and seismic data, the BE was found between ca. 0.2 s (TWT) and ca. 2.1 s (TWT), and is associated with a medium-amplitude reflector (Figs. 3b, 4b and 5). In the N Crotone area, the BE is displaced by a N-dipping transpressional fault (*Fault 2*) and forms the base of a depocentre filled by over 1.5 s (TWT) thick Messinian and Plio-Pleistocene deposits (Fig. 3b).

4.1.4. Upper Messinian Unconformity

The Upper Messinian Unconformity (UMU) was recognized in both the onshore and offshore sectors of the basin and corresponds to the base of the Zanclean Unit (Zecchin et al., 2020). On the basis of wells and seismic lines, it was identified up to ca. 2.6 s (TWT) and is associated with a medium-to high amplitude reflector (Fig. 3d–f, h, l, 4 b, d, 5). This reflector seems to be deformed by the activity of WSW-, ENE-, SW-, NE-N-, S-dipping transpressional faults and shows both antiformal and sinformal geometries (Fig. 3f–h, l, 4 b). The UMU truncates the underlying reflectors, while the overlying reflectors show downlap and onlap terminations against it. In the N offshore sector, the UMU is part of the backlimb of the Cariati Nappe, where it is onlapped by the Zanclean deposits (Fig. 3d). In the Crotone area, the UMU is displaced by the Tacina, Sant'Antonio, Marcedusa-Steccato and Fosso-Umbro faults, which are part of the PSFZ, and characterized by both transtensional and transpressional movements Massari and Prosser (2013); Civile et al. (2022), (Fig. 4d).

4.1.5. Zanclean Surface

The Zanclean Surface (ZS) was interpreted in the S sector of the Crotone area and represents the top of the Latest Messinian Unit (Zecchin et al., 2020) (Fig. 4b). Based on geological maps (Fig. 2b) and the high acoustic impedence contrast in seismic profile 6 (Fig. 4a), the ZS has been associated with a high amplitude reflector that reaches a depth of 1.6 s (TWT). The ZS onlaps the underlying reflectors and is onlapped by the overlying Zanclean Unit. The ZS is also dissected by two N- and S-dipping shear surfaces, inferred to be the subsurface counterpart of the Sant'Antonio and Marcedusa-Steccato faults (Fig. 4b).

4.1.6. Mid-Pliocene Unconformity

The Mid-Pliocene Unconformity (MPCU) was interpreted in the whole basin and represents the base of Piacenzian/Early Gelasian deposits (Zecchin et al., 2020). On the basis of the available wells, it has been found between ca. 0.1 s (TWT) and ca. 2.0 s (TWT), and correlated with a medium-to high-amplitude reflector in seismic profiles (Fig. 3d–f, h, l, 4 b, d, 5). For most part of the offshore area, the MCPU is a correlative conformity and is deformed by WSW-, ENE-, SW-, NE-, S- and N-dipping transpressional and transtensional faults, which led to the formation of antiformal and sinformal geometries. In the Crotone area,

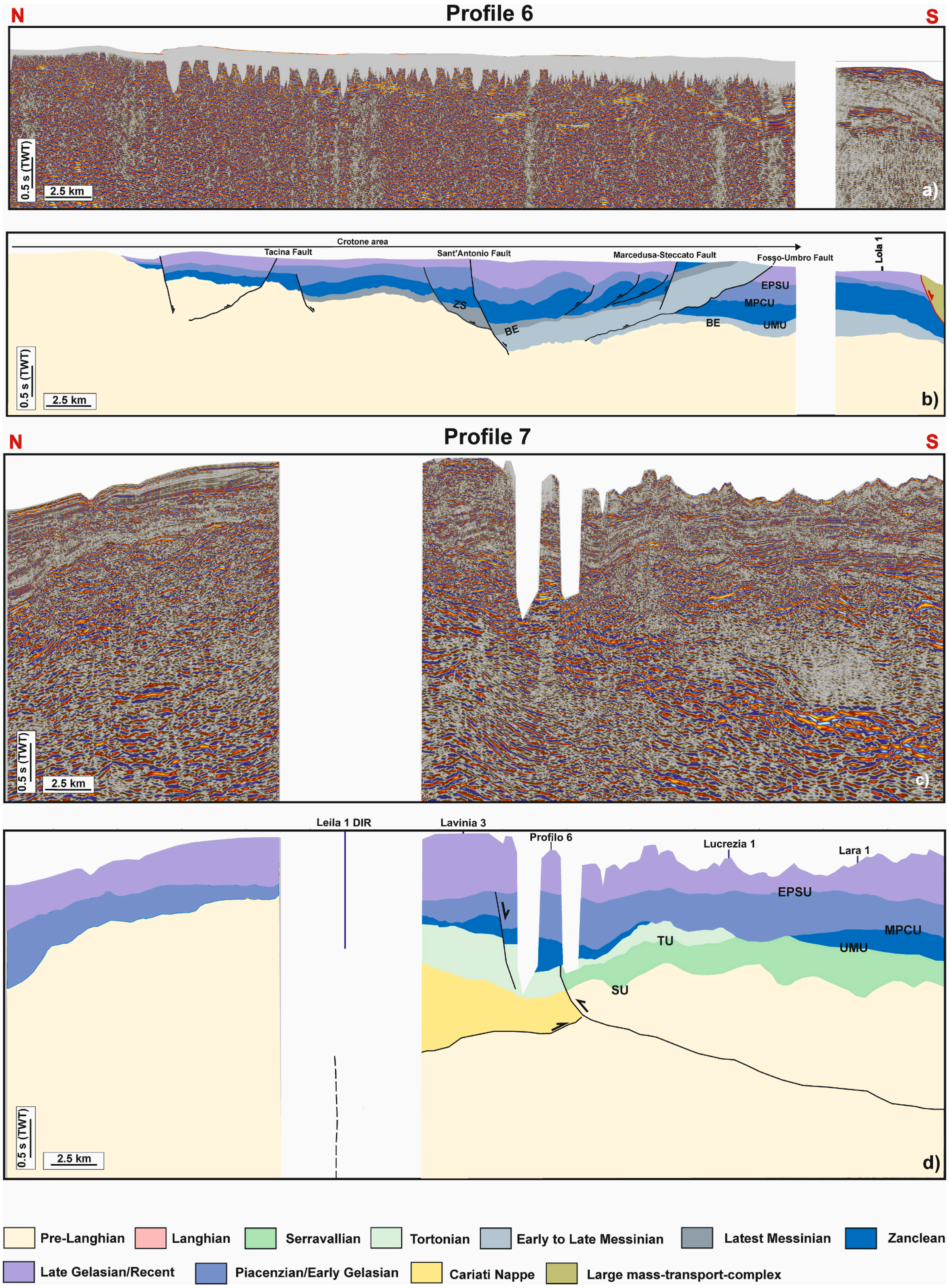

Fig. 4. Uninterpreted and interpreted seismic profiles 6 and 7 a) to d) showing the main seismic-stratigraphic units separated by unconformities. Black-colored segments indicate faults. Abbreviations: SU – Serravallian Unconformity; TU – Tortonian Unconformity; UMU – Upper Messinian Unconformity; ZS – Zanclean Surface; MPCU – Middle Pliocene Unconformity; EPSU – Early Pleistocene Unconformity. See Fig. 5 for their locations. Seismic data have been provided by ENI Natural Resources.

