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SERVIZIO GEOLOGICO D'ITALIA
Organo Cartografico dello Stato (legge n° 68 del 2.2.1960)

EMODnet
European Marine Observation and Data Network

CNR ISMAR Istituto di Scienze Marine · Istituto Nazionale di Geofisica e Vulcanologia · OGS Istituto Nazionale di Oceanografia e di Geofisica Sperimentale · Università di Genova · Università degli Studi di Palermo · Roma Tre Università degli Studi Dipartimento di Scienze · Università degli Studi di Trieste

STRUCTURAL MAP OF SEAS SURROUNDING ITALY

Scale 1:1 250 000

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FOREWORD

The Geological Survey of Italy (currently a Department of the National Institute for Environmental Protection and Research, ISPRA) is the official geological mapping office of Italy. The geological mapping section of the Survey, besides its main task of maps production, carries out research activities and participates in international projects.

The marine geology team of the mapping section is Partner of the Consortium, originated in the frame of the Marine Geology Expert Group of EuroGeoSurveys (Association of European Geological Surveys), which carries out the Geology Lot of the European Marine Observation and Data network (EMODnet). EMODnet Geology aims at creating Europe wide digital maps of marine areas and at providing free access to the underlying databases.

Seabed studies have been considerably boosted in the last thirty years, thanks to technological innovation which allowed to increase and update the knowledge of submerged areas, providing additional information on seafloor features as well as on buried geological structures.

The comprehensive national database realized within the Italian Geological Mapping Project (CARG) allowed the Geological Survey of Italy, together with its long experience in cartographic representation, to contribute succesfully to the diverse products of EMODnet Geology. However, other Italian public research institutions and universities have been involved in the activities of the Project in order to provide the most comprehensive and updated products, particularly concerning geological events (earthquakes, submarine landslides, volcanic centers, tsunamis, fluid emissions and tectonics), which constitute the object of the work package of EMODnet Geology coordinated by the Geological Survey of Italy.

The data gathered for EMODnet Geology, allowed the Geological Survey of Italy, in collaboration with CNR-ISMAR, INGV, OGS and the universities of Genova, Palermo, RomaTRE and Trieste, to realize, as one of its publications, the present “Structural map of seas surrounding Italy” which represents a case study of EMODnet applications. It aims to be an update, relative to submerged areas, of the Structural Model of Italy, published at the beginning of the 90s, and provides information concerning the structural setting of seas surrounding Italy.

Marco Amanti
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INTRODUCTION

The structural map of seas surrounding Italy supplements the Structural Model of Italy (composed of six sheets at 1:500,000 scale published in subsequent years: Bigi *et alii*, 1990a, 1990b, 1991a, 1991b, 1992a, 1992b), by adding new information on the submerged, seafloor areas. Its objective is to gather information collected during the last decades and convey it as a single map product. Starting from the Structural Model of Italy and the Neotectonic map of Italy (Ambrosetti *et alii*,1987), new data have been included from publications as well as from scientific surveys carried out by the Authors or by the Authors' Institutions. This new map is made available in both printed and digital format. The digital version is an OGC standard database (doi: 10.15161/oar.it/212660) for storage and direct use of vector geospatial features and tabular data that can be used in order to access data sources and other information. It provides an overview of existing data enabling further detailed investigations to be planned to study natural hazards and to support marine spatial planning and management.

The launch in 2009 of the European Project EMODnet (European Marine Observation and Data Network), provided the opportunity to start systematically organizing marine data and summarising them in digital maps freely available on the EMODnet website (https://emodnet.ec.europa.eu/en).

In 2013 the Geological Survey of Italy invited geologists who had been involved in studies on tectonics to participate in a discussion concerning a possible update of the Structural Model of Italy. The discussion proceeded through meetings organized remotely and via special sessions at conferences, such as the 2013 AIQUA (Italian Association for the Study of the Quaternary) Congress in Naples.

During the following years the Geological Survey of Italy joined the consortium carrying out the EMODnet Geology Project, providing products related to all the planned data layers and started to coordinate a work package focused on geological events including earthquakes, volcanoes, submarine landslides, fluid emissions, tsunamis and Quaternary tectonics. This Project provided an opportunity to collate, standardize and spatially and semantically harmonize (i.e. according to European Commission instructions, to organize features attributes in order to obtain homogeneous Europe wide representation of data across countries borders) data from submerged areas to be represented on digital maps. At the same time, it allowed the establishment of a permanent group of Italian public research Institutions (Consiglio Nazionale delle Ricerche - Istituto di Scienze Marine - CNR-ISMAR; Istituto Nazionale di Geofisica e Vulcanologia - INGV; Istituto Nazionale di Oceanografia e di Geofisica Sperimentale - OGS, Universities of Genova, Palermo, RomaTRE, Trieste), that conduct marine geology studies or have specific expertise in the topics included in the Project. The group has been cooperating in order to make the Italian contribution to the project as complete and integrated as possible; besides Project products, the work carried out also suggested that an update of the Structural Model of Italy concerning submerged areas would have been possible.

Emerged areas were beyond the scope of the Project; however, in the last two years, a sister project carried on by a research group promoted by INGV has been working on an update of the Structural Model for emerged areas as well, which will be a future publication.

EMODnet Geology is currently into its fifth phase and the list of tectonic features included in the mapping project, as well as of their attributes, has been refined through the years according to the foreseen, higher resolution, data.

Features included in the map (superimposed on shaded relief bathymetry) are tectonic elements (faults, folds axes, high-deformation crustal zones), earthquakes, submerged volcanic structures and rocky outcrops, main onshore volcanic deposits and tectonic elements; whereas the inset maps include thickness of the Plio-Quaternary succession, shelfbreak and foot of the continental slope, depth of the Moho discontinuity and heat flow.

The top of Messinian evaporites was considered for inclusion in the map as a potential reference layer, but the idea was dismissed as being impractical, as well as the direct identification of crustal domains.

Geomorphic features were not considered in the map. However, the major physiographic discontinuities (shelfbreak and foot of the slope) are reported in an inset map. Volcanic submarine structures (seamounts) were considered as rock outcrops focusing on their age and lithology rather than geomorphology because they provide insight into the tectonic evolution of the basins and its timing.

OBJECTIVE AND DATA SOURCES

The EMODnet Project conveys into a single map all existing data delivered by each country organization from their marine jurisdictions. The main task of the present work was to gather, standardize and harmonize information on all of the seafloor features listed above, from existing publications and other unpublished sources. Data were collected and analysed according to common standards established by EMODnet Geology: tectonics, earthquakes and submarine volcanic structures, within the work package on geological events, and rocky outcrops, within the work package on seafloor geology.

Geodatabase of the Structural Map of seas surrounding Italy

Although EMODnet Geology did not involve the acquisition of new data, it initiated the systematic inventorying of existing data and their standardization. Data from the Italian Geological Mapping Project (CARG), coordinated by the Geological Survey of Italy, were combined with data and thematic maps from the other Italian institutions and universities involved, to be merged with the existing and available marine geological information of European countries, complying with FAIR principles such as interoperability and reuse of geological data.

Although the creation of databases does not negate the need for new data, such databases do provide useful research tools and insights that were not previously visible (i.e. the whole of a map is more than the sum of its parts). New thematic or specialistic maps may arise from the creation of a new synthesis of existing data.

The guidelines for the compilation of GIS layers developed in EMODnet for the “Geological Events work package” were taken as a basis for the identification of parameters for feature characterization, including the attribute tables already structured to be compliant with the European INSPIRE directive.

Due to the different geological settings of the Italian seas, it was necessary to revise and integrate an updated and detailed pattern of attributes for the different features in order to represent each occurrence at the designated reference scale.

An extensive consultation was carried out within the working group to implement the *codelists* for the fields of the Attribute tables of each GIS layer plus any relevant additional information.

In some locations data are overly abundant and particular attention was dedicated to the representation of data to conform with the scale of the map. This is necessary to allow for easy reading of the map. Where occurrences are too abundant, a single representative feature is recorded on the map, although the underlying data can be accessed in the database.

Criteria for the cartographic representation of the data and its inclusion in the supporting database, are as follows:

a. File format: the Project required that data be provided in shapefile format (in line, polygon and point features, depending on the geometry of the data), which are then structured within a database as a GeoPackage, that is an open, standards-based, platform-independent, compact format for transferring geospatial information.
b. Scale: according to the 1:1,250,000 scale of representation:
   - the smallest representable line must have a length equal to or greater than 10 km;
   - the minimum distance between lines is 5 km;
   - the smallest representable polygon must have an area equal to or greater than 15 km^2.
c. Coordinate system: data have been geo-referenced in the WGS84 system in geographic coordinates (Lat / Lon).
d. Coastline: the coastline used was provided by the European Environment Agency (scale 1:100,000).
e. Bathymetric contour lines: isobaths were obtained by interpolation from the EMODnet Bathymetry DTM. The bathymetric contours shown were created from this DTM at 50 m intervals on the continental shelf to 200 m depth and at 500 m intervals at greater depths.

For all layers two fields are particularly important *Unique Identifier Code* and *References,* because they respond to the need for locating occurrences and providing information on data sources. The database structure is designed to be flexible in order to accommodate as many data as possible. Furthermore, since very specific data might not fit into any field of the *Attribute table*, the Comments field was created specifically to store any other information and to prevent it from getting lost.

The working group was organized into subgroups based on geographic areas; each subgroup collected regional datasets compiled from unpublished survey results and from the literature, including maps, databases and both national and European projects.

Data at different scales and deriving from different sources had to be standardized at the scale of representation. Data acquired at higher resolution had to be generalized and, in some cases, it was necessary to exclude features that would not match the resolution of the map. However, original detailed data are available through the EMODnet Portal.

Datasets were shared as shapefiles subdivided into layers depending on the type of data processed and into different geometric features related to the specific characteristics of each occurrence, *e.g.* lines for tectonics, points for earthquakes and polygons for volcanic and non-volcanic rock outcrops.

Data processing consisted of correcting and reorganizing information, in order to obtain an homogeneous product, spatially consistent and topologically correct. INSPIRE compliant terms provided the basis for a semantic standardization and integration for coded domains. Special styles for the symbols were created in order to have a representation in GIS environment that is as faithful as possible to the printed map.

Cartographic representation

The printed version of the map was produced at 1:1,250,000 scale in the UTM ED50 zone 33N cartographic projection. This projection was selected because the WGS84 projection would have generated a compressed view compromising the legibility of the map.

The main toponyms cited in the text (seas, mountain chains, regions, cities, etc.) are reported on the map; whenever other names are mentioned in the description of data, they are reported in the figures of the related section.

Colours

Colour scales were selected for geochronologic ages of polygons and lines. In case the age of an element is unknown, the corresponding symbol is black or grey. Colours were derived from the standards established in the Chromatic Handbook, which is part of the Guidelines for the Geological Map of Italy at 1:50,000 scale (Tacchia, 2007) and refers to the International Chronostratigraphic Chart (https://stratigraphy.org/chart). The Handbook provides a chromatic scale of 56 different colours according to geochronological units. For each colour there are five tones obtained by varying percentages of intensity. Such tones have been used to differentiate elements cropping out (more marked), buried (less marked) or in case it is not possible to know whether they are buried or crop out (lighter). However, due to the high number of classes necessary to represent the different time intervals, it was not always possible to strictly apply this procedure. Consequently, in order to reduce the number of different colours, which would be difficult to distinguish, age classes were grouped focusing on the age of the major or more recent tectonic phases, particularly in cases when a specific age was assigned to a limited number of occurrences.

Symbols

The selection of symbols adopted for the different elements of the Map derives from the consolidated graphic representation used for geological and geothematic maps produced by the Geological Survey of Italy. Symbols respect the size and thickness proportions, necessary to guarantee data legibility.

Styled lines are used to indicate the kinematics of tectonic elements; in case kinematics is unknown, tectonic elements are represented by simple lines without any additional mark. In addition to standard notations used for faults (normal, reverse, thrust, strike-slip, etc.), a few symbols have been created expressly to address specific features (normal fault reactivated as reverse fault, reverse fault reactivated as normal fault, etc., see Legend).

Polygons represent submarine volcanic structures and rock outcrops (see details below). On top of the colour corresponding to their age, overprinted patterns are used to indicate chemical composition/affinity for submarine volcanic structures and lithologies for rocky outcrops; in case these are unknown, no pattern is displayed on top of the polygons.

Point features have been used for earthquakes only. They are subdivided into two groups: circles, which refer to data recorded by instruments obtained from the Earthquake Catalogue of INGV, and diamonds, which refer to historical data (see below the seismicity paragraph for more details). In both cases, size and colour intensity of the symbols are proportional to earthquake magnitude.

Features reported in the map

Bathymetry

The Digital Terrain Model (DTM) represented as the underlying layer of the map, "Mean depth full coverage with land coverage", is one of the products available from the EMODnet Bathymetry Project. The version used here was produced in 2020 and displays the mean depth relative to Lowest Astronomical Tide (LAT). It has a grid of 1/16 * 1/16 arc minute of longitude and latitude (ca. 115 * 115 m) complemented by land DTM and GEBCO coverage in traditional atlas style colours. The isobaths represented were selected in order to outline seafloor geomorphology which contributes to evidence geological structures.

Tectonics

Tectonic elements, including faults, folds, synclines, anticlines and high-deformation crustal zones, are important features of the map. The relevance of structures re-activations was also evidenced.

Data were revised on the base of more recent studies (the main sources are reported in Tab. 1) and updated interpretations of the dynamics taking place throughout the Italian sea basins. Data were gathered at the highest resolution available and

Geographic area	Seismic data used	Maps referenced	Other information
Adriatic Sea	- OGS MCS profiles - ViDEPI - CROP profiles	- Structural Model of Italy - Neotectonic map of Italy - Geological Map of Italian Seas at 1:250,000 scale	- Literature
Ionian Sea	- Sparker profiles from CNR database - ViDEPI - CROP profiles	- Structural maps from literature - Neotectonic map of Italy - EMODnet Bathymetry	- Literature - Reports - METIQ (Evolutionary Model of the Italian Territory in the Quaternary)
Ligurian Sea	- Profiles from DISTAV-UNIGE dataset - MS profiles (OGS) - CARG Project - MALISAR Project - MaGIC Project	- Structural Model of Italy - Neotectonic map of Italy - EMODnet Bathymetry - CARG Project Map	- Literature - METIQ - CARG Project
Tyrrhenian Sea	- Sparker profiles from CNR database - MS, CS, ISTEGE, and MEDOC dataset profiles - CROP profiles	- Structural Model of Italy - Neotectonic map of Italy - EMODnet Bathymetry - Map of the thickness of the Plio-Quaternary succession	- Literature - METIQ
Sicilian Channel	- Profiles from UNIPA dataset - MS profiles (OGS) - Profiles from OGS dataset - ViDEPI - CROP Project	- Structural Model of Italy - Neotectonic Map of Italy - EMODnet Bathymetry - Maps of the Atlases in Geoscience 1 "CROP Project"	- Literature - Technical reports of scientific or industrial surveys
West Sardinia offshore	- MS profiles (OGS) - WS_2010 profiles (OGS) - ViDEPI	- Structural Model of Italy - EMODnet Bathymetry	- Literature

Tab. 1: Main sources of tectonic information used in this study subdivided by geographic area.

then generalized in order to be represented in a map at 1:1,250,000 scale.

