Journal of Maps

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tjom20

Seismotectonics and landslides of the NE border of the Calabrian Arc (Southern Italy)

Carlo Tansi, Salvatore Critelli, Michele Folino Gallo, Anna Gervasi, Gianpietro Imbrogno, Mario La Rocca, Michela Ponte, Vincenzo Tripodi & Francesco Muto

To cite this article: Carlo Tansi, Salvatore Critelli, Michele Folino Gallo, Anna Gervasi, Gianpietro Imbrogno, Mario La Rocca, Michela Ponte, Vincenzo Tripodi & Francesco Muto (2024) Seismotectonics and landslides of the NE border of the Calabrian Arc (Southern Italy), Journal of Maps, 20:1, 2347901, DOI: 10.1080/17445647.2024.2347901

To link to this article: https://doi.org/10.1080/17445647.2024.2347901

© 2024 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.

View supplementary material

Published online: 09 May 2024.

Submit your article to this journal

View related articles

View Crossmark data

Full Terms & Conditions of access and use can be found at
https://www.tandfonline.com/action/journalInformation?journalCode=tjom20

JOURNAL OF MAPS
2024, VOL. 20, NO. 1, 2347901
https://doi.org/10.1080/17445647.2024.2347901

SCIENCE

OPEN ACCESS Check for updates

Seismotectonics and landslides of the NE border of the Calabrian Arc (Southern Italy)

Carlo Tansi[a], Salvatore Critelli[b], Michele Folino Gallo[c], Anna Gervasi[d], Gianpietro Imbrogno[e], Mario La Rocca[f], Michela Ponte[e], Vincenzo Tripodi[a] and Francesco Muto[e]

[a]Italian National Research Council, Research Institute for Geo-Hydrological Protection (CNR-IRPI), Rende, Italy; [b]Department of Environmental Engineering, University of Calabria, Arcavacata di Rende, Italy; [c]Civil Protection of the Calabria Region Cittadella Regionale, Germaneto di Catanzaro, Italy; [d]National Institute of Geophysics and Volcanology (INGV), National Earthquake Observatory, Rome, Italy; [e]DiBEST, Department of Biology, Ecology and Earth Sciences, University of Calabria, Arcavacata di Rende, Italy; [f]Department of Physics, University of Calabria, Arcavacata di Rende, Italy

ABSTRACT
The north-eastern border of CA represents the accretionary system developed during its continuous collision with Apulian block. The tardive oblique tectonic component is highlighted by pervasive NW-SE crustal transpressive left-lateral strike slip faults developed from the Upper Miocene to Quaternary tectonic stages. The seismotectonic and landslides Main Map represents the update of the main faults, the style of their arrangement and kinematics, the seismotectonic features and landslide area distribution with risk implications. Seismotectonics allows us to recognise a vertical crustal zonation with the distribution of earthquakes and their focal mechanism solution. The prevalent modality of ruptures depicts a mainly transcurrent and compressive solution in mid-lower crust portions respectively. This data, together with the historical seismicity analysis of the area, lead to consider the NW-SE strike-slip faults improved on the Main Map, as recent and tectonically active. The areal distribution of landslide and susceptibility of the area is due to the interaction between seismotectonic peculiarity, lithological typologies and fault zone architectures. Landslides and flood phenomena of this sector involve many municipalities, major and minor infrastructures and economic and social activities. The landslides and the faults have been identified, mapped and classified, originally at detail scale and, then, represented at 1:50,000 scale in the Main Map, included as supplementary material. The geo-structural and geomorphological data were analysed in a geographic information system allowing data management and implementation. The work presents an updated knowledge framework of risk conditions of the study zone, available to plan and reduce the fundamental elements that determine the landslide and seismic risks in this region.

ARTICLE HISTORY
Received 21 June 2023
Revised 9 April 2024
Accepted 15 April 2024

KEYWORDS
Calabria; Seismotectonics; Mapping; GIS; Landslide hazard

1. Introduction and geological setting

The study area is located on the NE border of the Calabrian Arc (CA), Southern Italy, along an important NW-SE trending left-lateral regional tectonic lineament in the central Mediterranean area (Figure 1).

The CA is an arc-shaped accretionary wedge of the Mediterranean orogenic belt connecting the Maghrebian and Southern Apennine chains, trending E–W and NW–SE, respectively (Amodio-Morelli et al., 1976; Malinverno & Ryan, 1986) (Figure 1). It is the result of accretionary processes and the development of compressional structures on its eastern flank (Ionian Sea) and coeval rifting in the internal domain (Tyrrhenian Margin). These processes were produced by the subduction of the Ionian slab towards northwest and the roll back of the same towards south east, during the Neogene-Quaternary time span (Critelli, 1993, 2018; Critelli et al., 2013; Critelli & Martín-Martín, 2022, 2024; Zecchin et al., 2020). Collisional and post-collisional tectonics of this part of orogen is mainly influenced by oblique component of motion to which is referred the development of a composite transpressional and transtensional arrangement (Barone et al., 2008; Civile et al., 2022; Ferranti et al., 2009, 2014; Gori et al., 2017; Monaco & Tansi, 1992; Muto et al., 2015; Pirrotta et al., 2022; Tansi et al., 2007).

The chain consists of Alpine units made up of basement crystalline nappes and Mesozoic cover (Calabride complex; Ogniben, 1973) overthrusted since the Eocene on a series of ophiolite-bearing tectonic units of the Neo-Tethys domain (Liguride complex; Barbera et al., 2011; Critelli, 1993; Critelli & Martín-Martín, 2024; Ogniben, 1973). Pre-Mesozoic basement

CONTACT Vincenzo Tripodi vincenzo.tripodi@irpi.cnr.it
Supplemental map for this article is available online at https://doi.org/10.1080/17445647.2024.2347901.

© 2024 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.
This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial License (http://creativecommons.org/licenses/by-nc/4.0/), which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited. The terms on which this article has been published allow the posting of the Accepted Manuscript in a repository by the author(s) or with their consent.

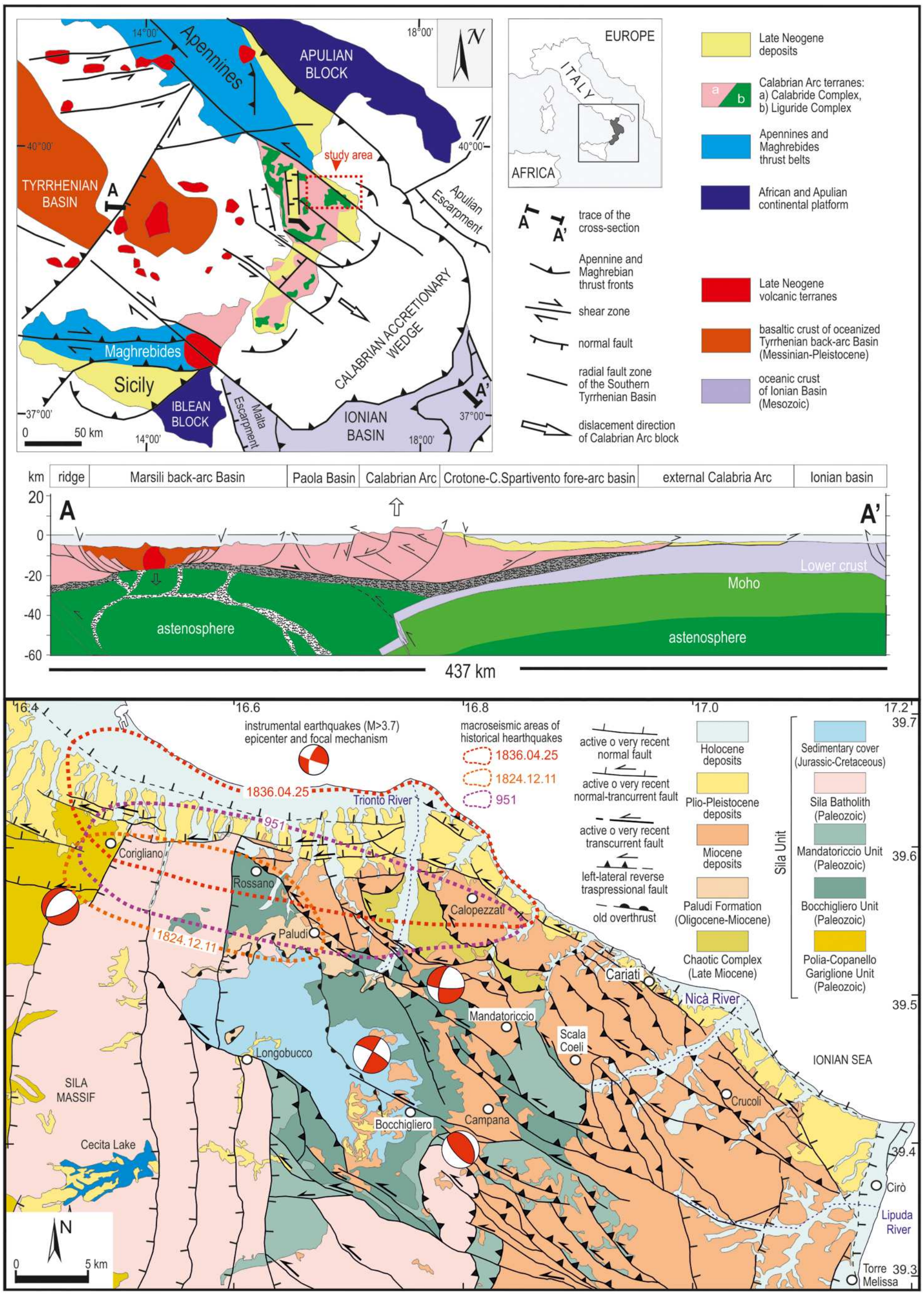

Figure 1. Geological sketch-map of the Central Mediterranean area and geological section on the bottom (after Tansi et al., 2007, modified), with tectonic simplified sketch of the Map.

consists of different tectonic units affected by Variscan metamorphism and emplaced during the Alpine orogenesis (Langone et al., 2010; Messina et al., 1994). Overlying the basement of the Sila Unit the sedimentary cover was subdivided into the Longobucco and Caloveto Groups; these Mesozoic successions reflect the submarine depositional system and the tectonic/sedimentary evolution (Innamorati & Santantonio, 2018).