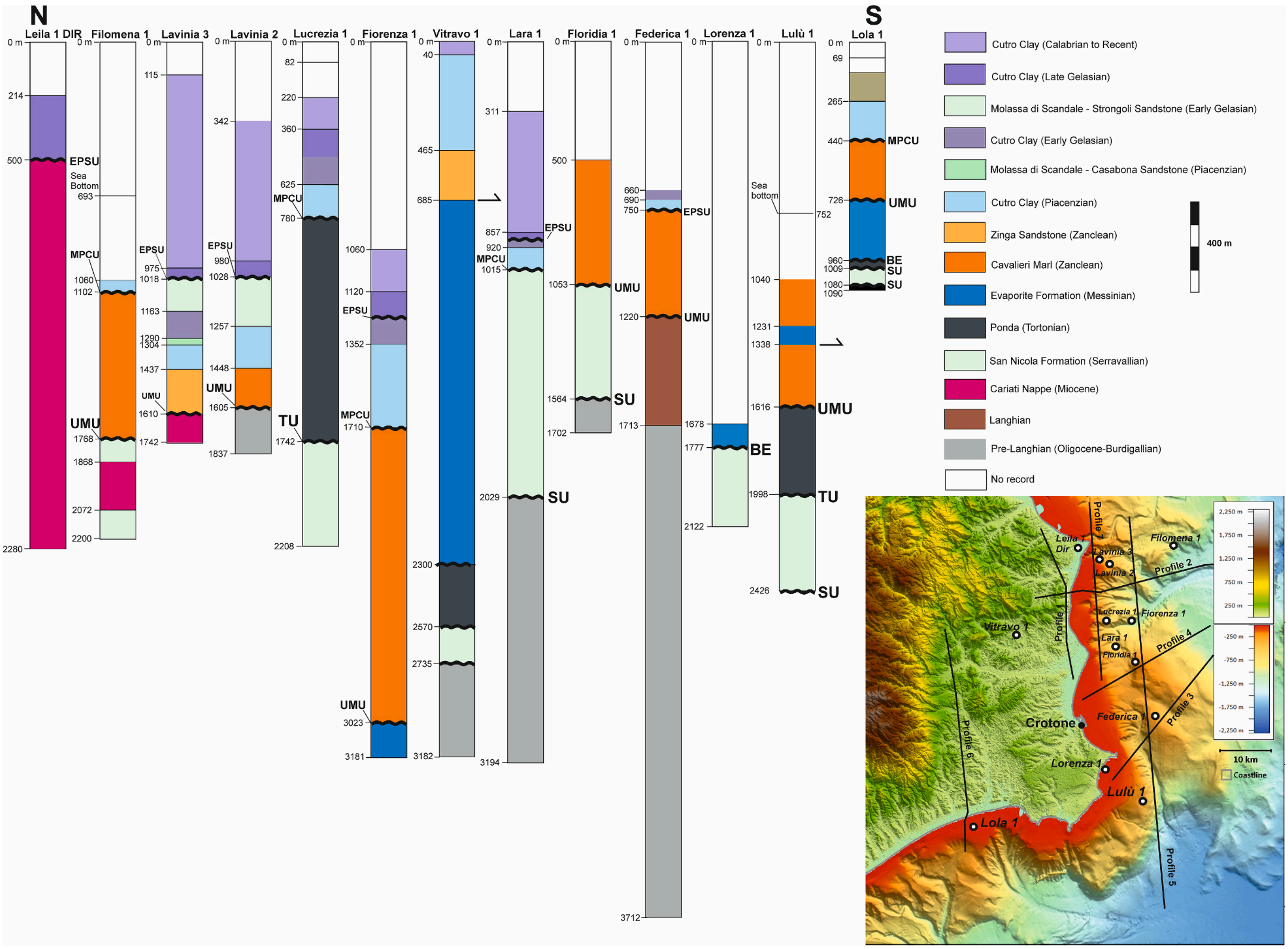

Fig. 5. Available wells have been provided by ENI National Resources. Locations of both wells and seismic profiles are illustrated on the right corner. See captions Figs. 3 and 4 for abbreviations.

the MPCU has been deformed by the Crotone Megalandslide (Zecchin et al., 2018; Mangano et al., 2020) (Fig. 3b). In the southern sector of the Crotone area, the MPCU is dissected by the Tacina, Sant'Antonio, Fosso Umbro and Marcedusa-Steccato faults associated with the PSFZ (Massari and Prosser, 2013; Civile et al., 2022) (Fig. 4b).

4.1.7. *Early Pleistocene Unconformity*

The Early Pleistocene unconformity (EPSU) was recognized in the whole offshore sector and represents the base of the Late Gelasian deposits (Zecchin et al., 2020). Based on the correlation between wells and seismic lines, it was identified between ca. 0.3 s (TWT) and ca. 1.2 s (TWT), and is associated with a medium-amplitude reflector (Fig. 3d–f, h, l, 4 b, d, 5). With respect to Zecchin et al. (2012, 2015, 2020), according to whom the EPSU was recognized as unconformable, in the present study the latter appears as a correlative conformity and is found both in morphological highs and depocenters in the distal area. This topography is seen to have been influenced by the activity of WSW-, ENE-, SW-, NE-, S- and N-dipping transpressional and transtensional faults (Fig. 3d–f, h, l).

4.2. *Shear zones in the Crotone Basin*

4.2.1. *The rossano-san-nicola fault zone (RSFZ)*

The RSFZ consists of several NW-oriented fault segments characterized by an alternation of transtensional and transpressional tectonic activity. These structures affect the mid-Miocene to Quaternary seismo-stratigraphic deposits and formed structural highs and depocentres (Figs. 3 and 4).

According to Muto et al. (2014, 2017), seismic profiles in the N Cirò area reveal a N-dipping shear surface associated with a SW-verging fault, named here as *Fault 1* (Fig. 3b–d). Towards the S, two contractional-transpressional faults, named *Fault 2* and *Thrust 1,* were identified (Fig. 3a–d). These faults dissect the Pre-Langhian-Tortonian deposits together with the SU and TU unconformities, while *Fault 2* dissects the Messinian units as well as the BE surface and is in turn cut by the basal shear surface of the Crotone Megalandslide (Mangano et al., 2021). It is assumed that *Fault 1* and *2* are connected to a deep-seated subvertical fault that generated a positive flower structure showing an orientation comparable with that of the RSFZ (Fig. 3d and 6). Following Zecchin et al., 2020, *Thrust 1* has been associated with the inferred S-verging thrust resulted in the uplifted Cirò area (Fig. 3b–d). In the E offshore sector, two deep-rooted faults dipping to the N and NE, here named *Fault 3* and *Fault 4,* are seen to crosscut reflectors of Pre-Langhian to Serravallian units and define a structural high delimited at the top by the UMU (Fig. 3h–l). It cannot be ruled out that the activity of such transpressional faults has driven the development of older structural highs defined by the SU (Fig. 3h–l). The orientation of these transpressional faults is similar to that shown by the outcropping fault system forming the RSFZ (Fig. 6).