Faults have been classified (whenever possible) according to their kinematics into normal, reverse, thrust, strike-slip, right/left lateral strike-slip, oblique slip and a number of combinations, including reactivation of pre-existing faults with a different type of movement.

Seismicity

The map shows the location of earthquakes that occurred offshore Italy, subdivided into two main categories represented by circles and diamonds. The size of both symbols is proportional to the magnitude, expressed as duration Magnitude (Md), for earthquakes that occurred up to 2012; Local Magnitude (ML), for events from 2012 onward; and Moment Magnitude (MW), for the most energetic earthquakes. Circles represent the collection of instrumental seismicity locations recorded from 1985 to 2022, as reported in various catalogues, including: i) the Catalogo della Sismicità Italiana (CSI; Castello *et alii*, 2006), ii) the Italian Seismic Bulletin (BSI; ISIDe working group, 2007), which is based on analysts' revisions of earthquakes with a magnitude value equal to or greater than 1.5 and is published every 4 months, starting from 2015; iii) the revised locations catalogues, published in several scientific papers. Diamonds represent the "historical" earthquakes that occurred in the Italian seas up to 1985 and documented in the Catalogo Forti Terremoti Italiani (CFTI; Rovida *et alii*, 2022) and in the Catalogo Parametrico Terremoti Italiani (CPTI) (Boschi *et alii*, 1989; 1995; 1997; Rovida *et alii,* 2022).

Unlike instrumental seismicity, the analysis of historical earthquakes is primarily based on historical, naturalistic observations and literary treaties. The reliability of epicentral locations is subject to considerable uncertainty, as they are directly based on the memory and perceptiveness of individuals, in which events were permeated by a specific and personal perspective. Consequently, some ancient energetic events (*e.g.*, 1169, Mw 6.5; 1693, Mw 7.3; 1783, Mw 7.1) that occurred near the coast, could have their source partially or totally offshore, as suggested by more recent revisions, based on factors such as the presence of tsunami deposits (*e.g.*, Bianca *et alii*, 1999; and references therein). For all these earthquakes, hypocentral parameters are estimated, albeit with relative uncertainty, using a defined procedure (Rovida *et alii*, 2022).

Earthquakes occurring in the Italian territory and surrounding areas are recorded by land seismic stations of the Rete Sismica Nazionale (RSN), managed by the Istituto Nazionale di Geofisica e Vulcanologia (INGV). Historically, the INGV monitoring network was born and took shape in the early 1980s, following the Irpinia earthquake of November 23rd, 1980 (www.ingv.it). At the time, the network was exclusively of the analogue type and included about 70 stations with only vertical sensors (Fig. 1a). To date, the RSN consists of more than 500 stations scattered throughout the Italian territory (Fig. 1b). Data are tele-transmitted to the INGV Seismic Room, where 24-hour seismic monitoring of the national territory is performed for civil protection purposes. Data are verified by the seismologists on surveillance duty and are promptly made public.

From the available seismological bulletins of INGV (from both the CSI and BSI catalogues), we extracted a seismological dataset of earthquakes occurred in Italian seas and in coastal areas from January 1985 to December 2022, that consists in several thousands of crustal and subcrustal events. We filtered the data extraction for magnitude and depth values, considering the minimum magnitude value of 1.5 and the maximum hypocentre depth of 100 km, collecting a seismological dataset that consists of 21,440 ($1.5 \leq$ Md-ML ≤ 5.6) crustal and sub-crustal earthquakes.

As many of these events were the object of revision in several scientific works, the following step was the collection of the published revised seismicity, included in all the seismological catalogues of earthquakes that were published in the near past. In these catalogues, earthquakes were relocated with the use of both 1D velocity models (*e.g.*, Sgroi *et alii*, 2006) and 3D tomographic models (*e.g.*, Scarfì *et alii*, 2018).

In recent years several seismological experiments have been carried out in the southern Tyrrhenian and western Ionian seas, the areas most affected by earthquakes. The aim is to expand the seismic network at sea through the deployment of Ocean Bottom Seismometers and Hydrophones (OBS/H) and seafloor observatories (*e.g.*, Dahm *et alii*, 2002; Favali & Beranzoli, 2006). In the southern Tyrrhenian Sea, an OBS/H network surrounding the Aeolian Islands operated for six months during the TYDE experiment (Dahm *et alii*, 2002), detecting an intense seismicity of tectonic and volcanic origin (Sgroi *et alii*, 2006; Sgroi *et alii*, 2009); the OBS/H deployment was accompanied by the deployment of the GEOSTAR seafloor observatory near Ustica Island (Beranzoli *et alii*, 2000; Sgroi *et alii*, 2006). In the Ionian Sea, the deployment of the NEMO-SN1 seafloor observatory (Favali & Beranzoli, 2006) allowed for synchronous recordings of time-series for multidisciplinary studies and provided useful information on oceanic areas and, in particular, on volcanic and tectonic structures (Sgroi *et alii*, 2007; Sgroi *et alii*, 2014; Sgroi *et alii*, 2021a,b). Moreover, in the Ionian Sea the SEISMOFAULTS project (www.seismofaults.it) has been the first experiment designed to illuminate geological active features of the Calabrian Arc subduction complex (offshore Sicily and south Calabria) through the deployment of an OBS network which consisted in seven seafloor stations (Billi *et alii*, 2020) that recorded seismological data from May 2017 to May 2018 (Sgroi *et alii*, 2021c). The recorded travel times data from OBS/H were integrated with those of land seismic stations and earthquakes were prevalently relocated using both 1D and 3D velocity models (Monna *et alii*, 2013; Sgroi et al, 2006; Sgroi *et alii*, 2021a,b,c). In general, the result of the integration processes is the improvement of earthquake location and a better focusing on tectonic structures that generate the events, as the distribution of the seismicity reflects the pattern of the main tectonic structure.

In the offshore Italian area, seismicity is prevalently concentrated in the Tyrrhenian and Ionian seas, related to plate collision and the opening of the back-arc basin (Fig. 2 and discussion in their respective sections), whereas consistent clusters of earthquakes occur in the Adriatic Sea (Fig. 2 and discussion in the Adriatic Sea section), associated to several episodes of reactivations of the Adriatic outer front of the Apennines. On the other hand, seismicity occurring in other marine areas is rather diffused or almost absent in connection with a reduced tectonic activity, as observed in western Sardinia. Several seismic sequences occurred in the southern Italy offshore from 1985 to 2022, while

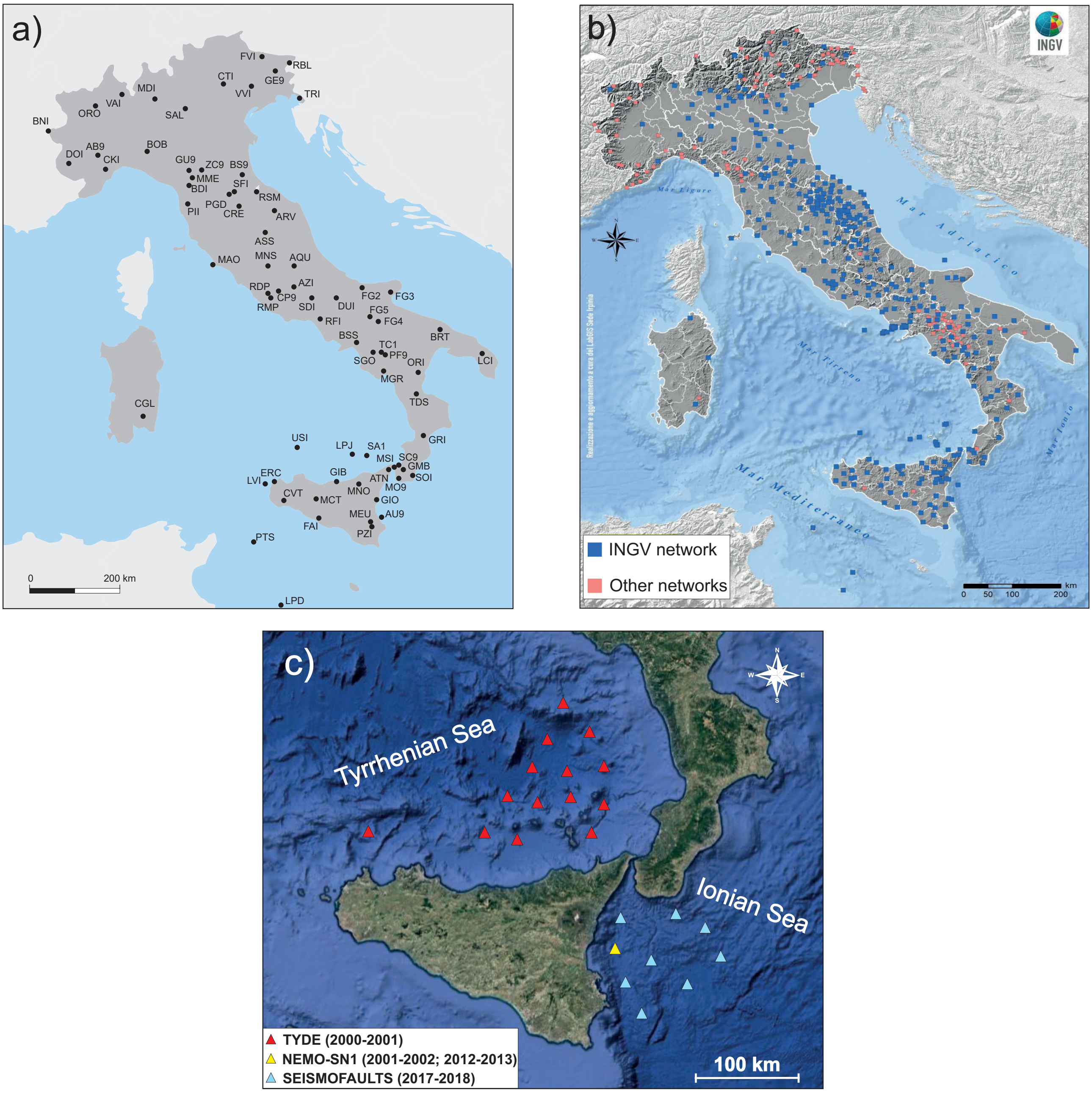

Fig. 1: The seismic networks managed by the INGV: a) in the early 90s the RSN was exclusively of the analogue type and included about 70 stations with only vertical sensors (www.ingv.it); b) to date, the RSN consists in about 500 broad-band stations (with 3C component sensors) scattered throughout the country (www.ingv.it); c) the marine networks (managed by the INGV) that included the NEMO-SN1 seafloor observatory (Favali & Beranzoli, 2006) deployed in the Ionian Sea and several Ocean Bottom Seismometers/Hydrophones (OBS/H) that were deployed both in the Ionian and Tyrrhenian Seas during some seismological experiments (TYDE, Dahm *et alii*, 2002; SEISMOFAULTS, Billi *et alii*, 2020; Sgroi *et alii*, 2021c).

in central-north Italy seismic sequences are mainly concentrated onshore, occurring prevalently in the Apennines mountains.

Calabria and Sicily are considered two of the regions with the highest seismic hazard in Italy, mostly due to the many strong earthquakes that struck the area in past centuries (Guidoboni *et alii*, 2018; 2019). Some active seismogenic sources are inferred from the location of past earthquakes and from the surface morphology, while other active faults remain debated due to the lack of instrumental seismicity (Chiappetta & La Rocca, 2023; and reference therein), related to network geometry problems influenced by the extended marine area.

In these regions, seismic sequences are associated to the Calabrian Arc, one of the most active tectonic structures in the Mediterranean area. Some sequences were followed by tens to hundreds of

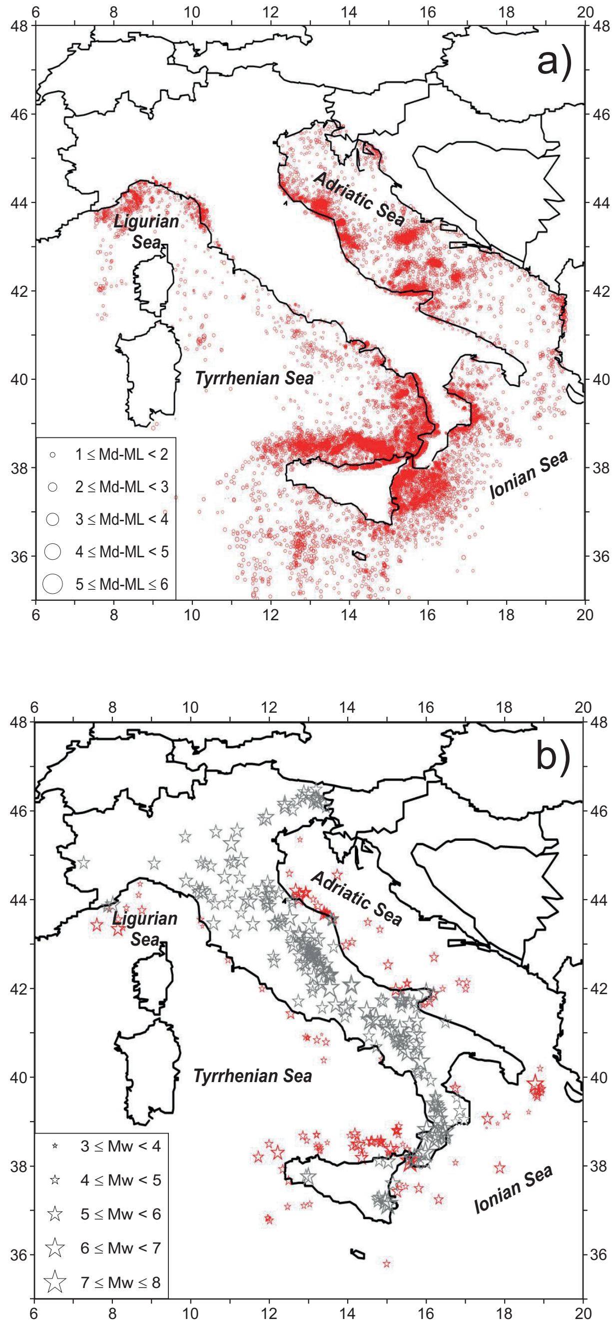

Fig. 2: (a) Location map of the instrumental seismicity (BSI and revised literature) occurred in the marine areas surrounding Italy from 1985 to 2022 (red circles; 1.5 ≤ Md-ML ≤ 5.6). (b) Location map of the historical high-magnitude earthquakes occurred prior to 1985 in the offshore (196 events, red stars; 3.1 ≤ Mw ≤ 7.2) and onland (215 events, gray stars; 5.5 ≤ Mw ≤ 7.3)

smaller, well-clustered earthquakes that occurred during the following weeks or months. In other cases, swarms of low-magnitude earthquakes occur without a classical mainshock-aftershock evolution (CHIAPPETTA & LA ROCCA, 2023).