External and Sicilide Mesozoic-derived terranes constitute the thick accreted Apennine thrust wedge terrane. Slices of Sicilide-derived succession were emplaced through the internal domain during the Neogene back thrusting phase recorded along the entire western Calabria margin (Cavazza & Barone, 2010; Tripodi et al., 2018).

The Alpine units, during the Oligocene-Early Miocene, overthrusted on the Mesozoic carbonate terranes belonging to the Apennines-Maghrebide Chain (Amodio-Morelli et al., 1976). An Oligocene to Quaternary basin successions overlay the Paleozoic Alpine units and their Mesozoic cover (Bonardi et al., 2005; Zecchin et al., 2012).

On the basement rests an Oligocene to Holocene sedimentary succession that shows inside a series of back thrusts on various stratigraphic levels. In particular, the Upper Tortonian–Messinian sequences show an internal architecture that reflects the interplay between tectonics and relative sea-level changes.

The Miocene units are unconformably overlain by Pliocene to Upper Pleistocene succession made up of clay, sand and conglomerate, the latter forming a staircase of terraces, as observed north and south of the study area (Carobene, 2003; Corbi et al., 2009; Lucà et al., 2011; Robustelli et al., 2009a, 2009b). To better understand the tectonostratigraphic architecture of the area, in the Map we used the stratigraphic subdivision as reported in chapter three of this manuscript.

In the Middle Miocene-Middle Pleistocene time, the CA was affected by a regional NW–SE left-lateral transcurrent fault system which dissected the orogenic belt generating transverse and longitudinal structural highs and basins (Corradino et al., 2023; Dewey et al., 1989; Ferranti et al., 2009; Gullà et al., 2005; Muto & Perri, 2002; Tripodi et al., 2013; Van Dijk et al., 2000). Tansi et al. (2007) documented that in the central sector of the CA, the strike-slip tectonics produced, at the tips or in areas of change of direction of the fault segments, transtensional or transpressional structures. Moreover, in the sector immediately adjacent to the western side of the study area, the strike-slip tectonics produced the transtensional Crati Graben, structured since the Pliocene by N–S normal faults still active (Tansi et al., 2005, 2016).

In the study area, transcurrent tectonics – started in Upper Miocene and still active – produced a complex network of NW-SE left-lateral strike-slip faults and associated thrusts and back thrusts, (Brutto et al., 2016; ; Maffione et al., 2013; Mangano et al., 2023; Muto et al., 2014, 2017; Tripodi et al., 2022; Zecchin, Civile, et al., 2013). Since the early Messinian, Neogene basins have been dissected by tectonic processes into sub-basins.

The catalogue of historical earthquakes (Guidoboni et al., 2019) reports three important events that occurred in the study area in the years 951, 1824 and 1836. The latter was the strongest, with an estimated Imax = X MCS. The lack of reliable seismic information does not permit associating these earthquakes with seismogenic structures recognised in the area. Sorriso-Valvo and Tansi (1996) have highlighted the recent character of NW-SE trending normal faults, active up to the Middle Pleistocene in the study area.

The study area is affected by many landslides, large-scale landslides and deep-seated gravitational and tectono-gravitational slope deformations.

The aim of this study is the development of a multidisciplinary approach combining geological mapping, macro and meso-structural lineaments, geomorphological analysis, and the study of the main historical and instrumental earthquakes, in order to define the seismotectonic and landsliding characteristics of an area of high geo-structural risk. The map may represent so a useful tool for territorial engineering-geological planning and Civil Protection (Petrucci et al., 2017).

The results of this approach are summarised in the 1:50,000 scale Main Map of the study area.

2. Methodology

Through geo-structural and geomorphological analysis, performed from the macro to the mesoscale, we have depicted on the Main Map the main faults, distinguished in ancient and recent-active. Field geological surveys and analysis of aerial photos at various scales and interpretation of satellite images were carried out, as well as the processing and interpretation of digital terrain models. Morpho-tectonic indicators such as fault scarps, triangular and trapezoidal facets, rectified waterways and morphological steps and saddles aligned along adjacent ridges, were identified through the macro-structural analysis carried out by aerial and satellite photographic interpretation. At the macroscale, we performed meso-structural studies collected at 30 stations located along the main fault zones. For each striated fault plane we measured strike, dip and pitch, and so determined the direction of movement.

Our studies led us to detail the most recent faults, these are closely associated with the morphodynamics recognisable in the current landscape and with the seismotectonic setting of the area.

Moreover, we have been mapped the most representative elements of gravitational and tectono-gravitational origin primarily using geomorphological criteria (detection of scarps and trenches along the ridges and on the slopes, the analysis of the shape of the latter and interference with the drainage network, etc.) and multi-temporal analysis of aerial photographs and satellite images followed by field surveys.

We leveraged velocity vector data from GPS measurements (Palano et al., 2023) to deepen our understanding of the current tectonic regime. In order to depict the present-day crustal stress in the study area and the correlation between seismicity and tectonic structures, we analysed the recent instrumental seismicity. A very important information about the current stress field comes from the earthquake kinematics. Therefore we collected the focal mechanism of past earthquakes from published papers (D'Amico et al., 2011; Frepoli & Amato, 2000; Orecchio et al., 2014; Presti et al., 2013; Totaro et al., 2013, 2016) and from online databases (Pondrelli & Salimbeni, 2006; Scognamiglio et al., 2006). Furthermore, we computed the focal mechanism of 20 earthquakes that occurred during the last decades in the investigated area. We used the software CAP (Tan et al., 2006; Zhao & Helmberger, 1994; Zhu & Helmberger, 1996), based on the comparison between observed and synthetic seismograms, and the software FOCMEC (Snoke, 1989; Snoke et al., 1984), based on the polarity of direct waves. Seismic results were

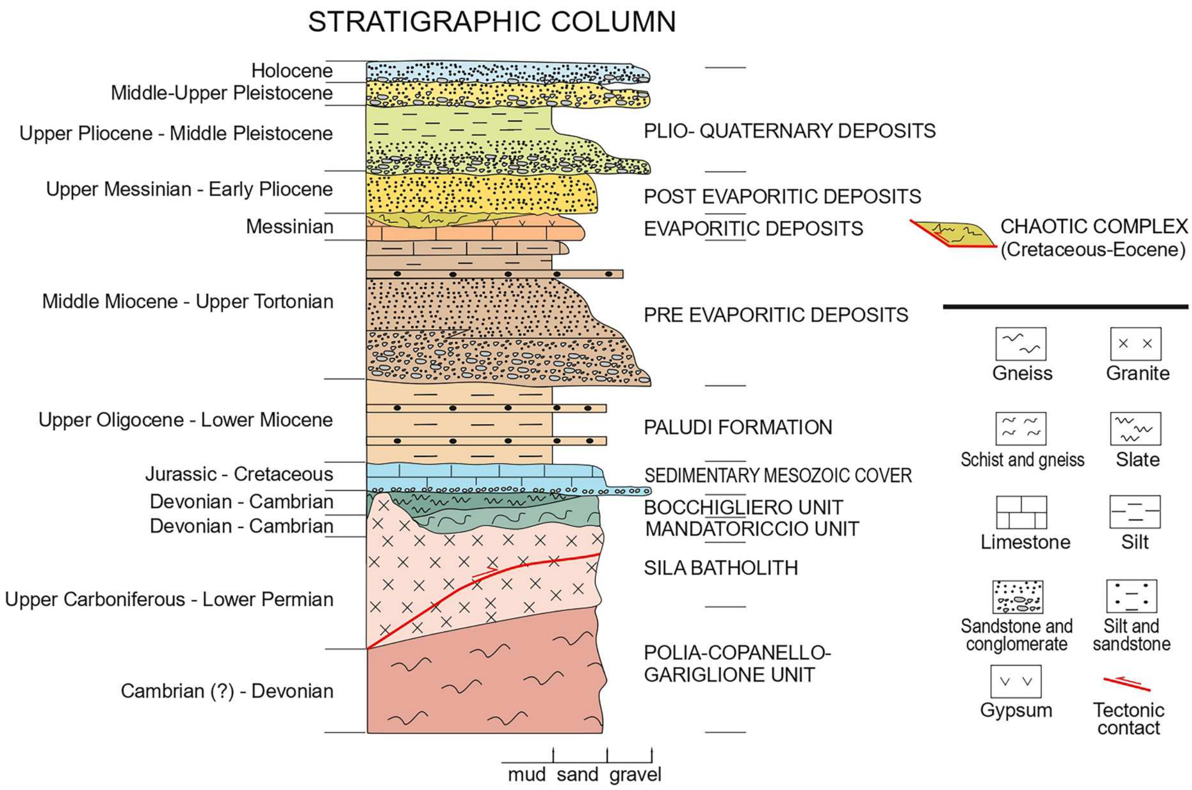

Figure 2. Tectono-stratigraphic scheme of the study area.

interpreted and correlated to the main tectonic structures by means of geological analysis.