Along the entire E offshore sector, the MPCU and EPSU along with

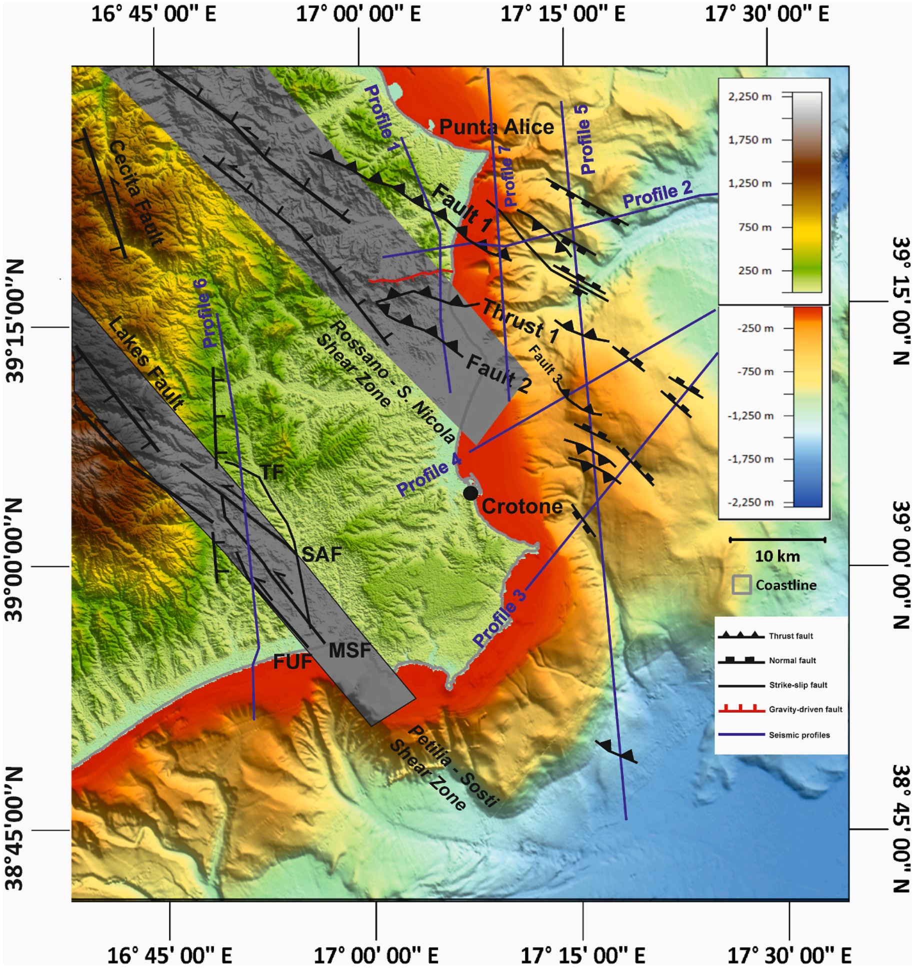

Fig. 6. Digital Terrain Model (DTM) map in projection UTM 33 (WGS84) of the onshore and offshore parts of the Crotone Basin showing the main fault segments belonging to the RSFZ and PSFZ. The DTM map was modified from Civile et al. (2022) and was generated using the following freely available datasets: The land data derived from: SRTM (Shuttle Radar Topography Mission) worldwide digital elevation data with 30 m (1 arc-second) resolution, released by NASA (SRTM PLUS Version 3.0) and made available by the U.S. Geological Survey (https://lpdaac.usgs.gov/search/); TinItaly DEM, a digital elevation model of the whole Italian territory that is available as a 10 m cell size grid (Tarquini et al., 2012, 2012; http://tinitaly.pi.ingv.it/Download_Area2.html). The bathymetry data derived from EMODnet Digital Terrain Model with a 1/16 * 1/16 arc minutes grid resolution (about 115-115 m), and extracted from the following link: https://www.emodnet.bathymetry.eu/. The vector data (coastline) derived from Copernicus, which is the European Union's earth observation programme based on satellite and in situ observations (https://land.copernicus.eu/imagery-in-situ/eu-hydro/eu-hydro-river-network-database). Structural map of the main elements recognized in seismic profiles.

the Zanclean to Recent deposits are deformed and dissected by a set of N-, NE-, S-, WSW- and ENE-dipping high-angle transtensional faults that define small-scale depocentres. and exhibit the same orientation as the outcropping NW-oriented structural lineaments of the RSFZ (Fig. 3d–f, h, l).

4.2.2. *The Petilia-Sosti Fault Zone*

The PSFZ consists of main fault branches represented by the Tacina, Sant'Antonio, Marcedusa-Steccato and Fosso-Umbro faults (Van Dijk, 1994; 2000; Massari et al., 2010; Massari and Prosser, 2013; Civile et al., 2022), and some other minor structures that dissect all the seismo-stratigraphic units and unconformities of the Mid-Miocene to Quaternary succession of the Crotone Basin (Fig. 4b). Along the W and SW sectors of the CB, seismic profiles document the presence of S- and N-ward dipping faults that displace Messinian to Recent deposits, as well as the BE, the UMU, the ZS and the MPCU (Fig. 4b). Following Massari and Prosser (2013) and Civile et al. (2022) (Fig. 2b), these fault segments may be associated with the subsurface counterpart of the outcropping Tacina, Sant'Antonio, Marcedusa-Steccato and Fosso Umbro faults. The two fault segments corresponding to the Sant'Antonio and Marcedusa-Steccato faults define a tectonic trough hosting Messinian to Quaternary units, which show lateral thickness changes. Within this tectonic trough, the Latest Messinian and Pliocene units form onlap relationships with the UMU and the ZS, perfectly matching the well-known Early Pliocene transgressive phase. A relative raised position of the Messinian Unit between the Marcedusa-Steccato and Fosso-Umbro faults, can also be appreciated in the S Crotone area (the southernmost part of seismic Profile 6, Fig. 4b).

5. Discussion

Although many authors contributed in the last decades to establish the basis of the stratigraphic and structural framework of Crotone Basin, questions that deserve further investigation related to the structural and stratigraphic record regards i) the timing of the emplacement of the Cariati Nappe, ii) the differentiation of the evolution between the Crotone and the Cirò areas, iii) the occurrence of very thick Messinian deposits in the northernmost Crotone area, in contrast with their absence in its offshore counterpart and in the Cirò area, iv) the characterization of the headwall region and timing of the large gravitational collapse. The analyses of high penetration data reveal before anything else the presence of a positive flower structure, inferred to be part of the RSFZ.

Such positive flower structure stands out as a key player that answers all the aforementioned questions. One more relevant advance in this study shows for the first time the subsurface counterpart of the PSFZ and provides an important update of the structural-stratigraphic framework of the Crotone Basin.

5.1. Serravallian and Tortonian

The opening of the Crotone basin dates back to the Serravallian, following a phase of basin uplift that contributed to the development of the SU (Zecchin et al., 2020 and references therein). The present data suggest that conditions of subaerial exposures leading to the formation of the SU persisted also in the considered part of the modern offshore sector, not only in the exposed part of the basin. Seismic profiles document that the SU truncates the underlying reflectors and delimit some structural highs (Fig. 3h, l, 4 d). This evidence suggests that the marine area during the formation of the SU was placed further seaward toward the Ionian Sea.