Submarine Volcanic Structures and Rock outcrops

Submarine volcanic structures (seamounts) are evidence of the opening of the Liguro-Provençal Basin, (between 30 and 15 Ma, FACCENNA *et alii*, 2002) and of the Tyrrhenian Back-Arc Basin (20 Ma-Recent, DOGLIONI *et alii*, 2004). They are represented in the map as rock outcrops characterized by their age and main chemical composition/affinity, since they are related to different types or different stages of the tectonic evolution of the basins.

Volcanic seamount attributes are: location, age, morphological type, chemical composition and activity type. All information is extracted from published scientific articles, PhD thesis, books, oceanographic and geophysics survey reports. In particular, information for 76 volcanic seamounts of the Ligurian Sea, Tyrrhenian Sea and Sicilian Channel is available from the database associated with the Atlas of Italian Submarine Volcanic Structures (PENSA *et alii*, 2019). In addition, other three seamount structures of recent identification have been added to the map: Ovidio smt, Scalea smt (DE RITIS *et alii*, 2019) and Aurelia smt (PALMIOTTO *et alii*, 2022), located in the eastern and central Tyrrhenian Sea, respectively.

Regarding the Sardinian western margin, small volcanic structures have been identified using information extracted from scientific articles, seismic profiles and geological maps (DPC-CNR, 2007-2013; SERVIZIO GEOLOGICO D'ITALIA, 2012, 2015a, 2015b; CONFORTI *et alii*, 2016; DEIANA *et alii*, 2021; FRISICCHIO *et alii*, 2025). These volcanic edifices are constituted mainly by isolated or grouped monogenic vents, located between 20 m and 150 m water depth (CONFORTI *et alii*, 2016). Although their morphological expression is not comparable with the volcanic submerged edifices located in the Tyrrhenian Sea, and each structure has not been singularly named (except for ALABE HILL, ROVERE & WÜRTZ, 2015), they have been included in the map as well as other volcanic seamounts.

The graphical representation of the three new volcanic edifices identified in the Tyrrhenian Sea, together with the small volcanic structures along the western Sardinian margin, followed the same criteria adopted by PENSA *et alii* (2019).

The outline of each polygon is drawn using the EMODnet Bathymetry DTM as background, taking into account geological and physiographic boundaries; it is extended to the main break in slope of the inferred base and on the volcanological interpretation of the morphology. It must be noted that the extent of the volcanic seamounts in some cases does not match the extent reported in the Structural Model of Italy mostly because the bathymetry used in the present map is much more detailed and allowed a better definition of the morphology of the seamounts and inference of the basal extent of each edifice reported in Pensa *et alii* (2019).

The age of the structures spans from Oligocene (Liguro-Provençal back-arc basin opening) to Quaternary (Marsili Basin spreading and NW-SE Sicilian Channel rift system development).

The main chemical composition/affinity of each volcanic structure is addressed in the map using different patterns overlain on top of the polygons. Approximating the scheme of the Atlas of Italian Submarine Volcanic Structures (Pensa *et alii*, 2019), five different magmatic series have been adopted to classify the volcanic submerged structures: K-alkaline, Na-alkaline, Calc-alkaline to shoshonitic; Na-alkaline/OIB type and Tholeiitic. All the structures whose volcanic origin is not characterised compositionally, have been addressed as "Undefined igneous rock".

Additional rock outcrops derive from the Structural Model of Italy and were complemented with information from the geological maps of the CARG Project and from other publications. In some cases, polygons actually refer to rocks which do not necessarily crop out on the seafloor but are rather covered by thin sediments. Polygons have been selected, interpreted and generalized based on recent data and/or observations.

Descriptions of rocky outcrops that are too vague or of variable composition were organized into a standardized scheme of lithologies, along with geochronological ages, as listed on the map. This simplification was necessary to reduce the number of symbols needed for representation on the map. In addition to igneous rocks, which have been classified according to the same criteria adopted for volcanic submarine structures, the resulting classes are: carbonate sedimentary, clastic sedimentary, clastic and evaporitic, crystalline, metamorphic, ophiolites and undefined.

A list of more than 70 different age intervals was derived from the various sources gathered. After an evaluation of the different age intervals, taking into account the number of occurrences of each interval, outcrop polygons were grouped into twelve age-ranges.

Features reported on land

The EMODnet Bathymetry Digital Terrain Model adopted as the layer underlying the map also includes land coverage, which provides information concerning the location of the main mountain chains. The principal tectonic elements occurring on land areas are also reported as well as the most relevant volcanic structures. Several toponyms help with understanding the location of the features reported.

Inset maps

Thickness of the Plio-Quaternary succession

To obtain information on the distribution of sedimentary basins in seas surrounding Italy and to relate them to the tectonics and distribution of the structures that have shaped the main marine domains, the thickness of the Plio-Quaternary succession of Italian seas is reported as an inset map, to prevent possible overlaps and confusion with the features included in the main map. The map at 1:4,000,000 scale represents thickness by areas contoured by isolines (isopachs) at 500 m intervals up to a maximum of 4,000 m. In areas where the thickness is less than 500 m, additional intervals (0, 100, 200 and 250 m) were considered.

The data used to map the thickness of the Plio-Quaternary succession were processed by geographic area, as follows: Tyrrhenian Sea, Ionian Sea, Adriatic Sea, Ligurian Sea, Sicilian Channel and Western Sardinia. Isopachs were interpolated in bordering areas, taking into account known geological structures. The Plio-Quaternary thickness was obtained by the difference in time between the depth of the base of the Plio-Quaternary succession and the seafloor bathymetry, both in two-way travel time (twtt). All Plio-Quaternary thickness data have been converted to m considering a constant seismic velocity of 2,000 m/s.

Areas with a very thick Plio-Quaternary succession of over 3,000 m are present in the Tyrrhenian Sea, mapped by Loreto *et alii* (2021a,b), such as the Paola Basin located offshore Calabria (see Tyrrhenian Sea section).

Ionian Sea isopachs were mapped from the 30-kJ sparker seismic database of ISMAR-CNR. For each transect two surfaces have been digitized: the sea bottom (seabed) and the base of the Plio-Quaternary succession, taking as reference the available well data from ViDEPI database (https://www.videpi.com/videpi/videpi.asp) and information from literature (Polonia *et alii*, 2011; Butler, 2009). The base of the Plio-Quaternary is characterized by a reflector that is quite continuous and easily traceable on all profiles. The thickness of the Plio-Quaternary is very high near the Calabrian coast, thinning offshore.

In the northern and central Adriatic Sea, the thickness of the Plio-Quaternary succession is based on the Geological map of Italian seas at 1:250,000 scale (Servizio Geologico d'Italia, 2001, 2011a,b,c,d; Trincardi *et alii*, 2001, 2011a,b,c,d) and the grid obtained from EMODnet Bathymetry, taking into account the tectonic features of the area.

In the southern Adriatic Sea (offshore Apulia), the Plio-Quaternary base was interpreted from ministerial seismic profiles (https://www.videpi.com/

videpi/videpi.asp), considering also the isochrons of the Plio-Quaternary base of the Gargano offshore (MORELLI, 2002). The seabed was obtained using the twtt values from the seismic profiles for the NE zone and the EMODnet bathymetry converted into twtt (using a water velocity of 1,530 m/s) for the SW zone, where the seabed is too shallow to be imaged by the seismic profiles.

The Ligurian Sea Plio-Quaternary thickness was derived from the Structural Model of Italy and from literature data (FANUCCI *et alii*, 1984). The thickness was interpolated from seismic reflection data of the National Institute of Oceanography and Experimental Geophysics - OGS and Ministerial lines for the Tuscan sector.

In the Sicilian Channel area, the base of the Plio-Quaternary succession was derived from literature data: the Structural Model of Italy (Sheet n. 6, BIGI *et alii*, 1991a) and a geophysical study performed by FINETTI (1984). These studies were based on ministerial seismic profiles and seismic data acquired through the OGS "Mediterranean Sea" project.

In the Western Sardinia sector the Plio-Quaternary base was mapped through the interpretation of ministerial and OGS (Mediterranean Sea and West Sardinia projects) seismic profiles. Subsequently, the Plio-Quaternary thickness was obtained by subtracting the EMODnet bathymetry assuming a water velocity of 1,500 m/s.

Maximum thicknesses are evident in the map, mainly related to the foredeep of the different compressive systems: the Ravenna Basin to the Northern Apennines and the Pescara Basin to the Central Apennines, separated by a relative minimum thickness relating to the offshore Apennine thrusts. An elongated minimum corresponds to the Tremiti Islands. The Gargano structure separates the Apennine foredeep from the Dinarides/Albanides (see Fig. 3) foredeep to the south, in the east Apulia offshore, continuing toward SE.

In the northern sector of the Ionian Sea, the Calabrian foredeep shows maximum thicknesses in the Sibari, Catanzaro and Spartivento basins. Furthermore, at the base of the Apulia and Malta Escarpment (NW-SE elongation in the latter) sediments accumulation has been fed by erosion and sliding.

To the south of Sicily, the Gela foredeep basin originated at the front of the Maghrebian Chain, while in the central Sicilian Channel, several pull-apart basins developed due to the presence of extensional oblique faults, active since Late Miocene times.

Several thick basins, as the Eastern Sardinia Basins (EBS) and the Corsica Basin are related to the middle Neogene - Lower Pliocene extensional phase related to the opening of the Back-Arc Tyrrhenian Basin. The three main deep sub-basins Vavilov, Magnaghi and Marsili received sediments from the close surrounding onshore areas, which partially cover the numerous volcanoes and seamounts that are widespread in the basin. North of Sicily, the tectonics connected to transtension produced the relatively thick Cefalù and Capo d'Orlando basins, while to the west of Calabria a very thick Plio-Quaternary deposit is present in the Paola Basin. Along the Campania-Latium coast, maximum thicknesses are present within grabens sometimes covered by thick clinoform successions.

The Western Sardinian margin is characterized by a considerable variability of the Plio-Quaternary thickness, due to the presence of volcanoes, seamounts and canyons on the continental shelf and slope. High Plio-Quaternary thicknesses are present in the bathyal plain of the West Mediterranean Sea, related to the Oligo-Miocene opening of the oceanic basin. Very small structures were produced by the Messinian salt tectonics.

A relative thickening of the Plio-Quaternary succession is present to the south of Sardinia, where both the collision between Sardinia and Africa continental plates and the opening of the Tyrrhenian Sea contributed to the formation of grabens with maximum local depositions.

The inset map also reports the shelfbreak and the foot of the continental slope that outline the physiography of the basins and help with understanding the distribution of the Plio-Quaternary succession depocenters.

Depth of Moho and Heat flow

The different geodynamic settings of the basins surrounding Italy have influenced their formation and evolution. The varying nature of Italian seafloors is reflected in the maps of the Mohorovičić discontinuity and Heat flow.

The map of the Moho (at 1:5,000,000 scale) shows the depth of the Mohorovičić discontinuity (i.e. the boundary between the lower crust and the upper mantle), represented by coloured areas elaborated starting from contour lines at 1 km intervals. All the main tectonic processes and regional geological structures are mirrored by the Moho depth which provides information relevant to study the distribution and interaction of the different types of crust. The map of the Moho is based mainly on the map by FINETTI (2005), which was produced from the interpretation of the reflection seismic profiles (~1,250 km on land and ~8,700 km at sea) database for crustal investigations of the CROP Project (Deep Seismic Exploration CROsta Profonda, http://www.crop.cnr.it/), a multidisciplinary research to study the Italian lithosphere, as a joint cooperation between the Italian National Research Council (CNR), the Ente Nazionale Idrocarburi (Eni) and the Ente Nazionale dell'Energia Elettrica (ENEL). Additional sources have been used to integrate previous maps and obtain a more updated and comprehensive product. For the Tyrrhenian Sea, regional maps of Cassinis *et alii* (2003) and Finetti (2005) were first digitized; then, new geophysical data (i.e. refraction seismic data acquired during the oceanographic cruise MEDOC in 2010; Moeller *et alii*, 2013; 2014; Prada *et alii*, 2014; 2016a,b) were merged with these two maps. The map of the Moho in the Ionian Sea is entirely from Finetti (2005). In the Adriatic Sea, the map by Finetti (2005) was modified and integrated in the central-eastern coastal area using data from Stipčević *et alii* (2011). In the Sicilian Channel, data from Finetti (2005) and Morelli (2007) were used. In the West Sardinian margin, the map of Finetti (2005) was integrated with data from Afilhado *et alii* (2015).

The heat flow is strictly related to the thickness of the crust and to the regional geological evolution. Regional heat flow data were obtained from the GeoThopica website (https://geothopica.igg.cnr.it/index.php/en/), the Italian geothermal data infrastructure created by the Institute of Geosciences and Georesources (IGG) of the National Research Council (CNR), and were implemented by heat flow data from Della Vedova *et alii* (2001).

The highest heat flow in the Tyrrhenian Sea results from the opening of the back-arc basin, which leads to continental crust thinning and the formation of new oceanic crust. In contrast, lower heat flow values are observed in the thickened Apennine Chain and in the corresponding Po Plain/Adriatic foreland. In the Sicilian Channel the heat flow distribution mirrors the main crustal structures. The major values, up to 100 mW/m^2 (Zolotarev & Sochelnikov, 1980), have been recorded in correspondence of the NW-SE trending tectonic rift of Pantelleria (see Sicilian Channel section), as well as close to the "Sciacca thermal field" (65 mW/m^2; Cataldi *et alii*, 1995), an offshore-onshore sector probably affected by a crustal scale fault system (Calò & Parisi, 2014; Civile *et alii*, 2018) and characterized by current, extensive geothermal activity (Caracausi *et alii*, 2005).