The above data were also digitised and analysed in a geographic information system (GIS), the data were georeferenced in UTM (Universal Transverse Mercator) with WGS84 Datum.

3. Lithostratigraphy

In the study area, the following main tectono-stratigraphic and tectono-metamorphic units (Figure 1) crop out, on which Paleogene-Quaternary succession lies unconformably. The units are briefly described from bottom to top (Figure 2):

- Polia- Copanello – Gariglione Unit – High-grade metamorphic rocks (biotite-sillimanite garnet gneiss) intruded by plutonic bodies. Garnetiferous sillimanite biotite gneiss. There are interbedded marble lenses, granulite lenses and metabasite lenses felsic veins of microgranites, aplites and pegmatites (Cambrian?-Devonian) (Amodio-Morelli et al., 1976).
- Plutonic Sila Complex – Plutonic and metamorphic rocks of the Sila Batholith, constituted by intrusive bodies of regional extension with variable composition from gabbro to tonalite, granodiorite and monzogranite intruded by felsic dykes, micro granite and aplite-pegmatite (upper Carboniferous – lower Permian) (Messina et al., 1994).
- Mandatoriccio Complex – Paragneiss micaschists with schistose structure and heterogeneous grain, intercalations of ortho gneisses, layers of marbles and metabasites, intrusion of lamprophyre veins (Cambrian-Devonian) (Messina et al., 1994).
- Bocchigliero Unit – Phyllites composed of quartz, mica, albite, chlorite and calcite, of very low metamorphic grade. Porphyroids, metarenites, meta-andesites and metalimestones (Cambrian-Carboniferous) (Messina et al., 1994).
- Sedimentary cover of Longobucco and Caloveto Groups – The Longobucco group consists of conglomerates, quartz arenites, sublitharenite and mudstones of a purplish-red to white colour at the base. The cover is also characterised by dark grey to blackish limestones, hybrid sandstones and ooid limestones, marls, grey marly limestones with thin intercalations of sandstones and turbiditic succession (Lower-Middle Jurassic) (Innamorati & Santantonio, 2018; Young et al., 1986).
- Paludi Formation – Conglomerates and polygenic breccias with a sandy matrix; reddish and greenish marls containing layers of feldspathic quartz sandstones and conglomerates (Upper Oligocene – Lower Miocene, Bonardi et al., 2005).
- Pre-evaporitic deposits – Conglomerates, sandstones, silts and silty clay, tripolaceous marls and marly clays (Serravallian-Upper Tortonian) (Barone et al., 2008; Zecchin et al., 2020).
- Evaporitic deposits: Light brown or whitish limestone. White – yellowish evaporite limestone with local thin marls, siltites and gypsum intercalations. In the northern sector the white limestones are

unconformably covered by conglomerate, breccias, and sandstones. Finely crystalline, well stratified gypsum, ranging from sandy gypsum or chalky sandstone to relatively pure gypsum (Messinian) (Barone et al., 2008; Gindre-Chanu et al., 2020; Massari et al., 2010; Zecchin, Caffau, et al., 2013; Zecchin, Civile, et al., 2013).

- Chaotic Complex – In the upper portion of Miocene succession is interbedded an exotic chaotic complex, characterised by varicoloured shales and clays with matrix ranging in colour from red to green, including olistoliths and blocks of limestones and marls, argillites, calcarenites (Cretaceous-Eocene) (Critelli et al., 2014a; 2014b; Ogniben, 1973).
- Post-evaporitic deposits – Siliciclastic argillaceous and arenaceous deposits during the late Messinian. These consist of greyish fossiliferous marl and clays alternating with thin turbidite sandstone beds and grades upward into shallower sandstones (Upper Messinian-Early Pliocene) (Barone et al., 2008).
- Conglomerates, sands, calcarenites and clays of alluvial fluvial, littoral, platform and bathyal environments (Middle Pliocene – Middle Pleistocene).
- Gravels, sands, silts and clays of alluvial, colluvial, lacustrine, aeolian, coastal and marine deposits (Middle/Upper Pleistocene-Holocene).

4. Tectonic structures

The examined area experienced a wrench tectonic setting starting at least from the Middle Miocene-Quaternary producing transpressional and transtensional fault zones displacing the older chain structures (Figure 1).

The main NW-SE-trending faults are characterised by strike-slip, reverse and normal kinematics. NW-SE-trending lineaments are arranged in an en-échelon pattern subparallel to the Rossano-San Nicola fault zone (Figure 3) (Mangano et al., 2023). Morphostructures between Cirò Marina and the Trionto River area are aligned parallel to the NW-SE regional lineaments and, in general, is characterised by an est dipping displaced growing monocline.

The faults with reverse kinematics, dipping both to the northeast and southwest (see Main Map and Figure 4), show pitch of nearly 90°, reverse kinematics appear on low angle-dipping thrust planes. These planes are displaced by high-angle dipping transcurrent and oblique-slip faults with the same strike. At the outcrop scale, the NW-SE fault planes commonly exhibit typical transpressive structures forming a braided pattern of anastomosing contemporaneous faults in the area between Cirò- Longobucco and Rossano (Figure 1(b) and Main Map). At the mesoscale, the fault system is characterised by transcurrent kinematics with variable values of pitch, between 0° and 25°, and fault planes dip towards NE and SW with variable angles (Figure 4). Left-lateral slip dominates, with subordinate right slip; on the same planes, the pitch may exceed 45° with a predominant reverse component of displacement. Tectonic structures belonging to the same trend, but with extensional kinematics of the planes, crosscut the deposits of the Lower-Late Pleistocene succession outcropping along the coast area, from the villages of Cirò towards the Cariati and Calopezzati countries (Main Map). The N-S oriented faults mainly outcrop along the western portion of the Main Map cutting the Sila Massif paleozoic rocks and the late quaternary cover deposits. This normal fault system is characterised by high-angle fault planes dipping top to the east and to the west, forming intramontane tectonic depression in correspondence with the Cecita Lake (Main Map). The system belongs to the regional extensional array faults that identify the Crati Graben (Tansi et al., 2007, 2016). Among others, the faults belonging to the Cecita Lake faults are part of this system; these are active faults which historically have produced high-magnitude earthquakes. These structures displace towards the eastern portion of the foreland system with respect to the metamorphic crystalline chain. The NE-SW faults have been identified and observed at the mesoscale and do not correspond with major mapped faults in the area. Ancient thrusts showing sub-horizontal planes E–W to NNW–SSE strikes, were also recognised. These thrusts do not show any morphological evidence and are documented only at the mesoscale, where they are commonly dislocated by the younger faults. These planes display reverse dip-slip slickensides, documenting – if tilting is ignored – an N–S-oriented sub-horizontal $\sigma 1$: they can be related to the overthrusts responsible for the Oligocene-Early Miocene building of the chain.

5. Seismotectonics

The northern sector of the Ionian Calabria was affected in the past centuries by many earthquakes with Imax = VIII–X MCS. Three of them occurred right in the middle of our study area (Figure 5). The strongest occurred near Rossano village on April 25, 1836, with Imax = X MCS (Tertulliani et al., 2017), generated by the Rossano fault (Galli et al., 2010), a NW-SE striking tectonic structure characterised by left lateral transcurrent kinematics. Another notable earthquake occurred on December 11, 1824, of Imax = VIII MCS (Rovida et al., 2020, 2022). Much less information is available about another earthquake that occurred in the same area in 951, with presumed Imax = IX MCS (Guidoboni et al., 2019).