The CB was dominated by a long-lasting subsidence phase during the Late Serravallian to Tortonian, despite an episode of tectonic tilting along the basin margin that led to the formation of the TU. The present data show that the TU is only found locally along the offshore sector, confirming previous results by Zecchin et al. (2020), which highlighted a development of the TU limited to the Cirò area. At the greater detail, considering that the TU is not found in the Crotone area, we exclude the occurrence of an extra-regional tectonic event and for this reason we infer that the TU terminates against the SU in the offshore counterpart of the Crotone area (Fig. 3l).

During the Late Tortonian, the Cirò area was affected by a transpressional tectonic regime that determined the superposition of the Cariati Nappe. This event occurred through the activation of a SW-verging transpressional fault "*Fault 1*" (Fig. 3b–d), which crosscut the Serravallian and Tortonian deposits, confirming the previous observations by Muto et al. (2014, 2017). A novelty of this study is the discovery that *Fault 1* connects to a NW-oriented positive flower structure, the position of which corresponds to that of the RSFZ (Fig. 3b–d, 6).

5.2. Latest Tortonian to Late Messinian

In order to justify the relative raised position of the Serravallian-Tortonian deposits of the Cirò area with respect to the Plio-Pleistocene succession of the Crotone area, Zecchin et al. (2020) hypothesized the presence of a S-verging thrust that also drove the formation of an E-W oriented depocenter in the Crotone area that accommodated the deposition of a ca. 1600 m thick Messinian Evaporites. According to the current results, the activity of a S-verging thrust (*Thrust 1*, Fig. 3b–d) during the Messinian is confirmed as a first-order control on the uplifting of the Cirò area as well as on the development of E-W-oriented depocenter in the Crotone area (Figs. 2 and 3b, d). We infer that such thrust shows a different orientation with respect to the RSFZ due to the distribution of the Messinian sediments filling the depocenter in the Crotone area along a E-W transect (Zecchin et al., 2020). Our inference is also supported by the model provided by Hancock (1985), according to whom dextral stress field in trascurrent regime along N140° trending shear zones generate E-W-oriented thrusts. In fact, dextral activation along the NW-trending shear zones in the Crotone Basin is documented throughout the Messinian with the associated inception of E-W-oriented anticlines (Massari and Prosser, 2013).

The available data allow to document that the offshore sector turned into a structural high and probably led to overall exposure conditions during the Late Messinian, as confirmed by the direct overlap of Zanclean on Tortonian and Serravallian deposits (Fig. 3f–h, l). This observation confirms previous findings from Zecchin et al. (2020), who already recognized an offshore structural high during the Late Messinian mainly based on core data. A linkage between such structural high and the RSFZ cannot be ruled out, as the deep-rooted fault segments (*Fault 3* and *Fault 4*) inferred to have controlled such structural high show an orientation compatible with that exhibited by the outcropping lineaments that compose the RSFZ (Fig. 3h, l, 6).

The sea-level lowering associated with the Messinian salinity crisis is inferred to have triggered isotastic/flecxural rebound processes, leading to exhumation and exposure conditions (DeCelles and Cavazza, 1995; Cavazza and DeCelles, 1998; Krijgsman et al., 1999; Hilgen et al., 2007; Govers et al., 2009). Conversely, the driving mechanism that drove the contractional/transpressional activity of the RSFZ in the completion of the Cirò and offshore structural highs, as well as the UMU, in the Late Messinian (ca. 5.4 Ma) is related to incipient collision and temporary coupling of the NE sector of the Calabrian Arc with the Apulian margin (Massari and Prosser, 2013).

A phase of extensional/transtensional tectonics during the Messinian was already documented by Massari and Prosser (2013), who have recognized the presence of transtensional faults that define a tectonic trough in the SW onshore area. Evidence of syn-sedimentary tectonics are also inferred from this study, where reflectors of Latest Messinian units are observed to show a fan-like geometry between the Sant'Antonio and Marcedusa-Steccato (Fig. 4b).

5.3. Zanclean to Piacenzian

Phases of extensional/transtensional tectonics were exterted by the PSFZ during the Zanclean in the SW sector of the Crotone Basin, where new data document onlap relationships between Zanclean Unit and the ZS inside a depocenter bounded by the Sant'Antonio and Marcedusa-Steccato faults (Fig. 4b). In light of this interpretation, we found a confirmation on previous studies, according to which the Zanclean was characterized by extensional/transtensional phases (Massari and Prosser, 2013; Zecchin et al., 2015, 2020). Further episodes of Zanclean extensional/transtensional tectonics are also inferred along the E offshore, where differences in thickness between the hangingwall and footwall are observed inside a depocenter controlled by fault lineaments belonging to the RSFZ (Figs. 3f and 6). The subsequent phase of contractional/transpressional tectonics occurred at the transition between the Zanclean and the Piacenzian is well constrained by the present data, as a reverse-component reactivation of the Fosso-Umbro and Marcedusa-Steccato faults, responsible for the development of a structural high along the southernmost part of the Crotone area, is recognizable (the southernmost part of seismic Profile 6, Fig. 4b). In this sector, Messinian to Zanclean units are seen to be raised with respect to the Zanclean to Quaternary units adjacent to the structural high and are bounded by two fault segments inferred to correspond to the Fosso-Umbro and Marcedusa-Steccato faults.

One of the most remarkable results from this study is that also *Fault 2* is part of the positive flower structure belonging to the RSFZ and responsible for the emplacement of the Cariati Nappe during the Late Tortonian (Fig. 3b–d). In light of this interpretation, the RSFZ is documented to have been an important player in the differentiation between the Cirò and the Crotone areas, determining a lateral contact between the Serravallian - Tortonian deposits to the N and the Plio-Pleistocene deposits to the S (Fig. 2). Despite the MPCU passes into a correlative unconformity towards the distal area, such unconformity has an extra-basinal significance, linked to the main tectonic events leading to basin uplift and closure (Zecchin et al., 2015, 2020).

One of the main achievements from this study regards timing and control factors of the large gravitational collapse involving the Crotone area. According to Mangano et al. (2020) the updip extensional domain of such large gravitational collapse is compatible with the presence of a fault set showing an arcuate pattern connected to an E-W-oriented normal fault in the N Crotone area. In fact, the integration between seismics and geological maps from this study recognized that the extensional fault set is the outcropping counterpart of a buried seaward dipping shear surface representing the basal detachment of the large-scale gravitational collapse (Fig. 3b). Importantly, one can see that such basal detachment surface dissects the front of the *Fault 2*, part of the positive flower structure composing the RSFZ, as well as the MPCU, which assumes a lobate shape typical of blocks composing the extensional domain of mass-transport complexes (Bull et al., 2009) (Fig. 3b). Based on this evidence, transpressional tectonics associated with the activity of the RSFZ at the end of the Zanclean is likely to have increased the slope gradient and contributed to the inception of the large-scale gravitational collapse (Zecchin et al., 2018; Mangano et al., 2020). At the regional scale, the Zanclean extensional/transtensional tectonic regime is associated with forward migration of the Calabrian Arc and active subduction of the Ionian lithosphere, concomitant with the spreading of the Vavilov sub-basin in the Tyrrhenian back-arc area (Zecchin et al., 2012, 2015, 2020).