Geological synthesis of the seas surrounding Italy

The map provides a synthesis obtained from the data available focusing mainly on the national marine jurisdiction of Italy. Hence the coverage does not always include areas beyond Italy's legal national boundaries (see for example the sediment thickness inset map). Considering the diverse geological settings of the seas surrounding Italy, the different geographic areas have been elaborated separately and are described in the following sections. Each section provides a review of the geologic history as it relates to the new data synthesis depicted in the map and includes a brief summary of physiography and morphology, lithostratigraphy of the main units, principal tectonic elements, geodynamic evolution and seismotectonics.

Adriatic Sea

The Adriatic Sea is shared among seven countries (Italy on the north and western side, and Slovenia, Croatia, Bosnia and Herzegovina, Montenegro, Albania on the eastern side) and this map primarily focuses on the Italian portion of the Adriatic Sea, providing only synthetic information for its eastern side.

The Adriatic Sea is a semi-enclosed epicontinental basin extending approximately NNE-SSW with a main length of about 850 km and a maximum width of about 200 km, covering an area of 138,516 km^2 with more than 50% shallower than 100 m (Vrdoljak *et alii*, 2021).

The northern Adriatic Sea forms the largest continental shelf of the Mediterranean, which is predominantly shallower than 100 m and gradually deepens to the Mid Adriatic Deep (or Jabuka Trough, see Fig. 3) with a maximum depth of 283 m, and to the southern Adriatic, where the continental shelf deepens to the South Adriatic Basin with a maximum depth of 1,244 m (Vrdoljak *et alii*, 2021).

The Adriatic Sea lies on the Adria microplate, which moves in a NNE direction with a counter-clockwise rotation with respect to the European plate. The Adria microplate is surrounded by orogens, being subducted under Europe to the west (Apennines) and to the east (Dinarides, Albanides, Fig. 3, and Hellenides, to the southeast of the figure), and indenting to the north (Alps). The current independent movement of Adria, with respect to Africa and Europe is claimed to have been confirmed by GPS measurements (*e.g.* Oldow *et alii*, 2002; Battaglia *et alii*, 2004), although it is still controversial whether the Adria microplate moved in conjunction with the African plate as a rigid promontory or if and when it moved independently (*e.g.* Mantovani *et alii*, 2006, considered that from the Permian to the Late Miocene Adria moved together with Africa and since Late Pliocene independently with a counter-clockwise rotation, while Handy *et alii*, 2010, considered intermittent, independent, movements since the Adria-Europe convergence in Late Cretaceous).

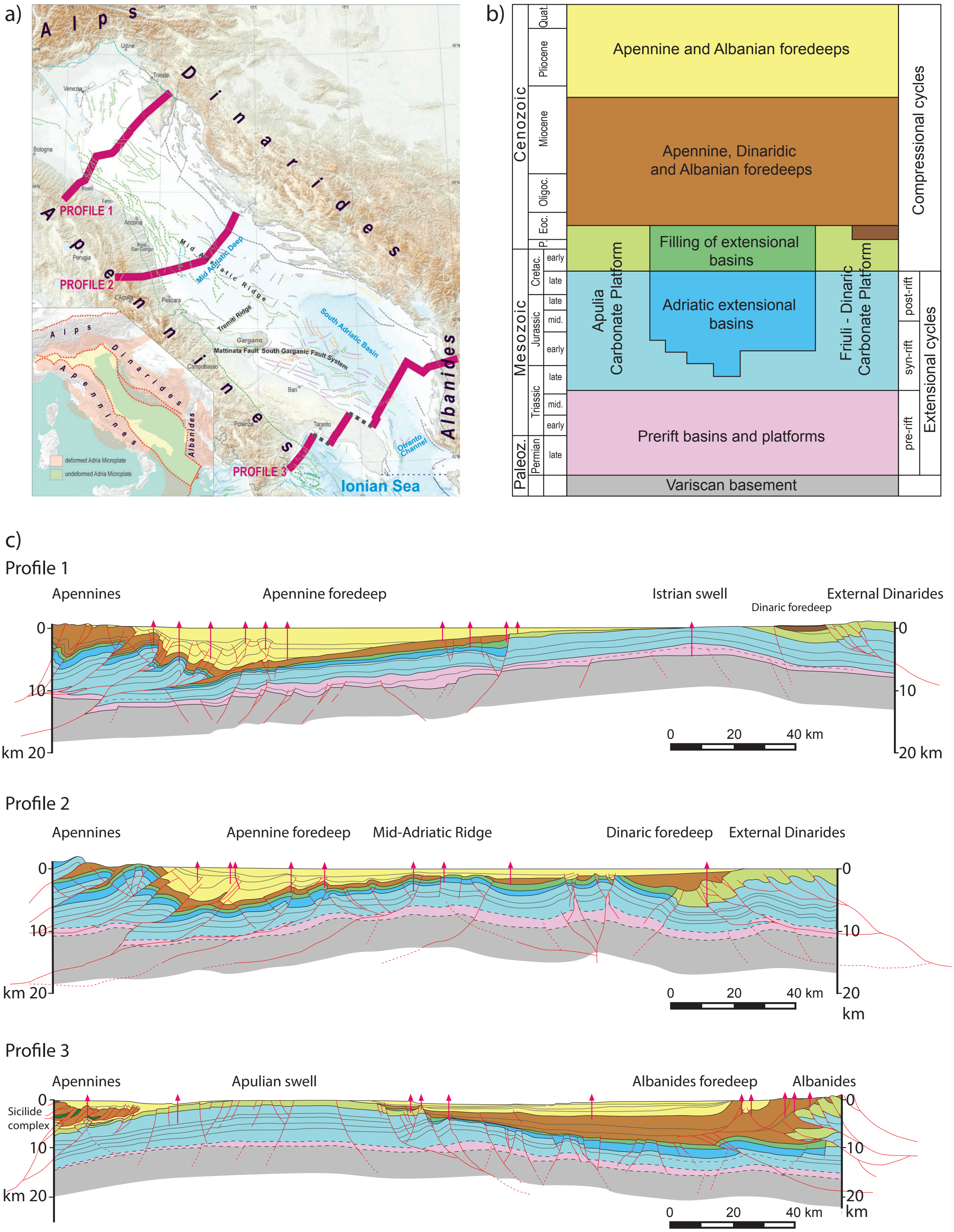

Fig. 3 - a) Tectonic map of the Adriatic Sea with location of the geological profiles and the inset with the Adria microplate (modified after HANDY *et alii*, 2010; LE BRETON *et alii*, 2017); b) the Meso-Cenozoic tectono-sedimentary cycles of the Adriatic area (modified after FANTONI & FRANCIOSI, 2010); c) the geological profiles 1, 2 and 3 with location of exploration wells with red triangles (modified after FANTONI & FRANCIOSI, 2010).

During the Triassic, the present-day Adriatic region belonged to the Tethyan continental margin, where the extensive Dolomia Principale and Burano evaporites were deposited. The Late Triassic - Late Cretaceous extensional tectonics led to the fragmentation of the Triassic carbonate platform into a horst and graben system and to the progressive subsidence of the margin. The rifting led to a NW-SE trending structural high in the eastern part, on which several kilometers of carbonate sediments were deposited and formed the Friuli-Dinaric Carbonate Platform (Vlahović *et alii*, 2005) and to a NE-SW elongated structural high in the south-western part, on which the Apulia Carbonate Platform was deposited (Mattavelli *et alii*, 1991; Del Ben *et alii*, 2010, 2015).

During the Cenozoic the northward movement of Adria microplate and the resulting collision with the European plate were the main factors controlling the evolution of the circum-Adriatic region that caused the following events (see also Fig. 3):

- the east-directed Adria slab with the building of the NE-SW Dinarides and N-S Albanides (Piromallo & Morelli, 2003), that caused the drowning of the Friuli-Dinaric Carbonate Platform and its involvement in the thrust belt deformation, the development of the foreland filled by the siliciclastic deposits ranging in age from Early Cretaceous to Early Miocene (Mattavelli *et alii*, 1991);
- the south-dipping slab of the European plate below the Adria microplate (Lippitsch *et alii*, 2003) since the Oligocene and the formation of the Alps; in the eastern Alps the main uplift phase occurred in the Miocene with the filling of the foreland with the late Oligocene/Miocene Molassa and the Plio-Quaternary clastic wedge, which affected also the extreme northern part of the present-day Adriatic Sea (Fantoni & Franciosi, 2010);
- the subduction of the Adria microplate leading to the formation of the Apennines since the Oligocene and its east- directed slab rollback (Doglioni *et alii*, 1999; Wortel & Spakman, 2000) related to the rotation of the Sardinian-Corsican Block during the late Eocene-Oligocene and the opening of the Tyrrhenian Sea during the Miocene; the Apennines thrust belt involved the Mesozoic carbonates and provided the filling of foredeep by several kilometers thick terrigenous sediment.

During the Messinian Salinity Crisis of the Mediterranean Sea, a complex interplay between the sea level drop, estimated in 800-900 m in the northern Adriatic (Amadori *et alii*, 2018) and compressional tectonics produced the subaerial exposure of the northern Adriatic favouring the erosional processes with a drainage system carving the pre-Messinian lithologies (Ghielmi *et alii*, 2013; Fantoni *et alii*, 2002).

The complexity of the tectonic history of the Adriatic region leads to the following fault systems, from north to south (see Fig. 3):

- Mesozoic extensional faults and Cenozoic compressional faults with approximate N-S and NW-SE orientations, that occur in the northern Adriatic and were reactivated as normal/reverse oblique-slip faults during the Plio-Quaternary (Busetti *et alii*, 2010, 2013; Brancolini *et alii*, 2019; Zecchin *et alii*, 2022);
- NW-SE thrusts with NE vergence of the Apennines which occur in the northern and central Adriatic (Ambrosetti *et alii*, 1987; Bigi *et alii*,1990a, 1990b, 1992b; Trincardi *et alii*, 2001, 2011a, 2011c);
- NW-SE thrusts with SW vergence of the Dinarides and NS with E vergence thrust of the Albanides which occur along the eastern side of the Adriatic Sea (*e.g.* Korbar, 2009 and ref. therein);
- the Mid-Adriatic Ridge, characterized by NW-SE structural highs from the Ancona Promontory toward the South Adriatic Basin (Grandić & Markulin, 2000; Scrocca *et alii*, 2007) associated to thrust-related folding (Argnani & Frugoni, 1997), active diapirism (Geletti *et alii*, 2008; Del Ben *et alii*, 2010) or to a combination of both processes (Bally *et alii*,1986);
- the right-lateral strike-slip SW-NE trending Tremiti Ridge (Finetti *et alii*, 1987; Argnani *et alii*, 1993; Scisciani & Calamita, 2009);
- the Jurassic extensional faults associated with a horst and graben system, mainly with NW-SE orientation, occurring in the southern Adriatic Sea with Cenozoic compressional reactivation (Morelli, 2002), and intersected by the E-W South Garganic Fault System (SGFS) also known as Gondola Line, as the offshore extension of the Mattinata Fault onland;
- the NNW-SSE thrusts with WSW vergence of the Albanides in the southern Adriatic (Scrocca *et alii*, 2022).

The distribution of earthquake epicenters show small-to-moderate seismic activity distributed both onshore and offshore along the Adriatic coastal zone, where focal mechanisms primarily delineate compression and transpression tectonic structures (PONDRELLI AND SALIMBENI, 2006; SCOGNAMIGLIO *et alii*, 2006). While most events are isolated, several seismic sequences occurred in the offshore. The oldest sequence in our dataset took place close to the coast of Porto San Giorgio (south of Ancona), lasting from July to December 1987, comprising more than 130 earthquakes with a mainshock of magnitude 5 (BATTIMELLI *et alii*, 2019).

The most recent sequence started on November 9, 2022 and affected the Northern Adriatic offshore, about 29 km from the coast of Fano (north of Ancona). Two main shocks (a ML 5.7 earthquake followed by a ML 5.2 earthquake) triggered a seismic sequence with about 400 aftershocks within the first week alone, followed by several hundreds of events until the end of December (LATORRE *et alii*, 2023).

Approximately one-third of offshore historical seismicity (59 events out of a total of 196) occurred in the Adriatic Sea, between Rimini and Ancona offshore, with 22 earthquakes exceeding magnitude 5 and 4 events with Mw 5.8 (ROVIDA *et alii*, 2022).

Seismic sequences of low-moderate magnitude (ML max 5.4) occurred in central Adriatic between Gargano promontory and Croatian coastline (VANNUCCI *et alii*, 2004). A diffuse seismicity characterizes the promontory offshore, where important historical earthquakes occurred (1484, Mw 5.8; ROVIDA *et alii*, 2022).

The southern Adriatic Sea appears almost aseismic in recent times, but the Otranto channel was suggested as the possible source area of significant earthquakes (*e.g.*1743, Mw 6.7; ROVIDA *et alii*, 2022), linked to deformation of Apulian foreland induced by the opposite verging Albanides and Apennine thrust belts (ARGNANI *et alii*, 2001).

Ionian Sea

The Ionian Sea hosts a wide basin more than 4,000 m deep, filled by deformed sediments piled up to form the Calabrian accretionary prism (ROSSI & SARTORI, 1981). The prism shows a well-rounded shape subdivided in two lobes (see Fig. 4), one in the northeast and the other in the southwest, whose separation corresponds with a NW-SE oriented, high-deformation crustal zone. Series of small basins, elongated according with the frontal thrust trend, are present inside the two lobes. Immediately offshore Crotone (see Fig. 4), a minor lobe mimics the morphology of the coast. From the Messina Strait to the Taranto Gulf several large canyons cut the slope following irregular paths. The Calabrian prism is laterally confined to the southwest by the Malta escarpment and to the northeast by the Apulia platform and the Mediterranean Ridge (see Fig. 4).

The Calabrian Arc is part of the eastward migrating Apennine system connecting the NW trending segment in the peninsula with the E-W oriented thrust belt in Sicily (PATACCA & SCANDONE, 2004). It is a NW-ward subduction system resulting from the convergence of the African plate against Eurasia, presently occurring at a very slow rate (ca. 3.9 mm/yr; SERPELLONI *et alii*, 2007), as reported by recent GPS studies (CALAIS *et alii*, 2003; REILINGER *et alii*, 2006; SERPELLONI *et alii*, 2007). Despite these very slow convergence rates, subduction may still be active in the Arc as also confirmed by the instrumental seismicity recorded within the prism and along several faults affecting the Calabrian and Sicilian margins (PIATANESI & TINTI, 1998). Inside the Arc, the thick sedimentary succession, accreted from Late Miocene to Quaternary, is folded, faulted and shows a SE-vergence, while within the external part the prism becomes thin and the Plio-Quaternary unit moves towards SE detaching above the Messinian salts (POLONIA *et alii*, 2011). Indeed, the emplacement of the accretionary wedge is related to off scraping and underplating of the thick sedimentary succession resting on the lower African plate whilst shortening takes place along the outer deformational front and in the inner portions of the accretionary wedge (ROSSI & SARTORI, 1981; FINETTI, 1982).