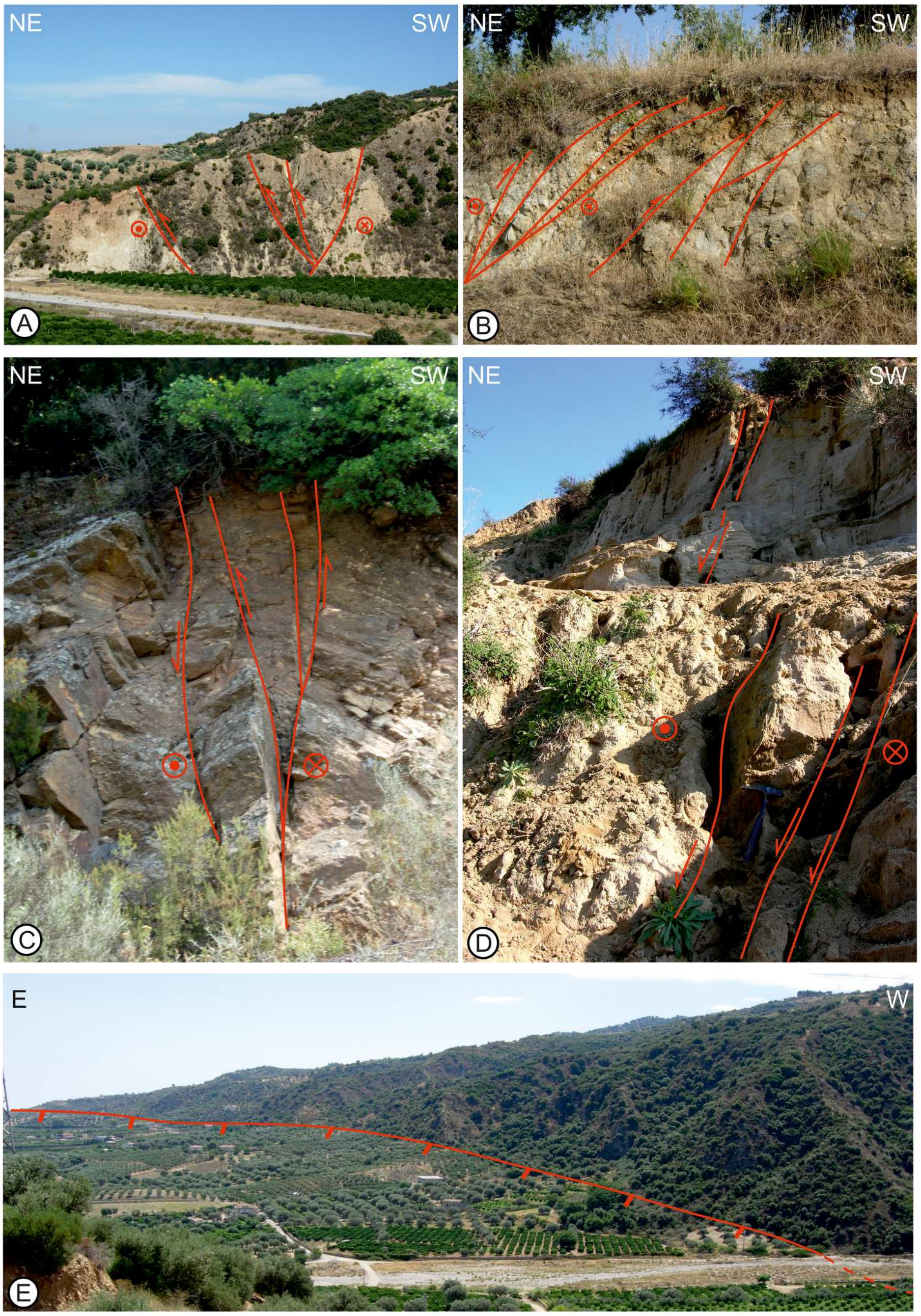

Figure 3. (A) Panoramic view of a flower structure bordered by left-lateral strike-slip faults with inverse component (Corigliano-Rossano town); B) Thrust ramps NNW-SSE trending, with left component, involving the Palaeozoic crystalline-metamorphic bedrock and soil horizons (Corigliano-Rossano town); C) Flower structure crossing the crystalline-metamorphic bedrock; D) Normal fault with left-lateral component affecting the Miocene pre-evaporitic deposits (Cariati town); E) Panoramic view of the fault scarp with triangular facets of a left normal-transcurrent structure WNW-ESE trending (Corigliano-Rossano town).

During the last few decades, an increasing number of seismic stations managed by Università della Calabria (www.sismocal.org) and by Istituto Nazionale di Geofisica e Vulcanologia (www.ingv.it) allowed for reliable detection and location of low magnitude earthquakes. Figure 5 shows the epicentres of earthquakes with magnitude $M \geq 2$ located in the area during the last 43 years. The official catalogue (www.ingv.it) reports more than 4000 earthquakes located in the study area, occurred from 1981 to 2023. Among them, about 1250 have $M \geq 2$, 149 have $M \geq 3$, and 11 earthquakes have magnitude $M \geq 4$. The strongest recorded events in the last 40 years were two earthquakes of magnitude M4.7 that occurred in 1988 and in 2002, both of them located offshore Mirto Crosia. Regarding the depth distribution, 65% of this seismicity is located in the upper crust, from the surface to 20 km depth. The epicentre distribution of the recent seismicity is characterised by some places where earthquakes have been more numerous than other areas. Earthquake swarms have been recorded offshore Mirto Crosia, at Punta Alice, at Umbriatico, near

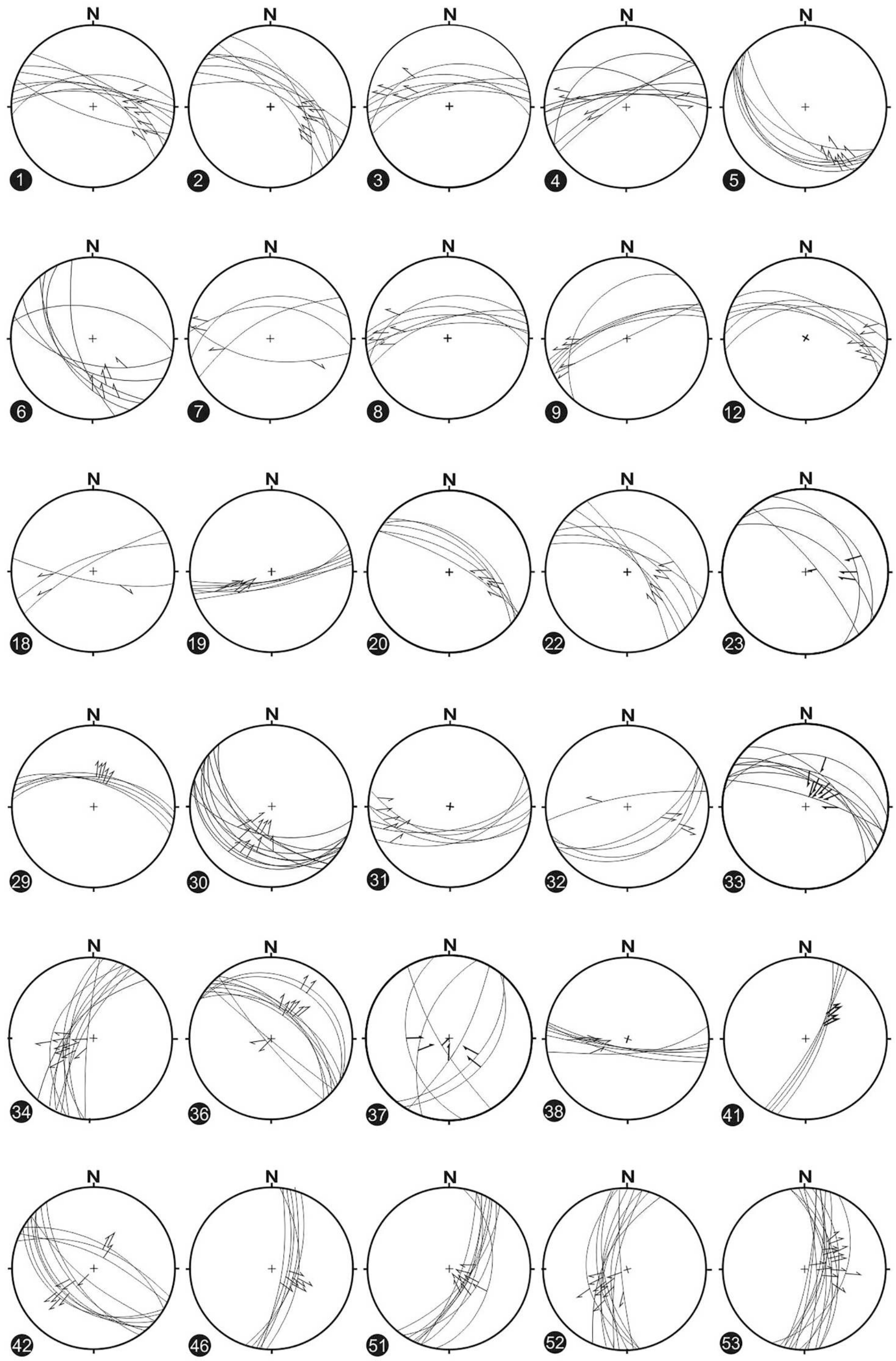

Figure 4. Mesoscopic-scale structural data gathered at the stations shown on the Map. Diagrams (Schmidt's net, lower hemisphere) show the attitude of fault planes, slickensides (arrows). Data elaboration was performed by means of the software Daisy 3.