In contrast, the Latest Zanclean - Earliest Piacenzian tectonic phase might be related to a temporary pause of the arc migration, due to the convergence between the Calabrian accretionary system and the continental crust of the Apulian margin (Fabbri et al., 1982; Van Dijk, 1991; Van Dijk and Scheepers, 1995; Doglioni et al., 1996; Gueguen et al., 1998; Sartori, 2003; Praeg et al., 2009), concurrently with a temporary spreading interruption or slowdown in the Vavilov sub-basin (Zecchin et al., 2012, 2020).

5.4. Early Gelasian to recent

We favour the scenario that contractional/transpressional activity took place during the Early Gelasian as documented by the folding of the EPSU. It is not excluded that the Early Gelasian contractional/transpressional tectonic event have occurred also along the PSFZ and completed the evolution of the structural high in the S sector of the Crotone area, through the reverse-component reactivation of the Fosso-Umbro Fault. This is documented by the relative raised position of the Messinian to Zanclean Units bounded to the SW by the NE-dipping fault segments corresponding to the Fosso-Umbro Fault (Fig. 2b and 4b). In consideration of our interpretations, this study confirms phases of contractional/transpressional tectonics highlighted by previous authors (Zecchin et al., 2020 and reference herein). This study also confirms that further episodes of extensional/transtensional tectonics followed the Early Gelasian tectonic regime. In fact, tectonic subsidence is documented in the E offshore sector, where Late Gelasian reflectors appear to be dissected by transtensional faults and form depocenters (Fig. 3f). According to Zecchin et al. (2012), the contractional/transpressional tectonic event is inferred to be linked with the termination of the migration of northern Calabria toward the Apulian plate and with the end of the development of the Vavilov sub-basin. In contrast, the Late Gelasian tectonic subsidence is inferred to be coeval with the onset of oceanization of the Marsili sub-basin (Massari et al., 2010; Zecchin et al., 2012; Massari and Prosser, 2013) occurred at ca. 2.1 Ma (Nicolosi et al., 2006), and with a contemporaneous clockwise rotation of ca. 20° and SE-ward migration of the arc (Speranza et al., 2011; Mattei et al., 2004, 2007; Chiarabba et al., 2008).

6. Conclusions

The integration of seismic reflection profiles, well data and geological maps has allowed to provide an update of the structural-stratigraphic framework of the CB. The main conclusions are as follow.

- Conditions of subaerial exposure and erosion are inferred to have characterized the modern offshore area, just before the basin opening, as the SU is observed to truncate the underlying reflectors in this sector.
- The activity of the S-verging thrust, which occurs during a right-lateral kinematic stage associated with the RSFZ led to the uplift of the Cirò area, concomitant with the development of an E-W-oriented depocenter in the N Crotone area during the Messinian. This is documented by a N-dipping shear surface below the raised position of the Serravallian/Tortonian sediments of the Cirò area. This shear surface terminates before an up to 1600 m thick depocenter filled by Messinian to Plio-Pleistocene sediments.
- The presence of a positive flower structure associated with the RSFZ has been recognized for the first time. Its activity drove the superimposition of the Cariati Nappe, completed the formation of the Cirò area and contributed to trigger the large-scale gravitational collapse involving the basin. This is proven by the presence of two major faults giving rise to a positive flower structure, whose orientation is compatible with that of the RSFZ. One of this two faults lies below the Cariati Nappe, whereas the second one appears below the Cirò area and is crosscut by the basal detachment of the large gravitational collapse.
- Continental settings dominated the present-day offshore area of the CB during Late Messinian, as this sector turned into a structural high probably due to the activity of the RSFZ. The structural lineaments that controlled such structural high show an orientation compatible with that of the RSFZ and are seen to deform the UMU which constitutes a direct contact between Zanclean and Tortonian or even older sediments.
- Phases of basin subsidence occurred during the Zanclean, Piacenzian and since the Late Gelasian in the SW onshore as well as in the offshore, where transtensional faults are seen to define small depocenters.

Funding

No funding was received for this work.

CRediT authorship contribution statement

Giacomo Mangano: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Massimo Zecchin:** Writing – review & editing, Visualization, Validation, Supervision, Formal analysis, Data curation, Conceptualization. **Dario Civile:** Writing – review & editing, Validation, Formal analysis, Data curation, Conceptualization. **Salvatore Critelli:** Writing – review & editing, Validation, Investigation, Formal analysis, Conceptualization.

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.

Acknowledgments

Geophysical and geological data were provided by ENI Natural Resources.

References

Amodio Morelli, L., Bonardi, G., Colonna, V., Dietrich, D., Giunta, G., Ippolito, F., Liguori, V., Lorenzoni, S., Paglionico, A., Perrone, V., Picarretta, G., Russo, M., Scandone, P., Zanettin-Lorenzoni, E., Zuppetta, A., 1976. L'Arco calabro–peloritano nell'orogene appenninico–maghrebide. MemORIE. Soc. Geol. Ital. 17, 1–60.

Arcuri, N., Muto, F., Chiarella, D., Critelli, S., 2023. The Miocene deposits of the Cirò Basin in the evolution of the peri-Ionian region, eastern Calabria. Rendiconti Online Soc. Geol. It. 59, 145–151. https://doi.org/10.3301/ROL.2023.24.

Barone, M., Dominici, R., Muto, F., Critelli, S., 2008. Detrital modes in a Late Miocene wedge-top basin, northeastern Calabria, Italy: compositional record of wedge top partitioning. J. Sediment. Res. 78, 693–711.

Bonardi, G., Cavazza, W., Perrone, V., Rossi, S., 2001. Calabria-Peloritani terrane and northern Ionian sea. In: Anatomy of an Orogen: the Apennines and Adjacent Mediterranean Basins. Springer, Dordrecht, pp. 287–306.

Borrelli, M., Perri, E., Critelli, S., Gindre-Chanu, L., 2021. The onset of the Messinian Salinity Crisis in the central Mediterranean recorded by pre-salt carbonate/evaporite deposition. Sedimentology 68, 1159–1197. https://doi.org/10.1111/sed.12824.

Borrelli, M., Perri, E., Avagliano, D., Coraggio, F., Critelli, S., 2022. Paleogeographic and sedimentary evolution of north calabrian basins during the messinian salinity crisis (south Italy). Mar. Petrol. Geol. 141, 105726.

Brutto, F., Muto, F., Loreto, M.F., De Paola, N., Tripodi, V., Critelli, S., Facchin, L., 2016. The neogene-quaternary geodynamic evolution of the central Calabrian Arc: a case study from the western catanzaro trough basin. J. Geodyn. 102, 95–114.

Bull, S., Cartwright, J., Huuse, M., 2009. A review of kinematic indicators from mass-transport complexes using 3D seismic data. Marine and Petroleum Geology 26 (7), 1132–1151.