The submerged portion of the Calabrian Arc (Fig. 4) consists of a north-westward thickening wedge of deformed sediments (FINETTI, 1982; CERNOBORI *et alii*, 1996) composed of Plio-Quaternary marine sediments overlaying Messinian deposits, enriched in evaporites, that in turn overlaps the Triassic basement. In the inner part, close to the continent, Tortonian units have been mapped below Messinian units (POLONIA *et alii*, 2011). Evaporitic diapirisms and mud volcanoes are widespread in the inner arc (POLONIA *et alii*, 2011; CERAMICOLA *et alii* 2014) which may indicate dewatering of the prism due to compression. Close to the continent several drill-well logs (Videpi database; https://www.videpi.com/videpi/) define the entire sedimentary succession whereas the lithology of units offshore is not well constrained due to lack of drill-wells.

Tectonic features mapped in the Ionian domain were obtained from several papers (POLONIA *et alii*, 2011, 2017; GUTSCHER *et alii*, 2017; DEL BEN *et alii* 2008; MAESANO *et alii*, 2020; ZECCHIN *et alii*, 2020; CIVILE *et alii*, 2022, ARGNANI & Bonazzi, 2005) combined with the old Structural Model of Italy and other published maps. The Ionian domain is shaped by numerous thrust faults as seen on the map. Indeed, the accretionary prism bounded by the large half-circle frontal thrust, a long thrust fault, that extends from the Malta Escarpment to the Apulian microplate is formed of highly deformed sediments

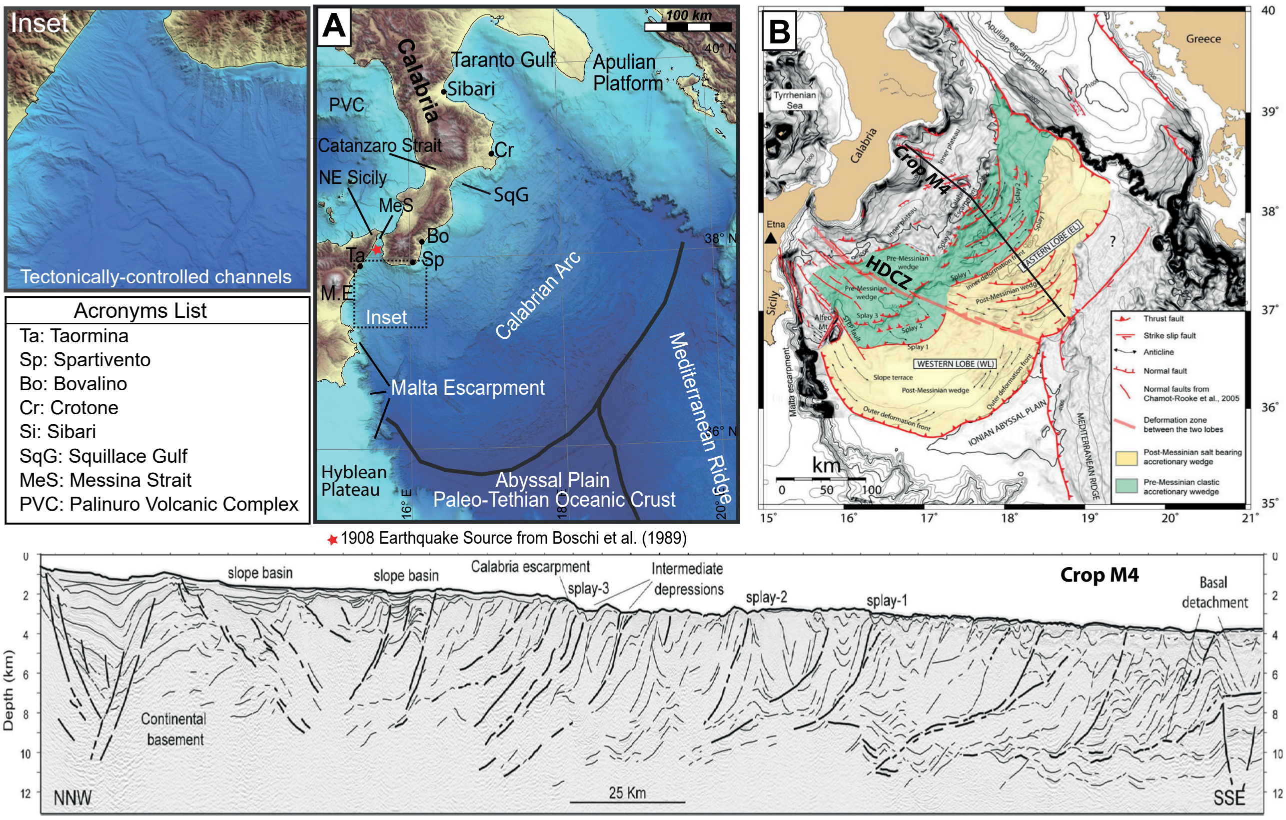

Fig. 4 - Ionian Sea. Top-left: inset map showing canyons in the area between Calabria and Sicily; A: morphobathymetric map of the Ionian sea including the main localities and crustal domains; B: structural map of the Calabrian Arc region derived from integrated interpretation of available seismic data and multibeam bathymetry (modified from Polonia *et alii*, 2011); bottom: multi-channel seismic profile Crop M4 that crosses the entire Calabrian Arc, with a structural interpretation (modified from Polonia *et alii,* 2011).

(Polonia *et alii*, 2011). All thrust faults mapped mimic the frontal thrust trend, especially in the outer part of the prism (yellow part in Fig. 4B). The main lobe of the prism is divided by a long, NW-trending, high-deformation crustal zones (HDCZ) composed of several well-aligned segments connecting the frontal thrust with eastern Sicily, where it intercepts a large canyon belonging to a system of tectonically-controlled channels (Fig. 4, inset). HDCZ ends against NE-SW oriented normal faults proposed as the responsible for the 1908 earthquake/tsunami event (Valensise & Pantosti, 2001; Barreca *et alii*, 2021). Several NW-trending right lateral strike-slip faults are present from the HCDZ toward the Malta Escarpment (see Fig. 4); some of them with a normal component (right-lateral normal oblique-slip faults) and normal faults bounding highs or NW-SE trending elongated basins. The inner part of the prism is affected by a series of normal faults and thrust faults with a dominating ENE-WSW direction. Towards Calabria, the faults become more complicated, comprised of a series of systems connected to transtension and transpression, orthogonally oriented to the shoreline, some of Quaternary age (the Bovalino and Spartivento systems (Del Ben *et alii*, 2008), and some others of Plio-Quaternary age (such as the Catanzaro strike-slip system; Del Ben *et alii*, 2008). Within the Crotone Basin a NW-trending right-lateral, normal, oblique-slip fault system deforms both the outcropping onshore rocks and the offshore units, also interrupting the reverse and orthogonally oriented normal faults. Towards the Gulf of Taranto, several NW-trending lateral oblique faults, some with reverse component, deform offshore sediments. Within the Gulf, a series of antiform axial traces, bounded by normal faults and reverse faults are oriented in NW-SE direction, parallel to the frontal thrust and to the Calabrian block trend. Some of these faults may be connected with the onshore fault systems. To the southwest and to the northeast of the prism, the deformation is dominated by normal faults. The Malta Escarpment is affected by several normal faults, oriented NNW-SSE and WSW-ENE, while the Apulian block is affected by a system of NW-SE oriented normal faults, some of which form an anastomosed graben system.

The tectonic evolution of the Calabrian Accretionary Prism (Fig. 4) is coeval with the opening of the Tyrrhenian back-arc basin and with the Apennines chain (Malinverno & Ryan, 1986). During the middle-late Neogene, the subduction of the Ionian oceanic crust (ancient Tethys) led to the formation of the inner accretionary wedge whose thrust faults were probably verging eastward (Malinverno & Ryan, 1986). During the Pliocene and Quaternary, the wedge continued to migrate and grow up but changed direction to SE-ward (Sartori, 2003). This change is likely due to the interaction of the Apennines with the Apulian microplate, to the north-east, and the Hyblean Plateau to the south-west (Sartori, 2003). Changes from subduction to collision at the end of the Pliocene, well-recorded within the Tyrrhenian Basin, led to the reorganization of plates as suggested by Sartori (2003). Different sinking and narrowing of slab led to the formation of high-deformation crustal zones (i.e. STEP faults or tear faults; Govers & Wortel, 2005) within the subduction system, one of which is identified along eastern Sicily where Mt. Etna is present and related to it. This fault system produces a series of major sub-parallel dextral oblique-slip faults, sometimes with normal component, offshore Mt. Etna and south of the Strait of Messina (Fig. 4, inset and main map) consistent with the relative motions between Calabria and the Peloritan domain (NE Sicily). Variations in structural style and seafloor morphologies within the prism are related to changes in sediment rheology and different tectonic processes. The presence of Messinian evaporites within the sedimentary succession subjected to compression caused an abrupt change in the wedge formation processes and morphology, i.e. the outer part of the prism grows very quickly and gives rise to a very thin and wide accretionary wedge; thus Messinian evaporites represent the basal detachment level (Polonia *et alii*, 2017).

The descriptions of some fault systems in the published literature were found to be contradictory. It was not possible to solve all critical issues, even after detailed discussion with the authors of the papers. A major concern is the paucity of data on the age of the accretionary prism units, also because of lack of deep drill wells. A Plio-Quaternary age was assigned to all faults with uncertain datation deforming the accretionary prism, but further research is needed.

Seismic activity in the Ionian Basin is rather diffused, with earthquake concentration in four main areas along the eastern Sicily coastline (see map): 1) the Hyblean Plateau in correspondence of the footwall of the Malta Escarpment; 2) along the underwater flank of Mount Etna; 3) offshore Taormina (see Fig. 4); and 4) in the western-south-eastern Calabria offshore. Despite the presence of a few events showing thrust and thrust-strike kinematics, mainly concentrated in the Taormina area, focal mechanisms reveal the existence of two active tectonic regimes, an extensional regime and a strike-slip regime coexisting in the Ionian Sea (Sgroi *et alii*, 2021b).

The eastern Sicily and Calabria margins have been struck repeatedly by high-magnitude earthquakes throughout historical times, including the largest events ever recorded in Italy (*e.g.*, 1169, Mw 6.6; 1693, Mw 7.4; 1908, Mw 7.2; Boschi *et alii*, 1997). However, the location and geometry of tectonic sources are still a matter of debate (*e.g.* Sgroi *et alii*, 2021b,c).

Ligurian Sea

The Ligurian margin can be subdivided into two main areas characterized by different geomorphic characteristics. To the west of the Genoa Valley (see Fig. 5), the Alpine margin displays very steep submarine slopes, with highly articulate morphologies (*e.g.* canyon systems and large landslide scarps) with a narrow shelf area incised by submarine canyons. The geomorphology of deeper basin areas is characterized by flat to gently sloping seabed, resulting from the interplay between multiple deep-sea fans (Morelli *et alii*, 2024 and references therein). These latter are locally articulated with seafloor channels and ridges, sometimes intersected by narrow and elongated seafloor highs produced by the Messinian salt diapirs (Soulet *et alii*, 2013; Fierro *et alii*, 2010).

The Apennine margin, extends to the east of the Genoa Valley, is bordered by Ligurian Seamounts (*i.e.*, a system of volcanic highs and Corsican block substratum ridges, NNW-SSE elongated) and shows a less articulated morpho-bathymetry. Here, the shelf is broader (up to ~8.5 km) where the slope is less marked by erosional processes (Fig. 5). The Ligurian margin delimitates the northern propagation of the Liguro-Provençal and Thyrrenian back-arc basins, developed since the upper Oligocene by the southeastern-ward roll-back of the Apennines-Maghrebides subduction zone (Larroque *et alii*, 2011). Due to the intricate coexistence of several crustal units and the complex geodynamic local framework (*e.g.*, Laubscher *et alii*, 1992;), the area is also known as the “Ligurian Knot” (Laubscher *et alii*, 1992).

The different geomorphologies observed along the two sectors of the Ligurian margin, the Alpine margin (to the west) and the Apennine margin (to the east), reflect their distinctive tectonic evolution. Along the Alpine margin, the structural setting of the westernmost sector between Ventimiglia and Taggia is dominated by two systems of normal faults, WSW-ENE and NNW-SSE oriented (Fig. 5). Here, the base of the slope coincides with a WSW-ENE