Cropalati, and others. Although the recent earthquakes are of low to moderate magnitude, the analysis of their kinematics is essential to infer the present stress field active in the area. The collection of focal mechanisms from published papers, from open databases and those computed in this work consists of 37 earthquakes of magnitude $M \geq 2.8$. The kinematics of these earthquakes indicate a quite complex picture, particularly in the upper crust. Figure 6 shows the focal mechanism solutions in four depth ranges. All kinds of mechanisms are observed in the area, but with a predominance of strike slip motions, while reverse mechanisms are very few. The direction of the P axis of strike slip and reverse motions is mostly oriented in the EW direction. This feature is more evident for earthquakes deeper than 20 km, while for shallow earthquakes normal kinematics is more frequent. This result indicates that in the study area the active stress field has an important compressive contribution in the EW direction in the middle and lower crust, while at shallow depth the gravity contribution is likely the most important at present.

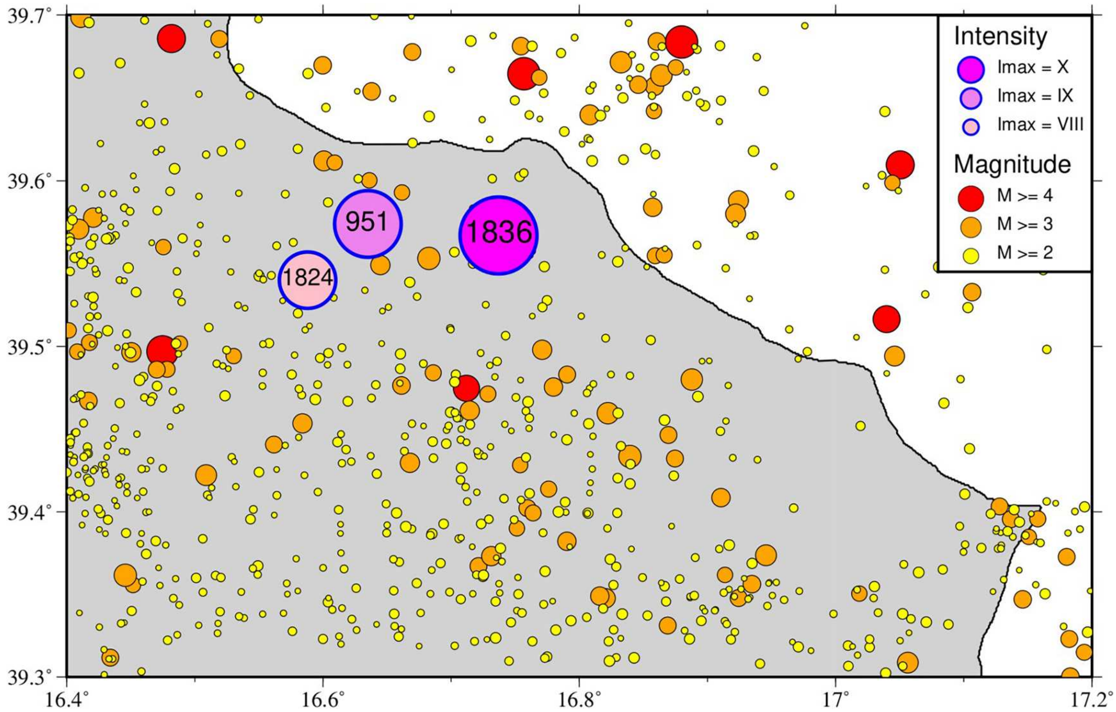

Figure 5. Historical earthquakes of Imax ≥ 8 MCS and epicenters of the earthquakes occurred since 1981.

The occurrence of earthquakes at depths greater than 30 km (nearly 40 km in some cases) in the study area indicates a complex crustal structure that is not surprising considering the subduction of the Ionian slab and the interaction with the Apulian crust in this sector of the Calabrian Arc. However, establishing if such earthquakes occur in the lower crust of the Calabrian Arc or in the crust of the subducting slab is not easy.

6. Gravitational and tectono-gravitational phenomena

The study area is marked by a large-scale instability of slopes. Many of these landslides are reactivated when particularly intense rainfall occurs: during the years 2008–2012 and in 2015, a strong rainy seasons, marked by exceptional weather conditions, have caused disasters that have damaged large areas of the territory,

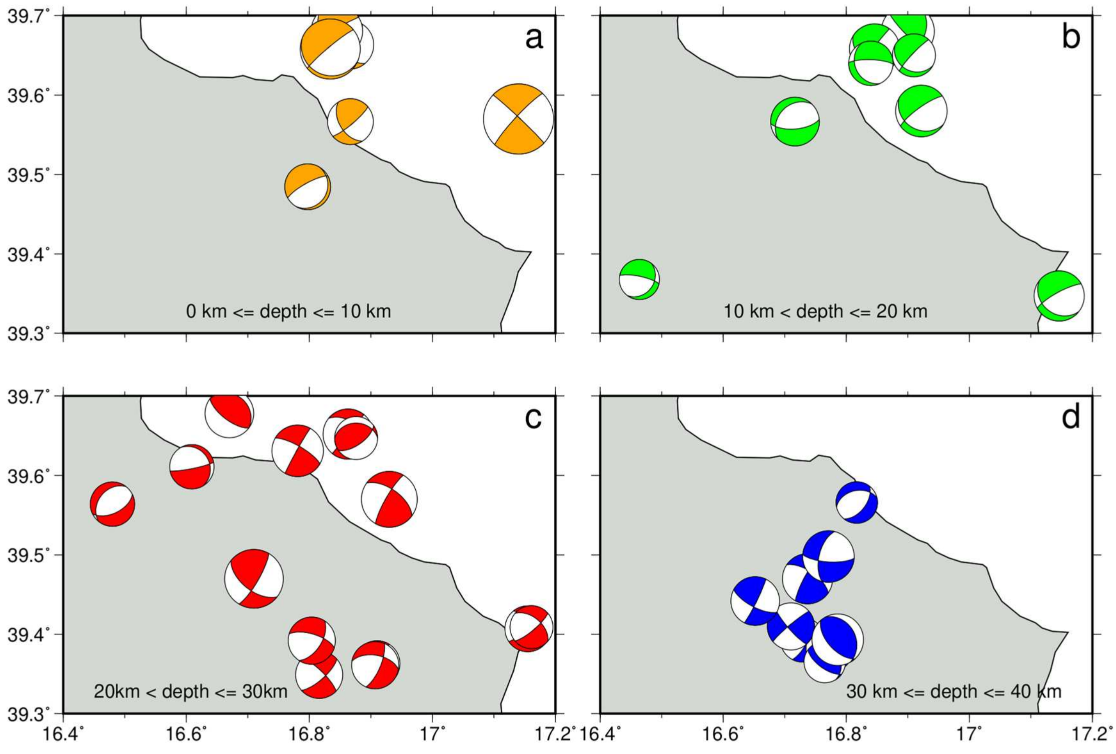

Figure 6. Focal mechanism of 37 earthquakes of magnitude $M \geq 2.8$ is shown in four depth ranges as indicated in each plot.

Figure 7. Landslides that occurred in Corigliano-Rossano town during the flood event of 12 August 2015. Historic centre of Rossano: (A) Vittorio Emanuele road, (B) Via Minnicelli road.

particularly affecting the road network and private construction, as well as economic activity in the study area and northern Calabria. In particular, the surroundings of Corigliano-Rossano town were damaged by a short-lasting and localised rainstorm on 12 August 2015, when more than 230 mm of rain in 16 h caused damage exceeding 100 million euros (Figure 7).

This instability is highlighted by widespread gravitational and tectonic-gravitational phenomena – of various types and dimensions – connected with the particular geodynamic context that determines a high relief energy along the slopes (produced by active tectonic uplift occurring in the Calabrian Arc), the degree of fracturing of the rock types involved in the tectonic deformations (Tansi et al., 2000) and the particular structural styles predisposing the slopes to instability. The tectonic pattern is also responsible for an underground water circulation strongly conditioned by the brittle tectonic structures (faults), locally causing strong increases in the neutral pressures and slope instability. Tectonic and hydrogeological conditions triggered the development and the kinematics of large landslides, deep gravitational slope (Conforti et al., 2014; Iovine et al., 1996; Tansi et al., 2005) and tectonic gravitational (Iovine & Tansi, 1998) deformations on land and in submarine environments (e.g. Mangano et al., 2022; Zecchin et al., 2018). All of which results in a close correlation between the distribution of faults, of every type, and the distribution of mass movements, of every order and degree. The Map summarises the efforts to integrate available databases with original surveying, trying to respect the original classifications. We have distinguished the following groups of gravitational and tectono-gravitational phenomena: *Fall* (FL), *Slide* (SL), *Intense Erosion Area* (IEA), *Shallow Landslide Area* (SLA), *Deep Landslide Area* (DLA), *Large Slide* (LS), *Deep-seated Gravitational Slope Deformation* (DGSD) and *Sackung* (SK). In addition, landforms were distinguished based on the period of activation as follows:

- *Landslides before 2001* affecting residential areas and roads, collected by the Basin Authority of the Region of Calabria within the definition of the Hydrogeological Plan For Soil Protection (PAI) – of the Region of Calabria, Italy (ABR-Calabria, 2001). They are represented by SL, SLA, DLA, DGSD.
- *Landslides activated in the period 2001–2016*. These data derive from both an update of 2016 year of the PAI – Basin Authority of Region of Calabria (ABR-Calabria, 2016) and the CNR-IRPI which collected data (landslides activated during the period 2008–2012) in the light of an agreement stipulated with the province of Cosenza for mapping the geo-hydrology of risk areas and the updating of the risk forecasting and prevention programme (Provincia di Cosenza, 2014). They are represented by FL, SL, IEA, SLA.