Butler, R.W.H., Mazzoli, S., Corrado, S., De Donatis, M., Di Bucci, D., Gambini, R., Naso, G., Nicolai, C., Scrocca, D., Shiner, P., Zucconi, V., 2004. Applying thick-skinned tectonic model to the Apennine thrust belt of Italy: limitations and implications. In: McClay, K.R. (Ed.), Thrust Tectonics and Hydrocarbon System, vol. 82. AAPG Memoir, pp. 647–667.

Butler, R.W.H., McClelland, E., Jones, R.E., 1999. Calibrating the duration and timing of the Messinian salinity crisis in the Mediterranean: linked tectonoclimatic signals in thrust-top basins of Sicily. J. Geol. Soc. London 156, 827–835.

Campilongo, G., Campilongo, E., Catanzariti, F., Muto, F., Ponte, M., Critelli, S., 2022. Subsidence analysis by mean of DeGloT software: application to the key-case of the miocene-quaternary Crotone Basin (Calabria, S. Italy). Mar. Petrol. Geol. 146, 10596 https://doi.org/10.1016/j.marpetgeo.2022.105964.

Cavazza, W., DeCelles, P.G., 1998. Upper Messinian siliciclastic rocks in southeastern Calabria (southern Italy): palaeotectonic and eustatic implications for the evolution of the central Mediterranean region. Tectonophysics 298, 223–241.

Catuneanu, O., Willis, A.J., Miall, A.D., 1998. Temporal significance of sequence boundaries. Sediment. Geol. 121 (3–4), 157–178.

Cella, F., Cirrincione, R., Critelli, S., Mazzoleni, P., Pezzino, A., Punturo, R., Fedi, M., Rapolla, A., 2004. Gravity modeling in fold-thrust belts: an example from the Peloritani Mountains, southern Italy. International Geology Review 46 (11), 1042–1050.

Ceramicola, S., Praeg, D., Coste, M., Forlin, E., Cova, A., Colizza, E., Critelli, S., 2014. Submarine mass-movements along the slopes of the active Ionian continental margins and thier consequences for marine geohazards (Mediterranean Sea). In: Krastel, S., et al. (Eds.), Submarine Mass Movements and Thier Consequences, Advances in Natural and Technological Hazards Research 37. Springer International Publishing Switzerland, pp. 295–306.

Chiarabba, C., De Gori, P., Speranza, F., 2008. The southern Tyrrhenian subduction zone: deep geometry, magmatism and Plio-Pleistocene evolution. Earth Planet Sci. Lett. 268 (3–4), 408–423.

Cifelli, F., Rossetti, F., Mattei, M., 2007. The architecture of brittle postorogenic extension: results from an integrated structural and paleomagnetic study in north Calabria (southern Italy). Geol. Soc. Am. Bull. 119, 221–239.

Civile, D., Zecchin, M., Tosi, L., Da Lio, C., Muto, F., Sandron, D., Affatato, A., Accettella, D., Mangano, G., 2022. The Petilia-Sosti Shear Zone (Calabrian Arc, southern Italy): an onshore-offshore regional active structure. Mar. Petrol. Geol. 141, 105693.

Clauzon, G., Suc, J.-P., Gautier, F., Berger, A., Loutre, M.-F., 1996. Alternate interpretation of the Messinian salinity crisis: controversy resolved? Geology 24, 363–366.

Clauzon, G., Suc, J.-P., Popescu, S.-M., Marunteanu, M., Rubino, J.-L., Marinescu, F., Melinte, M.C., 2005. Influence of Mediterranean sea-level changes on the dacic basin (eastern paratethys) during the late Neogene: the mediterranean lago mare facies deciphered. Basin Res. 17, 437–462.

Conforti, M., Muto, F., Rago, V., Critelli, S., 2014. Landslide inventory map of north-eastern Calabria (South Italy). J. Maps 10 (1), 90–102.

Criniti, S., Borrelli, M., Falsetta, E., Civitelli, M., Pugliese, E., Arcuri, N., 2023. Sandstone petrology of the Crotone basin, Calabria (Italy) from well cores. Rendiconti Online della Società Geologica Italiana. https://doi.org/10.3301/ROL.2023.10, 59.

Critelli, S., 1993. Sandstone detrital modes in the Paleogene Liguride Complex, accretionary wedge of the southern Apennines (Italy). Journal of Sedimentary Research 63 (3), 464–476.

Critelli, S., 1999. The interplay of lithospheric flexure and thrust accomodation in forming stratigraphic sequences in the southern Apennines foreland basin system. Italy. Rendiconti Lincei 10 (4), 257–326.

Critelli, S., 2018. Provenance of Mesozoic to Cenozoic Circum-Mediterranean sandstones in relation to tectonic setting. Earth Sci. Rev. 185, 624–648.

Critelli, S., Martín-Martín, M., 2022. Provenance, Paleogeographic and paleotectonic interpretations of Oligocene-Lower Miocene sandstones of the western-central Mediterranean region: a review, in the evolution of the Tethyan orogenic belt and, related mantle dynamics and ore deposits. Journal of Asian Earth Sciences Special Issue X8, 100124. https://doi.org/10.1016/j.jaesx.2022.100124.

Critelli, S., Martín-Martín, M., 2024. History of western Tethys Ocean and the birth of the circum-Mediterranean orogeny as reflected by source-to-sink relations. Int. Geol. Rev. 66 (2), 505–515. https://doi.org/10.1080/00206814.2023.2280787.

Critelli, S., Muto, F., Zecchin, M., Tripodi, V., Ceramicola, S., Ramella, R., Roda, C., 2014. Note Illustrative Della Carta Geologica d'Italia Alla Scala 1:50.000. Foglio 562 "Ciro" ISPRA - Servizio Geologico d'Italia, p. 148.

DeCelles, P.G., Cavazza, W., 1995. Upper Messinian conglomerates in Calabria, southern Italy: response to orogenic wedge adjustment following Mediterranean sea-level changes. Geology 23, 775–778.

Dewey, J.F., Helman, M.L., Knott, S.D., Turco, E., Hutton, D.H.W., 1989. Kinematics of the western mediterranean. Geological Society, London, Special Publications 45 (1), 265–283.

Doglioni, C., Harabaglia, P., Martinelli, G., Mongelli, F., Zito, G., 1996. A geodynamic model of the Southern Apennines accretionary prism. Terra. Nova 8 (6), 540–547.

Fabbri, A., Rossi, S., Sartori, R., Barone, A., 1982. Evoluzione Neogenica dei margini marini dell'Arco Calabro-Peloritano: implicazioni geodinamiche. Memor. Soc. Geol. Ital. 24, 357–366.

Faccenna, C., Becker, T.W., Pio Lucente, F., Jolivet, L., Rossetti, F., 2001. History of subduction and back-arc extension in the Central Mediterranean. Geophys. J. Int. 145, 809–820.

Faccenna, C., Piromallo, C., Crespo-Blanc, A., Jolivet, L., Rossetti, F., 2004. Lateral slab deformation and the origin of the western Mediterranean arcs. Tectonics 23, TC1012. https://doi.org/10.1029/2002TC001488.

Feraud, G., 1990. 39Ar-40Ar analysis on basaltic lava series of Vavilov basin, Tyrrhenian sea (ocean drilling program, leg 107, holes 655B and 651A). In: Kastens, K.A., Mascle, J. (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, vol. 107. Ocean Drilling Program, College Station, Texas, pp. 93–97.