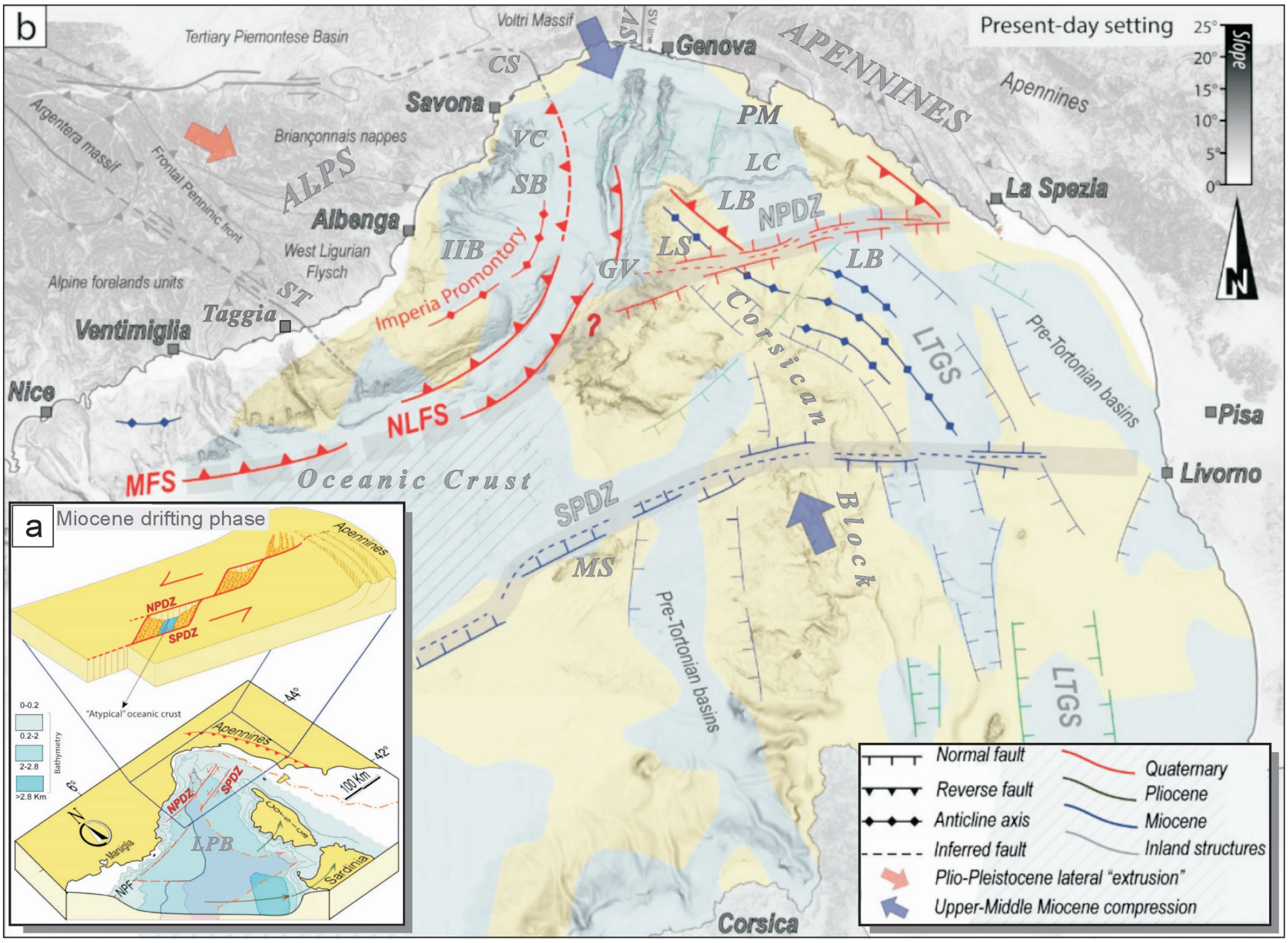

Fig. 5 - a) Simplified 3D kinematic model of the Miocene drifting phase of the "atypical" oceanic crust of the Liguro-Provençal Basin showing the role of the inherited Northern Principal Deformation Zone (NPDZ) and Southern Principal Deformation Zone (SPDZ) accommodating the Ligurian Basin drifting (Rollet *et alii*, 2002; Fanucci & Morelli, 2001; Morelli *et alii*, 2022). b) Schematic tectonic map of the late-Middle Miocene and the Plio-Pleistocene compressive deformation structures at the Alpine and Apennine margins and the inferred late-Middle Miocene compressive event (blue arrows) and the Plio-Pleistocene lateral "extrusion" of the southwestern Alps. The map also shows the distribution and the structural setting of the Pre-Tortonian basin areas (after Fanucci & Nicolich, 1984, modified) which were partially reactivated during the following extensional and compressive events related to tectonic inversion. CS: Celle-Sanda Fault Systems; GV: Genoa Valley; LC; Levante Canyon; LB: La Spezia Graben; LPB: Liguro-Provençal Basin; LS: Ligurian Seamounts; LTGS: Ligurian Tuscan Graben System; MFS: Marcel Fault System; MS: Median Seamount; NLFS: Northern Ligurian Fault System; NPDZ: Northern Principal Deformation Zone; PM: Portofino Promontory; SB: Savona Basin; SV: Sestri-Voltaggio Fault System; SPDZ: Southern Principal Deformation Zone; ST: Saorge-Taggia Fault System; VC: Vado Canyon.

oriented thrust fault system (Larroque *et alii*, 2011). The Plio-Quaternary reactivation under the compressional regime of this Fault System is consistent with the recent (*e.g.*, post-Pliocene) uplift along the Ventimiglia coast (*e.g.*, Foeken *et alii*, 2003; Breda *et alii*, 2009; Fig. 5). Within the middle slope area of this sector, remnants of Miocene sediment folding testify to a previous Middle/Late Miocene compressive event followed by extensional reactivation during the Pliocene. In the sector between Taggia and Albenga, the most prominent geomorphic features are the Imperia Promontory (a 40 km long, WSW-ENE trending anticline) and the subparallel Imperia intra-slope basin. Here, the WSW-ENE trending rectilinear fault escarpments and the adjacent narrow basin area represent the most evident surficial effects of the Plio-Pleistocene compressive reactivation of the WSW-ENE oriented North Ligurian Fault System (Larroque *et alii*, 2011 and 2012). This reactivation of older extensional structures (*e.g.* Eva *et alii*, 1997) propagated to the SE within the intra-slope basin where the deformation led to co-axial back-thrusting (Fig. 5). The occurrence of earthquakes and their focal mechanism analyses showing compression and transpression (*e.g.*, Larroque *et alii*, 2011) proves the present-day activity of these faults systems.

A recent structural reconstruction (Morelli *et alii*, 2022) shows that the North Ligurian Fault System propagates further to the northeast, toward the

Savona Basin. Here, compressive kinematics result in WNW-ESE trending gentle folds (Fig. 5) which progressively rotate to a N-S direction by the Vado Canyon. These structures coincide with a dense cluster of seismic epicenters, N-S aligned, characterized by compression/transpression testified by the focal mechanisms analyses (Fig. 5; BAROUX *et alii* 2001; MELE *et alii*, 2007).

In the Genoa Valley, the occurrence of NNW-SSE trending gentle folds and east-verging thrusts testify that the Plio-Pleistocene compressive deformation also affected the easternmost sector of the Alpine margin with decreasing intensity eastwards and towards the Apennine margin (MORELLI *et alii*, 2022). Such reconstruction is also supported by the Plio-Quaternary compressive reactivations within the northern sector of the La Spezia Graben bordered by a WSW-ENE-oriented fault system. In fact, recent (neo-)tectonic inversion reactivates the NW-SE Miocene normal fault systems located along the northeastern flank of the Ligurian seamounts and the shelf area near the head of the Levante Canyon (Fig. 5). Here, the WSW-ENE-oriented fault system has been interpreted by MORELLI *et alii* (2022) as a *Northern Principal Deformation Zone* (*NPDZ*) inherited by the Miocene basin opening phases and characterized by a complex polyphasic evolution. During the Plio-Quaternary reactivations, the *Northern Principal Deformation Zone* likely worked as a regional-scale transfer fault system able to drive the regional compressive stress (MORELLI *et alii*, 2022).

South of the Genoa Valley the structural setting of the Apennine margin is dominated by a set of NNW-SSE and NS normal faults delimiting the NNW-SSE trending grabens formed during the Lower-Middle Miocene extensional phase (the *Ligurian Tuscan Graben System, LTGS*; Fig. 5). In some cases, the western border of the *Ligurian Tuscan Graben System* shows remnants of NW-SE trending antiform structures involving Miocene deposits. These represent the effects of a Miocene compressive event preceding the main Late Miocene/Early Pliocene extensional tectonic reactivation (MORELLI *et alii*, 2022).

Further south, another regional-scale, WSW-ENE-oriented fault system known as the *Southern Principal Deformation Zone* (*SPDZ,* Fig. 5) cuts transversally the *Ligurian Tuscan Graben System.* The *Southern Principal Deformation Zone* extends toward the Liguro-Provençal Basin, locally marking the WSW-ENE boundary between the oceanic crust and the thinned continental margin of the Corsican block (*e.g.*, west of the Median Seamount; ROLLET *et alii*, 2002).

The sedimentary succession of the Ligurian Basin consists of siliciclastic deposits from the Early Miocene to the present day, overlaying basin bedrock belonging to the South-Western Alps and the Northern Apennines (MORELLI *et alii*, 2022 and references therein). This bedrock is composed both of basement units (*e.g.*, the Hercynian crystalline basement and the Mesozoic Ligurian-Piedmontese oceanic crust) and their Meso-Cenozoic sedimentary covers belonging to the Ligurian-Piedmontese Basin (*e.g.*, the Tethyan oceanic and continental sedimentary successions, including the late-stage flyschoid units). These were folded and overthrust during the Alpine and/or Apennine orogeny and subsequently affected by Oligo-Miocene extensional tectonics (FANUCCI & MORELLI, 2001). This latter was responsible for the emplacement of the volcanic substratum cropping out along the Ligurian seamounts (*e.g.*, ROLLET *et alii*, 2002).

In the Ligurian Basin the Neogene-Quaternary sedimentary cover reaches a thickness of up to 3 km, composed of a siliciclastic pre-evaporitic basal sequence (Early and Middle Miocene in age) covered by a thick Messinian evaporite sequence (made of interlayered limestones, gypsum and salt levels) topped by Plio-Pleistocene hemipelagic deposits (SOULET *et alii*, 2016; FIERRO *et alii*, 2010).

Since the Early Oligocene, the roto-translation of the Sardinian-Corsican block and the emplacement of new oceanic crust in the Liguro-Provençal Basin have driven the rifting and subsequent drifting of the south Alpine collisional tectonic units (ROLLET *et alii*, 2002; LAUBSCHER *et alii*, 1992; FANUCCI & MORELLI, 2001). This resulted in the separation of the Ligurian Alps from the Corsican Alps and the structuring of the Ligurian margin (*e.g.*, FANUCCI *et alii*, 2002 and references therein). At the same time, active extensional tectonic along the westernmost sector of the Apennines fold and thrust units (*i.e.*, the proto-Thyrrenian basin; FANUCCI & NICOLICH, 1984) led to the opening of the narrow, NNW- SSE trending, *Ligurian Tuscan Graben System*. Later, since the Late Miocene - Late Pliocene, the same sector of the Apennines margin was affected by reactivation under extensional tectonics, responsible for the recent morpho-structural setting of the chain (i.e., the Thyrrenian stage; LORETO *et alii*, 2021a; SARTORI, 2003). During this polyphasic evolution, the WSW-ENE trending *NPDZ* and *SPDZ* fault zones had accommodated, chiefly as basin-scale transfer faults systems, the opening of the Liguro-Provençal Basin and the Miocene evolution of the *Ligurian Tuscan Graben System* (locally affected by tectonic inversion; *e.g.* FANUCCI & NICOLICH, 1984; ELTER & PERTUSATI, 1973; BOCCALETTI *et alii*, 1984; MORELLI *et alii*, 2022).

At regional scale, the *Northern Principal Deformation Zone* and *Southern Principal Deformation*

Zone show a somewhat north facing convex trend, subparallel to the Ligurian orocline (Fig. 5). Such geometry would be compatible with the N-S oriented compressional phase that affected the area during the late-Middle Miocene (including the onshore regions; *e.g.*, Crispini *et alii*, 2009) after the main early-Middle Miocene extensional drifting phase (*e.g.* 21-16 Ma) of the Liguro-Provençal Basin (Rehault *et alii*, 1984). In the Western Ligurian margin, basin floor subsidence in the Pliocene testifies to post-drifting tectonic reactivation, which also produced regional, compressive, fault reactivations along the Alpine Ligurian margin (*e.g.* Bethoux *et alii*, 1992; Larroque *et alii*, 2009, 2011) and post-Pliocene coastal uplift (Marini, 2001; Foeken *et alii*, 2003; Breda *et alii*, 2009).

Compressive tectonism in the alpine margin continues to the present day, manifested as widespread submarine mass movements, erosion phenomena and higher seismicity (*e.g.* Fanucci & Morelli, 2013; Corradi *et alii*, 2002; Migeon *et alii*, 2011; Fierro *et alii*, 2010). The instrumental and historical seismicity of the Ligurian Sea is principally concentrated in the western margin, but it is neither consistent nor continuous and localized at the foot of the continental margin. In detail, such low seismicity in the offshore Ligurian Sea seems to be coincident with a high heat-flow zone (Pasquale *et alii*, 1994). The instrumental record of seismicity is mostly confined to events of magnitude up to 4.7, with only a few historical earthquakes reaching larger magnitudes (*e.g.*, 1963, Mw 6.0; Augliera et al, 1994; Rovida *et alii*, 2022).

A dominant transpression/compression tectonic regime is suggested by seismic data analysis and interpretation (*e.g.* Bethoux *et alii*, 1992; Eva *et alii*, 1997; Larroque *et alii*, 2012; Morelli *et alii*, 2022; Nocquet & Calais, 2004; Wortel & Spakman, 2000; Eva & Solarino, 1998). The present-day distribution and intensity of compressive deformation is manifest by on-land fault systems that extend offshore. For example, the *Saorge-Taggia* and *Celle-Sanda* fault systems (Molli *et alii*, 2010) and their offshore prolongation represent the kinematic boundary accommodating the lateral "extrusion" of the southwestern Alps towards SE (*e.g.* Tapponnier, 1977; Vialon *et alii*, 1989; Giglia *et alii*, 1996; Viti *et alii*, 2021).

At regional scale, the extensional tectonics produced by the Early Miocene drifting and Late Miocene post-drifting phases of the Liguro-Provençal and North Tyrrhenian back-arc basins were primarily responsible for both margins' evolutions. Nevertheless, their morpho-structural setting was strongly conditioned by (at least two) regional-scale compressive events during the Middle-Late Miocene and the Plio-Pleistocene. The latter compressive event mainly affected the Alpine margin and continues to the present day, as shown by the widespread, low-magnitude seismicity of the area. In this context, the lateral "extrusion" of the southwestern Alps and Ligurian margin towards the SE, that began in the Plio-Pleistocene, is consistent either with the gravitational collapse of the Alpine orogen (*e.g.* Tapponnier, 1977; Vialon *et alii*, 1989) and with the activation of a wide, regional scale, compressional, stress field due to the collision of the African and European tectonic plates (*e.g.* Larroque *et alii*, 2009; Morelli *et alii*, 2022).

Tyrrhenian Sea

The Tyrrhenian Sea is a large, triangular basin, bounded to the west by the Sardinian-Corsican block, to the south by Sicily and to the east by the Italian peninsula (Fig. 6A). The morphology of the seabed is extremely irregular with a maximum depth of 3,634 m (Palmiotto & Loreto, 2019). The continental slope contains a number of volcanoes associated with the Aeolian Volcanic Arc, Ustica-Drepano ridge, Palinuro volcanic complex. The abyssal plain includes three large sub-basins, each surrounding a central isolated volcano from which takes its name: Magnaghi Basin (4,700 km^2), Vavilov Basin (8,700 km^2) and Marsili Basin (5,000 km^2). The large (13,300 km^2) Cornaglia Terrace (Fig. 6A) is located between the Magnaghi Basin and the Sardinia margin. Tectonically controlled structures include the Baronie and the Sirene seamounts.