Landslides are differentiated as *dormant* or *active*, and distinguished in the same typologies of the above class according to the Cruden and Varnes (1996) classification.

Finally, the *large-scale gravitational* and *tectonic-gravitational phenomena* (LS, SK) – identified by Sorriso-Valvo and Tansi (1996), Iovine and Tansi (1998) and Conforti et al. (2014).

Tables 1–3 summarise the results of statistical analysis on the different types of the analysed mass movements.

Table 1. Statistical data on the landslides activated before 2001.

Type of movement	n. landslides	% landslides	Area (km^2)	% area
SL	226	57.36	6.10	20.37
SLA	73	18.53	2.77	9.24
DLA	93	23.6	18.72	62.48

(*Continued*)

Table 2. Statistical data on the landslides activated in the period 2001–2016.

Type of movement	n. landslides	% landslides	Area (km^2)	% area
FL	2	2.74	0.03	1.06
SL	3	4.11	0.03	1.08
IEA	60	82.19	1.56	63.17
SLA	8	10.96	0.86	34.69
Total	73	100.00	2.48	100.00

Note: Total area of the Map: 1541 km^2.

Table 3. Statistical data on the LS and SK phenomena.

Type of phenomena	n. phenomena	% phenomena	Area (km^2)	% area
LS	25	71.43	26.15	58.21
SK	10	28.57	18.78	41.79
Total	35	100.00	44,93	100.00

Note: Total area of the Map: 1541 km^2.

7. Conclusions

The eastern area of the Sila Massif is mainly controlled by several tectonic structures documenting the transition between fold and thrust belt deformation to wrench-dominated tectonic modality. The NW-SE transpressive left lateral transcurrent faults offset the entire studied area determining up-thrust blocks along the main faults and associated N-S transpressional upthrust. Major faults of this margin of Calabria conditioned the development of wedge-top basins of the southern Apennines-Calabrian Arc system in consequence of oblique collision between Calabria and Apulia blocks. Relationships between the NW-SE main faults and the seismicity of the area are testified by the distribution of earthquake epicentres.

The examined area is affected by recent and active faults and by historical and present earthquakes. The mechanisms measured in the area show mainly strike-slip left-lateral movement. These results are more evident for the earthquakes deeper than 20 km, indicating that in the study area compressive stress is present and active in the middle and lower crust. The deeper compressive mechanism could also testify the persistence of active subduction with geodynamic implications on this oblique collisional segment.

The main seismogenic structures were compared with historical and instrumental seismicity, in order to identify numerous severe crustal earthquakes (IX–X MCS) that occurred in the 17th and 19th centuries in onshore and offshore study areas.

Tectonic deformation strongly conditioned the degree of faulting and fracturing and as well as the weathering grade of a crystalline and metamorphic complex of the Sila basement rocks. These factors, together with widely outcrops of clay and silty neogenic and quaternary lithologies in the entire piedmont ionian area, predispose the slopes to large and deep landslides, to shallow and flood events.

The large-scale seismotectonic assessment and landslides map may represent a useful tool for territorial engineering-geological planning and Civil Protection.

Software

The basemap and related layout were drafted using the software open source QGIS. Daisy 3 software (Salvini, 2002) was used for the stereoplot representation of faults. Adobe Illustrator was used to produce the final layout of the Map.

Acknowledgments

The Authors warmly thank the Editor Mike Smith and the three Reviewers Steven Bernard, Mohsen Ehteshami-Moinabadi and Ray Y. Chuang for the significant improvements to the map and manuscript. We are indebted to Federica Lucà for precious suggestions and support during the cartographic revision.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

ABR-Calabria. (2001). *Piano stralcio per l'Assetto Idrogeologico (PAI)*. Segreteria Tecnica, Autorità di Bacino, Regione Calabria. https://www.distrettoappenninomeridionale.it/

ABR-Calabria. (2016). *Aggiornamento del Piano stralcio per l'Assetto Idrogeologico (PAI)*. Segreteria Tecnica, Autorità di Bacino, Regione Calabria. https://www.distrettoappenninomeridionale.it/

Amodio-Morelli, L., Bonardi, G., Colonna, V., Dietrich, D., Giunta, G., Ippolito, F., Liguori, V., Lorenzoni, S., Paglionico, A., Perrone, V., Piccarreta, G., Russo, M., Scandone, P., Zanettin-Lorenzoni, E., & Zuppetta, A. (1976). L'arco Calabro-Peloritano nell'orogene appenninico Maghrebide. *Memorie Della Societa' Geologica Italiana*, *17*, 1–60.

Barbera, G., Critelli, S., & Mazzoleni, P. (2011). Petrology and geochemistry of Cretaceous sedimentary rocks of the Monte Soro Unit (Sicily, Italy): Constraints on weathering, diagenesis and provenance. *The Journal of Geology*, *119*(1), 51–68. https://doi.org/10.1086/657340

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. *Journal of Sedimentary Research*, *78*(10), 693–711. https://doi.org/10.2110/jsr.2008.071

Bonardi, G., De Capoa, P., Di Staso, A., Perrone, V., Sonnino, M., & Tramontana, M. (2005). The age of the paludi formation: A major constraint to the beginning of the Apulia-verging orogenic transport in the northern sector of the Calabria–Peloritani Arc. *Terra Nova*, *17*(4), 331–337. https://doi.org/10.1111/j.1365-3121.2005.00618.x

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. *Journal of Geodynamics*, *102*, 95–114. https://doi.org/10.1016/j.jog.2016.09.002

Carobene, L. (2003). Genesi, età sollevamento ed erosione dei terrazzi marini di Crosia-Calopezzati (costa ionica della Calabria-Italia). Il Quaternario. *Italian Journal of Quaternary Science*, *16*(1), 43–90.

Cavazza, W., & Barone, M. (2010). Large-scale sedimentary recycling of tectonic melange in a forearc setting: The Ionian basin (Oligocene-Quaternary, Southern Italy). *Geological Society of America Bulletin*, *122*(11–12), 1932–1949. https://doi.org/10.1130/B30177.1

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. *Marine and Petroleum Geology*, *141*, 105693. https://doi.org/10.1016/j.marpetgeo.2022.105693

Conforti, M., Muto, F., Rago, V., & Critelli, S. (2014). Landslide inventory map of north-eastern Calabria (South Italy). *Journal of Maps*, *10*(1), 90–102. https://doi.org/10.1080/17445647.2013.852142

Corbi, F., Fubelli, G., Lucà, F., Muto, F., Pelle, T., Robustelli, G., Scarciglia, F., & Dramis, F. (2009). Vertical movements in the Ionian margin of the Sila Massif (Calabria, Italy). *Bollettino della Società Geologica Italiana*, *128*(3), 731–738.

Corradino, M., Morelli, D., Ceramicola, S., Scarfì, L., Barberi, G., Monaco, C., & Pepe, F. (2023). Active tectonics in the Calabrian Arc: Insights from the Late Miocene to recent structural evolution of the Squillace Basin (offshore eastern Calabria). *Tectonophysics*, *851*, 1–14. https://doi.org/10.1016/j.tecto.2023.229772

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

Critelli, S. (2018). Provenance of Mesozoic to Cenozoic Circum-Mediterranean sandstones in relation to tectonic setting. *Earth-Science Reviews*, *185*, 624–648. https://doi.org/10.1016/j.earscirev.2018.07.001

Critelli, S., & Martín-Martín, M. (2022). Provenance, paleogeographic and paleotectonic interpretations of Oligocene-Lower Miocene sandstones of the Western-Central Mediterranean region: A review. *Journal of Asian Earth Sciences: X*, *8*(Special Issue), 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. *International Geology Review*, *66*(2), 505–515. https://doi.org/10.1080/00206814.2023.2280787

Critelli, S., Muto, F., Tripodi, V., & Perri, F. (2013). Link between thrust tectonics and sedimentation processes of stratigraphic sequences from the southern Apennines foreland basin system, Italy. *Rendiconti Online della Società Geologica Italiana*, *25*, 21–42. https://doi.org/10.3301/ROL.2013.03

Critelli, S., Muto, F., Zecchin, M., Tripodi, V., Ceramicola, S., Ramella, R., & Roda, C. (2014a). *Note Illustrative della Carta Geologica d'Italia Alla Scala 1:50.000, Foglio 554 "Crucoli"*. ISPRA - Servizio Geologico d'Italia. pp. 148.

Critelli, S., Muto, F., Zecchin, M., Tripodi, V., Ceramicola, S., Ramella, R., & Roda, C. (2014b). *Note Illustrative della Carta Geologica d'Italia Alla Scala 1:50.000, Foglio 562 "Cirò"*. ISPRA - Servizio Geologico d'Italia. pp. 148.