Galli, P., Scionti, V., 2006. Two unknown M>6 historical earthquakes revealed by paleoseismological and archival researches in eastern Calabria (Southern Italy). Seismotectonic implications. Terra. Nova 18 (1), 43–48.

Gliozzi, E., 1987. I terrazzi del Pleistocene superiore della Penisola di Crotone (Calabria). Geol. Rom. 26, 17–79.

Govers, R., Meijer, P., Rijgsman, W., 2009. Regional isostatic response to messinian salinity crisis events. Tectonophysics 463, 109–129.

Gueguen, E., Doglioni, C., Fernandez, M., 1998. On the post-25 Ma geodynamic evolution of the western Mediterranean. Tectonophysics 298 (1–3), 259–269.

Hancock, P.L., 1985. Brittle microtectonics: principles and practice. Journal of structural geology 7 (3–4), 437–457.

Hilgen, F.J., Kuiper, K.F., Krijgman, W., Snel, E., van der Laan, E., 2007. High-resolution integrated stratigraphy and astronomical tuning as prerequisites for deciphering the intricate history of the Messinian salinity crisis. Stratigraphy 4, 231–238.

Iannace, A., Vitale, S., D'errico, M., Mazzoli, S., Di Staso, A., Macaione, E., Messina, A., Reddy, S.M., Somma, V., Zamparelli, V., Zattin, M., Bonardi, G., 2007. The carbonate tectonic units of northern Calabria (Italy): a record of Apulian palaeomargin evolution and Miocene convergence, continental crust subduction, and exhumation of HP–LT rocks. J. Geol. Soc. 164 (6), 1165–1186.

Knott, S.D., Turco, E., 1991. Late cenozoic kinematics of the Calabrian Arc, southern Italy. Tectonics 10, 1164–1172.

Krijgsman, W., Hilgen, F.J., Raffi, I., Sierro, F.J., Wilson, D.S., 1999. Chronology, causes and progression of the Messinian salinity crisis. Nature 400, 652–655.

Lanzafame, G., Tortorici, L., 1981. La tettonica recente della valle del fiume Crati (Calabria). Geogr. Fis. Din. Quaternaria 4, 11–21.

Malinverno, A., Ryan, W.B., 1986. Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the lithosphere. Tectonics 5 (2), 227–245.

Mangano, G., 2022b. Mid-Miocene to Recent Tectono-Stratigraphic Evolution of the Crotone Basin (Southern Italy): Impact on Gravitational Collapse and Seabed Morphology. PhD Thesis. University of Calabria, Italy.

Mangano, G., Alves, T.M., Zecchin, M., Civile, D., Critelli, S., 2023a. The rossano–san Nicola Fault Zone evolution impacts the burial and maturation histories of the Crotone Basin, Calabrian Arc, Italy. Petrol. Geosci. 29 (2) petgeo2022-p2085.

Mangano, G., Ceramicola, S., Alves, T.M., Zecchin, M., Civile, D., Del Ben, A., Critelli, S., 2023b. A new large-scale gravitational complex discovered in the Gulf of Squillace (central Mediterranean): tectonic implications. Scientific Reports 13 (1), 14695.

Mangano, G., Ceramicola, S., Zecchin, M., Brancatelli, G., Critelli, S., 2021. Geohazard-related geomorphic features in the crotone-spartivento basin (southern Italy): an expression of Calabrian Arc kinematics. In: Offshore Mediterranean Conference and Exhibition. OMC, OMC-2021.

Mangano, G., Zecchin, M., Civile, D., 2020. Large-scale gravity-driven phenomena in the Crotone Basin. southern Italy. Marine and Petroleum Geology 117, 104386.

Mangano, G., Zecchin, M., Civile, D., Ceramicola, S., Donato, A., Muto, F., Tripodi, V., Critelli, S., 2022a. Mid-miocene to recent tectonic evolution of the punta stilo swell (calabrian arc, southern Italy): an effect of calabrian arc migration. Mar. Geol. 448, 106810.

Martín-Martín, M., Perri, F., Critelli, S., 2023. Cenozoic detrital suites from the Internal Betic-Rif Cordilleras (S Spain and N Morocco): implications for paleogeography and paleotectonics. Earth Sci. Rev. 243, 104498 https://doi.org/10.1016/j.earscirev.2023.104498, 1-16.

Massari, F., Prosser, G., 2013. Late Cenozoic tectono-stratigraphic sequences of the Crotone Basin: insights on the geodynamic history of the Calabrian arc and Tyrrhenian Sea. Basin Res. 25 (1), 26–51.

Massari, F., Prosser, G., Capraro, L., Fornaciari, E., Consolaro, C., 2010. A revision of the stratigraphy and geology of the south-western part of the Crotone Basin (South Italy). Italian journal of geosciences 129 (3), 353–384.

Mattei, M., Cifelli, F., D'Agostino, N., 2007. The evolution of the Calabrian Arc: evidence from paleomagnetic and GPS observations. Earth Planet Sci. Lett. 263 (3–4), 259–274.

Mattei, M., Cipollari, P., Cosentino, D., Argentieri, A., Rossetti, F., Speranza, F., Di Bella, L., 2002. The Miocene tectono-sedimentary evolution of the southern Tyrrhenian Sea: stratigraphy, structural and palaeomagnetic data from the on-shore Amantea basin (Calabrian Arc, Italy). Basin Res. 14, 147–168.

Mattei, M., Petrocelli, V., Lacava, D., Schiattarella, M., 2004. Geodynamic implications of Pleistocene ultrarapid vertical-axis rotations in the Southern Apennines. Italy. Geology 32 (9), 789–792.

Minelli, L., Billi, A., Faccenna, C., Gervasi, A., Guerra, I., Orecchio, B., Speranza, G., 2013. Discovery of a gliding salt-detached megaslide, Calabria, Ionian Sea. Italy. Geophys. Res. Lett. 40, 4220–4224.

Muto, F., Spina, V., Tripodi, V., Critelli, S., Roda, C., 2014. Neogene tectonostratigraphic evolution of allochthonous terranes in the eastern Calabrian foreland (southern Italy). Italian J. Geosci. 133, 455–473.

Nicolosi, I., Speranza, F., Chiappini, M., 2006. Ultrafast oceanic spreading of the Marsili Basin, southern Tyrrhenian Sea: evidence from magnetic anomaly analysis. Geology 34 (9), 717–720.

Patacca, E., Sartori, R., Scandone, P., 1990. Tyrrhenian basin and Apenninic arcs: kinematic relations since late Tortonian times. Memor. Soc. Geol. Ital. 45, 425–451.

Praeg, D., Ceramicola, S., Barbieri, R., Unnithan, V., Wardell, N., 2009. Tectonically-driven mud volcanism since the late Pliocene on the Calabrian accretionary prism, central Mediterranean Sea. Mar. Petrol. Geol. 26 (9), 1849–1865.

Roda, C., 1964. Distribuzione e facies dei sedimenti Neogenici nel Bacino Crotonese. Geol. Rom. 3, 319–366, 1964.