The Tyrrhenian Basin is a young, back-arc basin that started to open during the Middle Miocene (Langhian(?)-Serravallian; Loreto *et alii*, 2021b), predating the largely accepted Tortonian age (Kastens *et alii*, 1988), in response to the extensional processes related to the African and Eurasian plate convergence and subduction/roll-back of the Ionian oceanic crust (Malinverno & Ryan, 1986). Continental crustal thinning and break-up was followed by exhumation of mantle rocks into the central parts of the Magnaghi (Messinian age) and Vavilov (Pliocene age) basins (Fig. 6B). Mantle exhumation was followed by several magmatic intrusions that led to the formation of the Gortani, D'Ancona and Tibullo ridges, and the Vavilov and Marsilli volcanoes (Fig. 6A). Tectonic reorganization in the Early Pleistocene (Sartori, 2003) led to a change in the opening direction from W-E to NW-SE and the opening of the Marsili Basin, accommodated by a transfer zone (Palmiotto *et alii*, 2022). The slab subduction is still active below the Calabrian Arc (see Fig. 4), as inferred by the distribution of the seismicity with depth below the Marsili Basin (see main map), and it controls the activity and evolution of the Aeolian

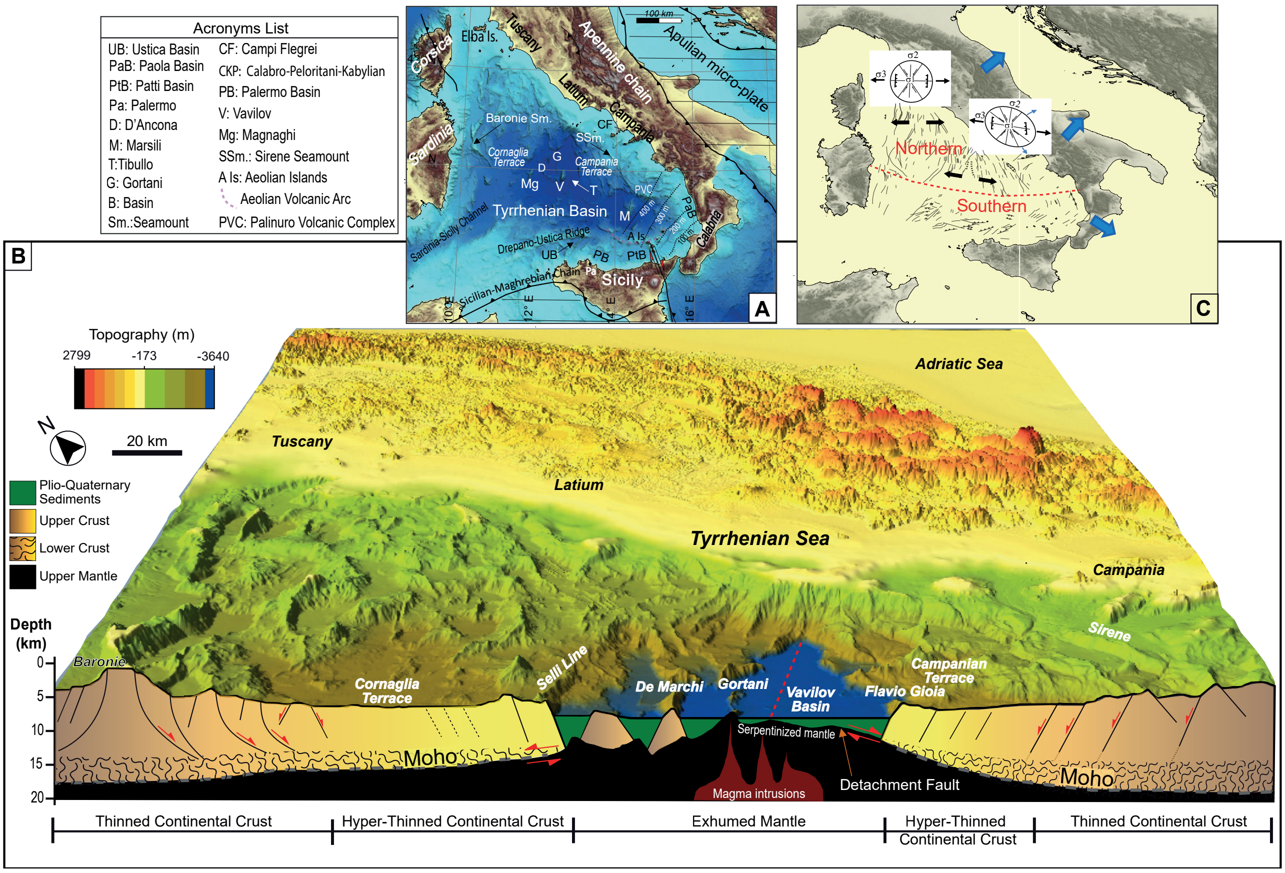

Fig. 6 - Tyrrhenian Sea. A) morpho-bathymetric map (produced gridding data downloaded from the EMODnet portal and released in 2018) and DEM (produced gridding data SRTM90; http://www.cgiar-csi.org/) of the Tyrrhenian Basin. The map shows the main morphological features and the depth of the slab (dotted lines, from CHIARABBA *et alii*, 2008). B) 3D-simple shear model for detachment fault built using seismic profiles MEDOC 8 (modified from LORETO *et alii*, 2021b). C) Sketch map of fault distribution in the Tyrrhenian Basin used also to estimate the ellipses of deformation.

Volcanic Arc and eruptions of the Marsili seamount. The Palinuro Complex and the M. Etna volcano (Fig. 4A) are related to the formation of high-deformation crustal zones (GOVERS & WORTEL, 2005; DE RITIS *et alii*, 2019) and upwelling of depleted mantle, resulting in OIB-type magma eruptions (TRUA *et alii*, 2004).

The main lithological units (see main map) occurring in the Tyrrhenian Basin are: 1) marine sediments of Pliocene and Quaternary age filling all basins, including those along the peri-Tyrrhenian margin, such as Paola Basin, Patti Basin, Palermo Basin, etc. (Fig. 6A); 2) marine sediments lying on top of exhumed mantle and oceanic crust in the central and abyssal Tyrrhenian Sea (KASTENS *et alii*, 1988; PRADA *et alii*, 2016a,b) and upon volcanoes; 3) seamounts comprised of small blocks of Sardinia, Variscan, basement composed of metamorphosed Paleozoic rocks (SARTORI & FINETTI, 2005); and 4) the Sicilian-Maghrebian Chain, to the south, composed of metamorphic and granitic Hercynian basement, deformed during the Alpine orogeny (SARTORI & FINETTI, 2005).

A series of normal, some reverse and strike-slip faults are distributed in the Tyrrhenian Basin (see main map). Along the eastern side of the Sardinia and Corsica margin, most normal and listric normal faults mapped are from N to NNE-SSW oriented, E- and W-dipping, bounding a series of ca. N-S elongated basins confined by seamounts. The age of these faults ranges from Middle Miocene to Plio-Quaternary (LORETO *et alii*, 2021b). East of Corsica some NW-SE oriented faults are mapped at the border of the Corsica Basin. Between Corsica and Tuscany, a complex system surrounding the Elba Island is composed of normal faults, ca. E-W and N-S oriented (of Miocene age), overprinting older ca. N-S oriented reverse faults (Eocene-Miocene age; BUTTINELLI *et alii*, 2024). In the Sicily-Sardinia Channel, Pliocene and Plio-Quaternary, NW- and SE-dipping, NE-SW normal and listric normal faults, bound the Channel basins along the continental margin. These faults also bound some antiform structures, from NE-SW to ENE-WSW oriented. Some Pliocene reverse faults, ENE-WSW oriented, overprint the normal faults affecting the Sicilian margin. North of Sicily, NW-SE, NE-SW and ENE-WSW normal and reverse faults bound a series of basins, as the Palermo Basin and Ustica Basin, and the Drepano-Ustica Ridge (see main map and Fig. 6A). Normal faults with orientation from NW-SE to NE-SW are present along the sides and offshore of volcanoes belonging to the Aeolian Volcanic Arc. The age of these faults ranges from Pliocene to Quaternary (LORETO *et alii*, 2021a,b and references therein). In the central Tyrrhenian Basin the normal faults are arranged in conjugate NE- and NW-trending systems bounding the Vavilov and Magnaghi basins, the Cornaglia Terrace and a series of minor, elongated basins to the north. Here some minor listric normal faults have also been mapped (LORETO *et alii*, 2021b). The age of these fault systems is from Miocene (in the northwestern part) to Quaternary (LORETO *et alii*, 2021b). Along the Latium and Campania margins, Miocene to Plio-Quaternary normal faults, with orientations spanning from NW to NE bound the basins, tectonic highs and volcanic structures. Along this stretch of slope a pair of conjugate reverse faults bounding the Sirene Seamount (Fig. 6) has been mapped. In the Marsili Basin (Fig. 6) a series of normal faults with orientation spanning from NW-SE to NE-SW and up to E-W bound the deeply thinned crust and affect the flanks of the Marsili and Palinuro volcanoes. Coastward, the age of faults ranges from Miocene, southeast of Marsili, to Quaternary and locally are arranged in graben settings (MILIA *et alii*, 2009; LORETO *et alii*, 2021b). Strike slip and normal or reverse oblique faults are mapped along the Palinuro Volcanic Complex (PVC in Fig. 6A), offshore Calabria and Sicily regions, along the thinned continental domain to northwest of Sicily. All the strike slip faults are Quaternary in age (COCCHI *et alii*, 2017).

Within the Tyrrhenian Basin four opening stages have been defined (LORETO *et alii*, 2021a): (1) the initial Langhian(?)/Serravallian phase, active in the central/southern Sardinia and western Calabria areas; (2) the Tortonian/Messinian phase, dominated by extension offshore of northern Sardinia-Corsica, the formation of the hyper-extended continental Cornaglia and Campania Terraces, or oceanic crust as suggested in PRADA *et alii* (2014), and by the opening of the Magnaghi Basin; (3) the Pliocene phase, dominated by mantle exhumation which was active mainly in the central Tyrrhenian (PRADA *et alii*, 2016a) and which led to the full opening of the Vavilov Basin; this phase has been also accompanied by the growth of the Magnaghi and Vavilov volcanoes; (4) the Quaternary phase, characterized by the opening of the Marsili back-arc basin and by the growth of the Vavilov and Marsili volcanoes.

Based on fault distribution, the southern Tyrrhenian Basin is dominated by normal, reverse and, likely, strike-slip or oblique slip faults, recalling a shear zone. In contrast, the northern/central Tyrrhenian Basin is dominated by listric normal faults, mainly along the Sardinia-Corsica margin, and by SW-dipping normal faults along the Campania margin. This extensional-style changing from west to east with respect to the Vavilov Basin is controlled by crustal-scale processes: the two tensional forces induced by the ca. southeastward rolled-back Ionian crustal slab and by the ca. eastward migration of the overriding Apennines (Fig. 6C). The resulting extensional deformation affecting the upper crust is in agreement with a large-scale, pure shear model, which results in symmetric rifting, evolving in time and space into a simple shear model resulting in an asymmetric rifting, hyperextended, margin (LORETO *et alii*, 2021a). Furthermore, the central Tyrrhenian Basin has undergone extension accommodated by a weak layer corresponding to the Ductile/Brittle Transition Layer (LORETO *et alii*, 2021b) and, where the crust is very thin, to the Moho (see the Moho inset map). This decollement layer evolves into a detachment fault responsible for mantle exhumation in the Vavilov and Magnaghi abyssal plains (Fig. 6B). Slab subduction is still active beneath the Calabrian Arc and the Marsili Basin, as evidenced by the high seismic and volcanic activity of the volcanic arc, although the back-arc basin is starting to undergo compression controlled by the Eurasia Africa convergence (ZITELLINI *et alii* 2020). Indeed, several compressive structures (anticlines, reverse faults and positive flower structures; LORETO *et alii*, 2021b) and compressive-related earthquakes (PONDRELLI *et alii*, 2006) have been detected along the peri-Tyrrhenian continental slope.

The seismicity is predominantly concentrated in the southern Tyrrhenian Sea (see main map), where the distribution of earthquakes is highly heterogeneous, also depending on the complex interaction between tectonics and volcanism. Seismic events occur mostly at crustal depths in the western and southern sectors of the Aeolian Islands, with the higher magnitude events located at a depth near the crust-mantle transition. Several seismic sequences, characterized by long duration (several months) and a significant number of earthquakes, have occurred. For instance, the Palermo sequence began on September 6, 2002, with a ML 5.6 earthquake (AZZARO *et alii*, 2004) and included several hundreds events until December 2002.

In the eastern sector of the Tyrrhenian Sea, earthquakes have a source in the crust and in the upper mantle, mainly associated with the subduction process. The Calabrian coastline area exhibits recent low magnitude seismicity but has been the site of significant damaging events, including the 1783 (Mw 7.1), 1905 (Mw 7.0) and 1908 (Mw 7.2) earthquakes.

Numerous seismic events occur up to a depth of 500-600 km, aligning with the subducting slab. Seismicity along the Calabria, Campania and Latium slope is controlled by extension due to the accommodation of the arc up-lift, whereas seismicity to north of Sicily is mainly related to the compression generated by the Africa-Eurasia convergence. Aeolian Arc volcanoes also exhibit intense seismicity controlled by magma upwelling and eruptions. Furthermore, there is an additional concentration of seismic activity in the area of Phlaegrean Fields, while a scattered and limited seismicity is observed in the central and northern sectors of the Tyrrhenian Sea.

Sicilian Channel

The Sicilian Channel (also known as the Strait of Sicily) is a stretch of sea running from north-west to south-east, bordered by the island of Sicily to the north and the African continent to the south. In general, it is a shallow water area that forms a bathymetric sill (Iudicone *et alii*, 2003) between the western and eastern Mediterranean Basins, both of which are characterized by a much greater water depth. The following important physiographic elements can be distinguished in the Sicilian Channel (see Fig. 7): (i) the western sector, characterized by a wide and shallow structural bank (Adventure Plateau), with water depths ranging from 50 to 150 m that was emergent during the Last Glacial Maximum (22-18 ky B.P; Civile *et alii*, 2015; Lodolo *et alii*, 2020); (ii) the Gela Basin near the Sicilian coast and the Pantelleria, Malta and Linosa grabens, which extend approximately WNW-ESE, and where water depth can exceed 1,500 m; (iii) the easternmost part of the channel, which consists of a large shallow water area from which the Maltese archipelago emerges; (iv) at the eastern edge of the channel, the seabed deepens abruptly along the Malta Escarpment, which marks the boundary between the Sicilian Channel and the Ionian Sea.