Cruden, D. M., & Varnes, D. J. (1996). Landslide types and processes. In A. K. Turner & R. L. Schuster (Eds.), *Landslides: Investigation and mitigation* (pp. 36–75, Special Report, 247). Transportation Research Board, National Research Council, National Academy Press.

D'Amico, S., Orecchio, B., Presti, D., Gervasi, A., Zhu, L., Guerra, I., Neri, G., & Herrmann, R. B. (2011). Testing the stability of moment tensor solutions for small earthquakes in the Calabro-Peloritan Arc region (Southern Italy). *Bollettino Geofisica Teorica ed Applicata*, *52*(2), 283–298. https://doi.org/10.4430/bgta0009

Dewey, J. F., Helman, M. L., Turco, E., Hutton, D. H. W., & Knott, S. D. (1989). Kinematics of the western Mediterranean. In M. P. Coward, D. Dietrich, & R. G. Park (Eds.), *Alpine tectonics. Special publication 45* (pp. 265–283). Geological Society.

Ferranti, L., Burrato, P., Pepe, F., Santoro, E., Mazzella, M. E., Morelli, D., Passaro, S., & Vannucci, G. (2014). An active oblique-contractional belt at the transition between the Southern Apennines and Calabrian Arc: The Amendolara Ridge, Ionian Sea, Italy. *Tectonics*, *33*(11), 2169–2194. https://doi.org/10.1002/2014TC003624

Ferranti, L., Santoro, E., Mazzella, M. E., Monaco, C., & Morelli, D. (2009). Active transpression in the northern Calabria Apennines, Southern Italy. *Tectonophysics*, *476* (1-2), 226–251. https://doi.org/10.1016/j.tecto.2008.11.010

Frepoli, A., & Amato, A. (2000). Fault plane solutions of crustal earthquakes in Southern Italy (1988-1995): Seismotectonic implications. *Annali di Geofisica*, *43*(3), 437–467.

Galli, P., Spina, V., Ilardo, I., & Naso, G. (2010). Evidence of active tectonics in Southern Italy: The Rossano fault (Calabria). In P. Guarnieri (Ed.), *Recent progress on earthquake geology* (pp. 49–78). Nova Science Publishers.

Gindre-Chanu, L., Borrelli, M., Caruso, A., Critelli, S., & Perri, E. (2020). Carbonate/evaporitic sedimentation during the Messinian salinity crisis in active accretionary wedge basins of the northern Calabria, Southern Italy. *Marine and Petroleum Geology*, *112*, 104066. https://doi.org/10.1016/j.marpetgeo.2019.104066

Gori, S., Falcucci, E., Fubelli, G., Muto, F., & Dramis, F. (2017). Active transpressive surface faulting in north-eastern Calabria, Southern Italy: Early results of geomorphological, stratigraphic and paleoseismological analyses. *Alpine and Mediterranean Quaternary*, *29*(1), 91–105.

Guidoboni, E., Ferrari, G., Tarabusi, G., Sgattoni, G., Comastri, A., Mariotti, D., Ciuccarelli, C., Bianchi, M. G., & Valensise, G. (2019). CFTI5Med, the new release of the catalogue of strong earthquakes in Italy and in the Mediterranean area. *Scientific Data*, *6*(1), 80. https://doi.org/10.1038/s41597-019-0091-9

Gullà, G., Antronico, L., Sorriso-Valvo, M., & Tansi, C. (2005). Proposta metodologica per la valutazione di indicatori di pericolo e rischio da frana a scala intermedia: L'area della Stretta di Catanzaro (Calabria, Italia). *Geologica Romana*, *38*, 97–121.

Innamorati, G., & Santantonio, M. (2018). Evidence for extended Hercynian basement and a preserved Jurassic basin-margin tract in Northern Calabria (Southern Italy): The Longobucco Basin. *Sedimentary Geology*, *376*, 147–163. https://doi.org/10.1016/j.sedgeo.2018.08.009

Iovine, G., Parise, M., & Tansi, C. (1996). Slope movements and tectonics in North-Eastern Calabria (Southern Italy). In K. Senneset (Ed.), *Landslides, Vol. 2* (pp. 785–790). Balkema.

Iovine, G., & Tansi, C. (1998). Gravity-accomodate "structural-wedges" along thrust ramps: A kinematic scheme of gravitational evolution. *Natural Hazards*, *17*(3), 195–224. https://doi.org/10.1023/A:1008078217930

Langone, A., Godard, G., Prosser, G., Caggianelli, A., Rottura, A., & Tiepolo, M. (2010). P-T-t path of the Variscan low-pressure rocks from the Mandatoriccio complex (Sila Massif, Calabria, Italy): New insights for crustal evolution. *Journal of Metamorphic Geology*, *28* (2), 137–162. https://doi.org/10.1111/j.1525-1314.2009.00858.x

Lucà, F., Conforti, M., & Robustelli, G. (2011). Comparison of GIS-based gullying susceptibility mapping using bivariate and multivariate statistics: Northern Calabria, South Italy. *Geomorfology*, *134*(3-4), 297–308.

Maffione, M., Speranza, F., Cascella, A., Longhitano, S. G., & Chiarella, D. (2013). A ~ 125° post-early Serravallian counterclockwise rotation of the Gorgoglione Formation (Southern Apennines, Italy): New constraints for the formation of the Calabrian Arc. *Tectonophysics*, *590*, 24–37. https://doi.org/10.1016/j.tecto.2013.01.005

Malinverno, A., & Ryan, W. B. F. (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. https://doi.org/10.1029/TC005i002p00227

Mangano, G., Alves, T. M., Zecchin, M., Civile, D., & Critelli, S. (2023). The Rossano-San Nicola Fault Zone evolution impacts the burial and maturation histories of the Crotone Basin, Calabrian Arc, Italy. *Petroleum Geoscience*, *29*(2), 1–22. https://doi.org/10.1144/petgeo2022-085

Mangano, G., Zecchin, M., Civile, M., Ceramicola, S., Donato, A., Muto, F., Tripodi, V., & Critelli, S. (2022). Mid-Miocene to recent tectonic evolution of the Punta Stilo Swell (Calabrian Arc, southern Italy): An effect of Calabrian Arc migration. *Marine Geology*, *448*, 106810. https://doi.org/10.1016/j.margeo.2022.106810

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.

Messina, A., Russo, S., Borghi, A., Colonna, V., Compagnoni, R., Caggianelli, A., Fornelli, A., & Piccarreta, G. (1994). Il Massiccio della Sila, Settore settentrionale dell'Arco Calabro-Peloritano (The Sila Massif, northern sector of the Calabrian-Peloritan Arc). *Bollettino della Società Geologica Italiana*, *113*(3), 539–586.

Monaco, C., & Tansi, C. (1992). Strutture transpressive lungo la zona trascorrente sinistra nel versante orientale del Pollino [Appennino calabro-lucano) (Transpressional structures along the left-lateral strike-slip zone on the eastern slope of Mt. Pollino (Calabrian-Lucanian Apennine]. *Bollettino della Società Geologica Italiana*, *111*, 291–301.

Muto, F., Critelli, S., Robustelli, G., Tripodi, V., Zecchin, M., Fabbricatore, D., & Perri, F. (2015). A Neogene-Quaternary geotraverse within the northern calabrian Arc from the foreland peri-Ionian margin to the backarc Tyrrhenian margin. *Geological Field Trips*, *7*(2.2), 1–65. https://doi.org/10.3301/GFT.2015.04

Muto, F., & Perri, E. (2002). Evoluzione tettono-sedimentaria del bacino di Amantea, Calabria occidentale [Tectonic-sedimentary evolution of the Amantea basin, western Calabria]. *Italian Journal of Geosciences*, *121*(3), 391–409.

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 Journal of Geosciences*, *133*(3), 455–473. https://doi.org/10.3301/IJG.2014.23

Muto, F., Tripodi, V., Chiarella, D., Lucà, F., & Critelli, S. (2017). Tectono-stratigraphic architecture of the Ionian piedmont between the Arso Stream and Nicà River catchments (Calabria, Southern Italy). *Journal of Maps*, *13*(2), 332–341. https://doi.org/10.1080/17445647.2017.1299642

Ogniben, L. (1973). Schema geologico della Calabria in base ai dati odierni. *Geologica Romana*, *12*, 243–585.