Rosenbaum, G., Lister, G.S., 2004. Neogene and quaternary rollback evolution of the Tyrrhenian Sea, the appennines, and the Sicilian Maghrebides. Tectonicas 23, 1013.

Roveri, M., Bassetti, M.A., Ricci Lucchi, F., 2001. The Mediterranean Messinian salinity crisis: an Apennine foredeep perspective. Sediment. Geol. 140, 201–214.

Roveri, M., Flecker, R., Krijgsman, W., Lofi, J., Lugli, L., Manzi, V., Sierro, F.J., Bertini, A., Camerlenghi, A., De Lange, G., Govers, R., Hilgen, F.J., Hubscher, C., Meijer, P.Th, Stoica, M., 2014. The Messinian Salinity Crisis: past and future of a great challenge for marine sciences. Mar. Geol. 352, 25–58.

Sartori, R., 1990. The main results of ODP Leg 107 in the frame of Neogene to Recent geology of peri-Tyrrhenian areas. In: Proceedings of the Ocean Drilling Program, Scientific Results, vol. 107, pp. 715–730.

Sartori, R., 2003. The Tyrrhenian back-arc basin and subduction of the Ionian lithosphere. Episodes 26 (3), 217–221.

Speranza, F., Macrì, P., Rio, D., Fornaciari, E., Consolaro, C., 2011. Paleomagnetic evidence for a post–1.2 Ma disruption of the Calabria terrane: consequences of slab breakoff on orogenic wedge tectonics. Bulletin 123 (5–6), 925–933.

Spina, V., Galli, P., Tondi, E., Critelli, S., Cello, G., 2007. Kinematics and structural properties of an active fault zone in the Sila Massif (Northern Calabria, Italy). Boll. Soc. Geol. Ital. 126, 427–438.

Sylvester, A.G., 1988. Tectonic processes and structural geology. Bull. Liaison Lab. Ponts Chaussees 17.

Tansi, C., Muto, F., Critelli, S., Iovine, G., 2007. Neogene-Quaternary strike-slip tectonics in the central Calabrian Arc (southern Italy). J. Geodyn. 43, 393–414.

Tarquini, S., Vinci, S., Favalli, M., Doumaz, F., Fornaciai, A., Nannipieri, L., 2012. Release of a 10-m-resolution DEM for the Italian territory: comparison with globalcoverage DEMs and anaglyph-mode exploration via the web. Comput. Geosci. 38, 168–170. https://10.1016/j.cageo.2011.04.018.

Tortorici, L., Monaco, C., Tansi, C., Cocina, O., 1995. Recent and active tectonics in the Calabrian arc (Southern Italy). Tectonophysics 243 (1–2), 37–55.

Tripodi, V., Muto, F., Critelli, S., 2013. Structural style and tectono-stratigraphic evolution of the neogene-quaternary siderno basin, southern Calabrian Arc. Italy. International Geology Review 55, 468–481.

Tripodi, V., Muto, F., Brutto, F., Perri, F., Critelli, S., 2018. Neogene-Quaternary evolution of the forearc and backarc regions between the Serre and Aspromonte Massifs, Calabria (southern Italy). Mar. Petrol. Geol. 95, 328–343. https://doi.org/10.1016/j.marpetgeo.2018.03.028.

Van Dijk, J.P., 1990. Sequence stratigraphy, kinematics and dynamic geohistory of the Crotone Basin (Calabrian Arc, central mediterranean): an integrated approach. Memorie Società Geologica. Italiana 44, 259–285.

Van Dijk, J.P., 1991. Basin dynamics and sequence stratigraphy in the Calabrian Arc (central mediterranean); records and pathways of the Crotone Basin. Geol. Mijnbouw 70, 187–201.

Van Dijk, J.P., 1994. Late Neogene kinematics of intra-arc oblique shear zones: the petilia-rizzuto Fault Zone (Calabrian Arc, central mediterranean). Tectonics 13 (5), 1201–1230.

Van Dijk, J.P., Bello, M., Brancaleoni, G.P., Cantarella, G., Costa, V., Frixa, A., Golfetto, F., Merlini, S., Riva, M., Torricelli, S., Toscano, C., Zerilli, A., 2000. A regional structural model for the northern sector of the Calabrian Arc (southern Italy). Tectonophysics 324 (4), 267–320.

Van Dijk, J., Okkes, M., 1991. Neogene tectonostratigraphy and kinematics of Calabrian basins; implications for the geodynamics of the Central Mediterranean. Tectonophysics 196 (1–2), 23–60.

Van Dijk, J.P., Scheepers, P.J.J., 1995. Neotectonic rotations in the Calabrian Arc; implications for a pliocene-recent geodynamic scenario for the central mediterranean. Earth Sci. Rev. 39 (3–4), 207–246.

Zecchin, M., Caffau, M., Di Stefano, A., Maniscalco, R., Lenaz, D., Civile, D., Muto, F., Critelli, S., 2013b. The Messinian succession of the Crotone Basin (southern Italy) II: facies architecture and stratal surfaces across the Miocene-Pliocene boundary. Mar. Petrol. Geol. 48, 474–492.

Zecchin, M., Civile, D., Caffau, M., Muto, F., Di Stefano, A., Maniscalco, R., Critelli, S., 2013a. The Messinian succession of the Crotone Basin (southern Italy) I: stratigraphic architecture reconstructed by seismic and well data. Mar. Petrol. Geol. 48, 455–473.

Zecchin, M., Accaino, F., Ceramicola, S., Civile, D., Critelli, S., Da Lio, C., Mangano, G., Prosser, G., Teatini, P., Tosi, L., 2018. The Crotone Megalandslide, southern Italy: architecture, timing and tectonic control. Sci. Rep. 8 (1), 1–11.

Zecchin, M., Caffau, M., Civile, D., Critelli, S., Di Stefano, A., Maniscalco, R., Muto, F., Sturiale, G., Roda, C., 2012. The Plio-Pleistocene evolution of the Crotone Basin (southern Italy): interplay between sedimentation, tectonics and eustasy in the frame of Calabrian Arc migration. Earth Sci. Rev. 115 (4), 273–303.

Zecchin, M., Civile, D., Caffau, M., Critelli, S., Muto, F., Mangano, G., Ceramicola, S., 2020. Sedimentary evolution of the Neogene-Quaternary Crotone Basin (southern Italy) and relationships with large-scale tectonics: a sequence stratigraphic approach. Mar. Petrol. Geol. 117, 104381.

Zecchin, M., Nalin, R., Roda, C., 2004. Raised Pleistocene marine terraces of the Crotone peninsula (Calabria, southern Italy): facies analysis and organization of their deposits. Sediment. Geol. 172 (1–2), 165–185.

Zecchin, M., Praeg, D., Ceramicola, S., Muto, F., 2015. Onshore to offshore correlation of regional unconformities in the Plio-Pleistocene sedimentary successions of the Calabrian Arc (central Mediterranean). Earth Sci. Rev. 142, 60–78.

Olivetti, V., Cyr, A.J., Molin, P., Faccenna, C., Granger, D.E., 2012. Uplift history of the Sila Massif, southern Italy, deciphered from cosmogenic 10Be erosion rates and river longitudinal profile analysis. Tectonics 31, TC3007 https://doi.org/10.1029/2011TC003037.