Orecchio, B., Presti, D., Totaro, C., & Neri, G. (2014). What earthquakes say concerning residual subduction and STEP dynamics in the Calabrian Arc region, south Italy. *Geophysical Journal International*, *199*(3), 1929–1942. https://doi.org/10.1093/gji/ggu373

Palano, M., Billi, A., Conti, A., Cuffaro, M., Orecchio, B., Presti, D., Scolaro, S., Sparacino, F., & Totaro, C. (2023). The intra-orogenic normal Lakes Fault (Sila, Calabria, Southern Italy): New insights from geodetic and seismological data. *Italian Journal of Geosciences*, *142*(3), 384–397. https://doi.org/10.3301/IJG.2023.18

Petrucci, O., Caloiero, T., Pasqua, A. A., Perrotta, P., Russo, L., & Tansi, C. (2017). Civil protection and damaging hydrogeological events: Comparative analysis of the 2000 and 2015 events in Calabria (southern Italy). *Advances in Geosciences*, *44*, 101–113. https://doi.org/10.5194/adgeo-44-101-2017

Pirrotta, C., Parrino, N., Pepe, F., Tansi, C., & Monaco, C. (2022). Geomorphological and morphometric analyses of the Catanzaro Trough (Central Calabrian Arc, southern Italy): Seismotectonic implications. *Geosciences*, *12*(9), 324. https://doi.org/10.3390/geosciences12090324

Pondrelli, S., & Salimbeni, S. (2006). Italian CMT Dataset [Data set]. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/rcmt/italy

Presti, D., Billi, A., Orecchio, B., Totaro, C., Faccenna, C., & Neri, G. (2013). Earthquake focal mechanisms, seismogenic stress, and seismotectonics of the Calabrian Arc, Italy. *Tectonophysics*, *602*, 153–175. https://doi.org/10.1016/j.tecto.2013.01.030

Provincia di Cosenza. (2014). Aggiornamento del Programma di Previsione e Prevenzione dei Rischi (PPPR) e del Piano d'Emergenza. Segreteria Tecnica, Provincia di Cosenza. 103 pp.

Robustelli, G., Lucà, F., Corbi, F., Fubelli, G., Scarciglia, F., & Dramis, F. (2009b). Geomorphological map of the Ionian area between the Trionto and Colognati River catchments (Calabria, Italy). *Journal of Maps*, *5*(1), 94–102. https://doi.org/10.4113/jom.2009.1044

Robustelli, G., Lucà, F., Corbi, F., Pelle, T., Dramis, F., Fubelli, G., Scarciglia, F., Muto, F., & Cugliari, D. (2009a). Alluvial terraces on the Ionian coast of northern Calabria, southern Italy: Implications for tectonic and sea level controls. *Geomorphology*, *106*(3-4), 165–179. https://doi.org/10.1016/j.geomorph.2008.12.010

Rovida, A., Locati, M., Camassi, R., Lolli, B., & Gasperini, P. (2020). The Italian earthquake catalogue CPTI15. *Bulletin of Earthquake Engineering*, *18*(7), 2953–2984. https://doi.org/10.1007/s10518-020-00818-y

Rovida, A., Locati, M., Camassi, R., Lolli, B., Gasperini, P., & Antonucci, A. (2022). Catalogo Parametrico dei Terremoti Italiani (CPTI15), versione 4.0, INGV [data set]. https://doi.org/10.13127/CPTI/CPTI15.4

Salvini, F. (2002). The Structural Data Integrated System Analyzer. Version 3.43b (11/12/2002). Department of Earth Sciences, University "Roma Tre", Rome, Italy. http://www.dea.uniroma3.it/begin.htm

Scognamiglio, L., Tinti, E., & Quintiliani, M. (2006). Time Domain Moment Tensor (TDMT) [Data set]. Istituto Nazionale di Geofisica e Vulcanologia (INGV). https://doi.org/10.13127/TDMT

Snoke, J. A. (1989). Earthquake mechanisms. In D. E. James (Ed.), *Encyclopedia of geophysics* (pp. 239–245). Van Nostrand Reinhold Company.

Snoke, J. A., Munsey, J. W., & Teague, A. C. (1984). A program for focal mechanism determination by combined use of polarity and SV -P amplitude ratio data. *Earthquake Notes*, *55*(3), 15.

Sorriso-Valvo, M., & Tansi, C. (1996). Grandi frane e deformazioni gravitative profonde di versante della Calabria - Note illustrative per la carta al 250.000. *Geografia fisica e dinamica quaternaria*, *19*, 395–408.

Tan, Y., Zhu, L., & Helmberger, D. V. (2006). Locating and modeling regional earthquakes with two stations. *Journal of Geophysics Research*, *111*(B1), 306. https://doi.org/10.1029/2005JB003775

Tansi, C., Folino Gallo, M., Muto, F., Perrotta, P., Russo, L., & Critelli, S. (2016). Seismotectonics and landslides of the Crati Graben (Calabrian Arc, Southern Italy). *Journal of Maps*, *12*(sup1), 363–372. https://doi.org/10.1080/17445647.2016.1223760

Tansi, C., Iovine, G., & Fòlino-Gallo, M. (2005). Tettonica attiva e recente, e manifestazioni gravitative profonde, lungo il bordo orientale del graben del Fiume Crati (Calabria settentrionale). *Bollettino della Società Geologica Italiana*, *124*(3), 563–578.

Tansi, C., Muto, F., Critelli, S., & Iovine, G. (2007). Neogene-Quaternary strike-slip tectonics in the central Calabrian Arc (Southern Italy). *Journal of Geodynamics*, *43*(3), 393–414. https://doi.org/10.1016/j.jog.2006.10.006

Tansi, C., Sorriso-Valvo, M., & Greco, R. (2000). Relationships between joint separation and faulting: An initial numerical appraisal. *Engineering Geology*, *58*(2), 225–230. https://doi.org/10.1016/S0013-7952(00)00060-0

Tertulliani, A., Cucci, L., Rossi, A., & Castellano, C. (2017). Tracking earthquakes in documentary sources of the sixteenth–eighteenth centuries: Examples from Calabria (Southern Italy). *Seismological Research Letters*, *88*(1), 159–170. https://doi.org/10.1785/0220160146

Totaro, C., Orecchio, B., Presti, D., Scolaro, S., & Neri, G. (2016). Seismogenic stress field estimation in the Calabrian arc region (south Italy) from a Bayesian approach. *Geophysical Research Letters*, *43*(17), 8960–8969. https://doi.org/10.1002/2016GL070107

Totaro, C., Presti, D., Billi, A., Gervasi, A., Orecchio, B., Guerra, I., & Neri, G. (2013). The ongoing seismic sequence at the Pollino Mountains, Italy. *Seismological Research Letters*, *84*(6), 955–962. https://doi.org/10.1785/0220120194

Tripodi, V., Gervasi, A., La Rocca, M., & Muto, F. (2022). Seismotectonics of southern Calabria Terrane (south Italy). *Journal of Mountain Science*, *19*(11), 3148–3162. https://doi.org/10.1007/s11629-022-7354-1

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). *Marine and Petroleum Geology*, *95*, 328–343. https://doi.org/10.1016/j.marpetgeo.2018.03.028

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*(4), 468–481. https://doi.org/10.1080/00206814.2012.723859

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. https://doi.org/10.1016/S0040-1951(00)00139-6

Young, J. R., Teale, C. T., & Bown, P. R. (1986). Revision of the stratigraphy of the Longobucco Group (Liassic, Southern Italy); based on new data from nannofossils and ammonites. *Eclogae Geologicae Helvetiae*, *79*, 117–135.

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.

Scientific Reports, *8*(1), 7778. https://doi.org/10.1038/s41598-018-26266-y

Zecchin, M., Caffau, M., Civile, D., Critelli, S., Di Stefano, A., Maniscalco, R., & Roda, C. (2012). L'evoluzione plio-pleistocenica del Bacino di Crotone (Italia meridionale): interazione tra sedimentazione, tettonica ed eustasy nel quadro della migrazione dell'arco calabrese. *Recensioni di Scienze della Terra*, *115*(4), 273–303.

Zecchin, M., Caffau, M., Di Stefano, A., Maniscalco, R., Lenaz, D., Civile, D., Muto, F., & Critelli, S. (2013). The Messinian succession of the Crotone Basin (Southern Italy) II: Facies architecture and stratal surfaces across the Miocene–Pliocene boundary. *Marine and Petroleum Geology*, *48*, 474–492. https://doi.org/10.1016/j.marpetgeo.2013.08.013

Zecchin, M., Civile, D., Caffau, M., Critelli, S., Muto, F., Mangano, G., & Ceramicola, S. (2020). Evoluzione sedimentaria del Bacino di Crotone Neogene-Quaternario (Italia meridionale) e relazioni con la tettonica a larga scala: un approccio sequenziale stratigrafico. *Geologia marina e petrolifera*, *117*, 104381. https://doi.org/10.1016/j.marpetgeo.2020.104381

Zecchin, M., Civile, D., Caffau, M., Muto, F., Di Stefano, A., Maniscalco, R., & Critelli, S. (2013). The Messinian succession of the Crotone Basin (Southern Italy) I: Stratigraphic architecture reconstructed by seismic and well data. *Marine and Petroleum Geology*, *48*, 455–473. https://doi.org/10.1016/j.marpetgeo.2013.08.014

Zhao, L. S., & Helmberger, D. V. (1994). Source estimation from broadband regional seismograms. *Bulletin of the Seismological Society of America*, *84*(1), 91–104. https://doi.org/10.1785/BSSA0840010091

Zhu, L., & Helmberger, D. V. (1996). Advancement in source estimation techniques using broadband regional seismograms. *Bulletin of the Seismological Society of America*, *86*(5), 1634–1641. https://doi.org/10.1785/BSSA0860051634