At the northern margin of the African plate the continental crust has an average thickness of 25-30 km, decreasing to less than 20 km in the Pantelleria Graben (Civile *et alii*, 2008) and to about 15 km at the Gela Nappe front (Scarascia *et alii*, 2000; Finetti, 2005). The present structural setting is the result of two main regional tectonic processes: 1) the Neogene-Quaternary continental collision

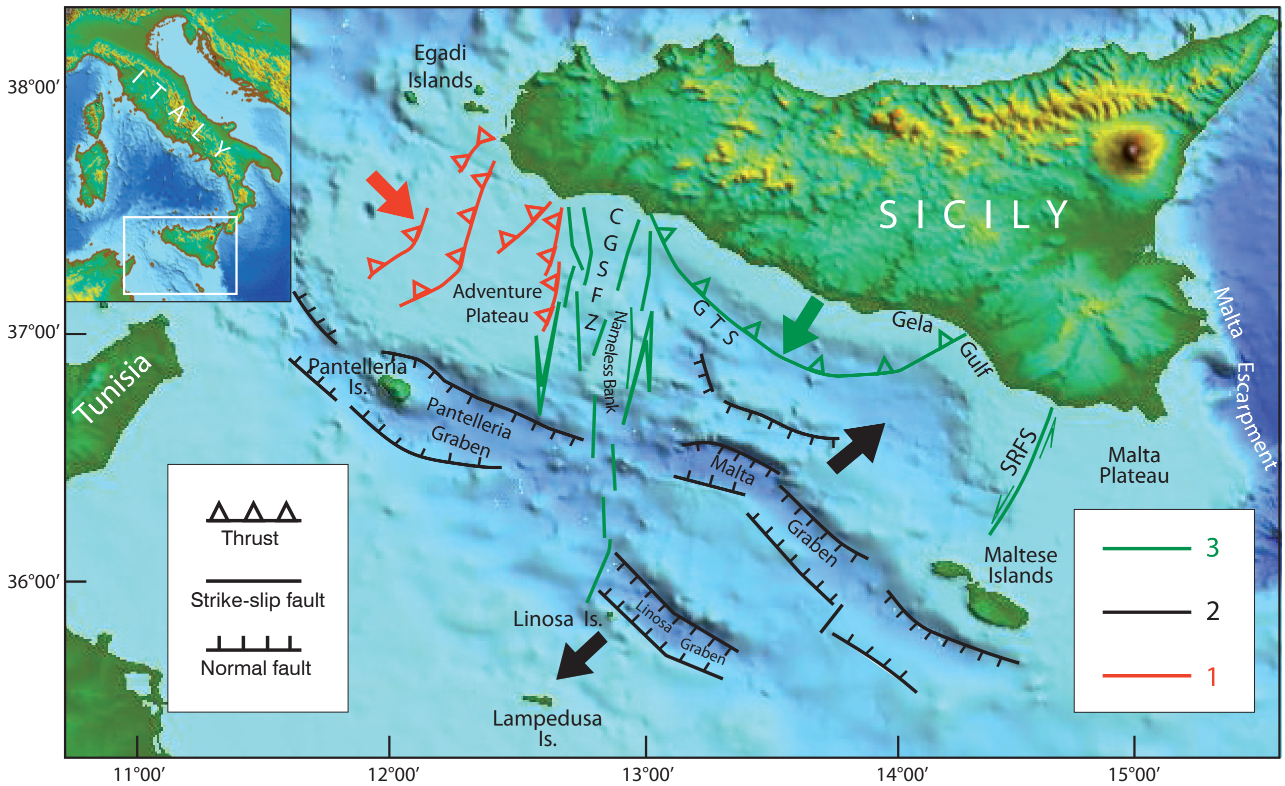

Fig. 7 - Simplified kinematic-structural sketch showing subsequent tectonic events, and related main structures, occurred in the Sicilian Channel since the Late Miocene (the coloured arrows suggest the kinematic of subsequent tectonic events): 1) Sicilian Fold and Thrust Belt, Late Miocene; 2) Sicilian Channel crustal rifting, Pliocene; 3) Gela Thrust System (GTS), Capo Granitola Sciacca Fault Zone (CGS-FZ) and Scicli-Ragusa Fault System (SRFS), Quaternary (bathymetric data from GEBCO (https://www.gebco.net/); tectonic structures modified from Civile *et alii*, 2018 and Maiorana *et alii*, 2023).

between the African and European plates, which produced the Sicilian-Maghrebian fold and thrust belt in the northern and northwestern part of the Sicilian Channel; 2) the Pliocene-Quaternary rift processes, which produced three NW-SE oriented troughs (Pantelleria, Malta and Linosa grabens) in the central part of the Sicilian Channel (Finetti, 1984; Jongsma *et alii*, 1985; Civile *et alii*, 2008), controlled by NW-trending normal faults (Fig. 7). The question of whether these two main geological processes are related to independent geodynamic processes or whether they are different manifestations of a single geodynamic process has not yet been resolved (Civile *et alii*, 2021; Maiorana *et alii*, 2023).

The sedimentary succession, which covers a Hercynian crystalline basement, is the result of sedimentation since the Triassic along a passive continental margin at the transition between the African plate in the south and the Tethys palaeo-ocean in the north.

Overall, the succession consists of (Colantoni, 1975; Antonelli *et alii*, 1991; Civile *et alii*, 2014): Triassic to Early Jurassic carbonate platform successions; Middle Jurassic to Eocene pelagic and open shelf limestones; Oligocene to Late Miocene carbonate and siliciclastic outer shelf deposits, which are overlain by Messinian evaporites in some places; pelagic, and finally hemipelagic and terrigenous Plio-Quaternary deposits, which are on average about 500 m thick, but are more than 1,500 m thick within the Pantelleria, Malta and Linosa grabens and in the Gela Basin. Within the Gela Basin there are considerable thicknesses of deposits formed by submarine landslides (Trincardi & Argnani, 1990; Cavallaro *et alii*, 2016), some of which have resulted in accumulations known as "deep-water thrust belts". Within the Meso-Cenozoic succession, there are significant deposits of hydrocarbons (oil and gas) trapped in carbonate or terrigenous reservoir rocks and derived from source rocks of different ages (Jurassic, Plio-Pleistocene).

The tabular or mound-shaped volcanic bodies are embedded in both the Mesozoic and Miocene successions and are also widespread in the Plio-Quaternary, especially in the central western part of the channel where a series of mainly Quaternary submerged volcanic cones have been identified (some of which were also active in historical times; Ferdinandea Island, 1831; NW off Pantelleria, 1891), in addition to the volcanic islands of Linosa and Pantelleria (both with alkaline products). This submerged volcanism is mainly concentrated in the Pantelleria graben (Civile *et alii*, 2021), on the Adventure Plateau and along the offshore sector between the coast of Sicily and the Nameless Bank (Colantoni *et alii*, 1975; Calanchi *et alii*, 1989; Cavallaro & Coltelli, 2019; Lodolo *et alii*, 2019; see Fig. 7).

Structurally, the Sicilian Channel is characterized by the coexistence and juxtaposition of different tectonic domains: fold and thrust belts, foredeep basins and foreland basins. In the north-western sector (Adventure Plateau and Egadi Islands offshore), an imbricate fan formed by NNE trending and west-dipping thrusts has been recognized (Fig. 7; Catalano *et alii*, 1993; Catalano *et alii*, 2000), together with back-thrusts. The tectonic units consist of Meso-Cenozoic shallow to deep-water carbonates and Tertiary siliciclastic and carbonate rocks. At the edge of this tectonic wedge is an offshore basin (Adventure Foredeep) filled with clastic to terrigenous deposits from the Upper Miocene, some of which are deformed (Argnani *et alii*, 1986, 1987). In the area of the Gulf of Gela there is a Plio-Quaternary tectonic wedge, the Gela Thrust System (GTS, also known as Gela Nappe), composed of Cenozoic, deformed units that have been shortened and southwards overthrust (Figs. 7 and 8; Antonelli *et alii*, 1991; Catalano *et alii*, 2013), and a foredeep basin (Gela Foredeep) filled with Plio-Quaternary deposits (Ghielmi *et alii*, 2012). This foredeep basin also develops on the southern Sicilian mainland northwest of the Hyblean Plateau and is collectively referred to as the "Gela-Catania foredeep basin" (Catalano *et alii*, 2013).

A roughly N-S trending "deformation belt" that extends from the southern coast of Sicily to the central-southern sector of the channel (Calò & Parisi, 2014; Civile *et alii*, 2021) separates the two sectors of the fold and thrust belt, which have different deformation ages and direction of the tectonic transport. In the sector closest to the Sicilian coast, this deformation belt consists of (Fig. 7) two main fault systems: the Capo Granitola Fault System to the west and the Sciacca Fault System to the east (Fig. 8), both dominated by positive flower structures (Civile *et alii*, 2018), due to Quaternary tectonic activity (Civile *et alii*, 2018; Ferranti *et alii*, 2019). These fault systems form a regional lithospheric "transfer zone" affecting the crust and upper mantle to a depth of at least 70 km (Calò & Parisi, 2014). Quaternary submarine volcanic activity is associated with this "deformation belt", concentrated at the Graham and Terrible Banks (located east of the Adventure Plateau) and near the Sicilian coast.

The eastern part of the Sicilian Channel and the southern part facing the North African coast consist of a wide, tectonically stable, less deformed area, the Hyblean-Pelagian foreland basin. The central part of the Sicilian Channel hosts the three prominent tectonic depressions of Pantelleria, Malta and

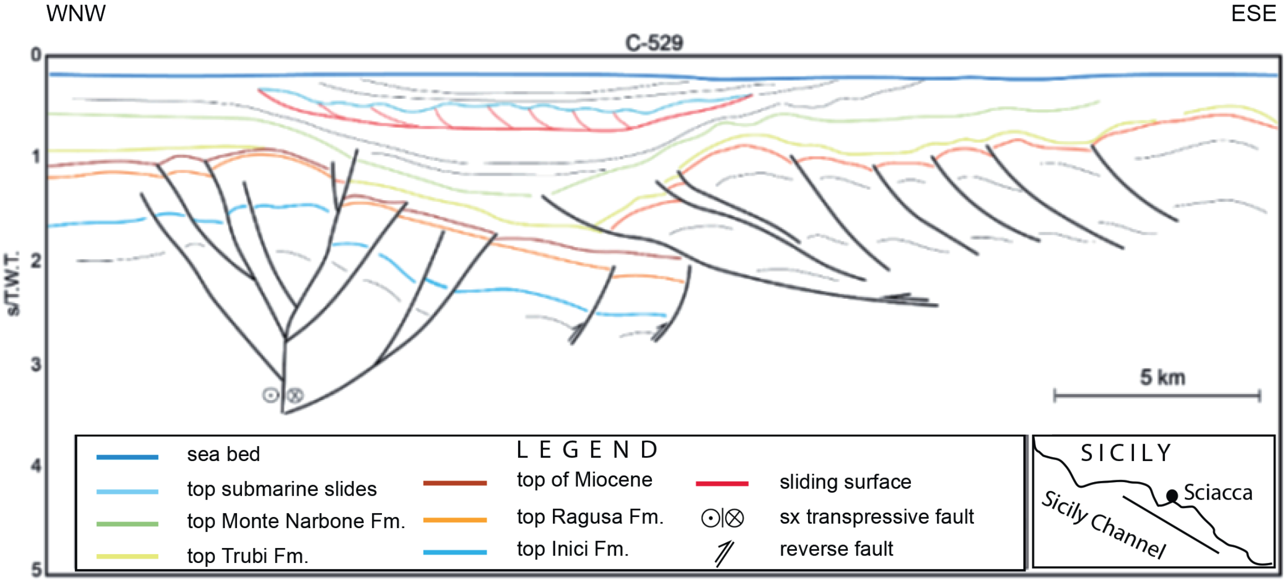

Fig. 8 - Interpreted line-drawing of a stretch of the multichannel seismic profile C-529 where tectonic structures related to CGSFZ (on the left) and GTS (on the right) have been depicted; top wards, in the upper portion of the Plio-Pleistocene sedimentary infill, a wide and thick submarine slide has been detected (from SULLI *et alii*, in prep.)

Linosa, which are bounded by faults connected to extension and transtension with significant throws (Fig. 9; CATALANO *et alii*, 1993; CIVILE *et alii*, 2008, 2010, 2021).

In the south-eastern sector of the Sicilian Channel, an important tectonic element is the NNE-trending Scicli-Ragusa Fault System (SRFS; Fig. 7), which is characterized by strike-slip tectonics and extends from the Malta Plateau northwards to the Hyblean Plateau (CATALANO *et alii*, 2008).

The easternmost margin of the channel, which consists of the Malta Escarpment, is characterized by an articulated system of normal faults or faults connected to transtension that extend in a roughly north-south direction and create a gradient of several hundred meters between the water depth of the Sicilian Channel and that of the Ionian Sea.

After the convergence of the African and European plates, the North African continental margin was involved in the subsequent processes of subduction and continental collision. During the process of continental collision, that occurred in the Middle to Late Miocene, the western sector of the channel was the first to be deformed, resulting in the creation of ~NNE-SSW trending thrust faults (CATALANO *et alii*, 1993; CATALANO *et alii*, 2000), some of which extend as far as the southern mainland of Sicily. The emplacement of these faults was accompanied by the formation of a foredeep filled by Tortonian to lower Messinian terrigenous deposits (Adventure Foredeep; ARGNANI, 1993). The extreme sea-level fall that occurred during the Messinian Salinity Crisis caused the emergence and subsequent widespread erosion of most of the banks of the Sicilian Channel (CIVILE *et alii*, 2021). Later, during the Plio-Quaternary, the foreland basin system of the Sicilian-Maghrebian fold and thrust belt developed further eastwards, but with a southward direction of the tectonic transport: this tectonic phase produced what is today the outermost and youngest tectonic unit of the fold and thrust belt, known as the Gela Thrust System (also called Gela Nappe; Figs. 7 and 8), a thin-skinned accretionary wedge that overthrusts the Plio-Pleistocene deposits of the Gela foredeep basin and the Hyblean foreland-derived regional monocline (ARGNANI *et alii*, 1987; ANTONELLI *et alii*, 1991; LICKORISH *et alii*, 1999; CATALANO *et alii*, 2013). At present, this outermost overthrust front is buried under middle Pleistocene and Holocene deposits.

The seismic activity in the Sicilian Channel is low-to-moderate and spatially dispersed (see main map), despite the complex setting associated with several coexisting tectonic processes, particularly the Europe-Africa convergence. Moreover, the seismicity is commonly linked to normal faulting related to the geothermal and volcanic activity of the region, coexisting with the rifting process (CALÒ & PARISI, 2014). The limited available focal mechanisms (www.bo.ingv.it/RCMT/) emphasize a prevailing strike-slip regime. Only six historical earthquakes, characterized by moderate magnitudes (Mw ranging from 4.4 to 4.7; ROVIDA *et alii*, 2022) have occurred in the area. Most earthquakes and volcanic centers of the Sicilian Channel are concentrated along the Capo Granitola Sciacca Fault Zone, where both seismological (SOUMAYA *et alii*, 2015) and seismic

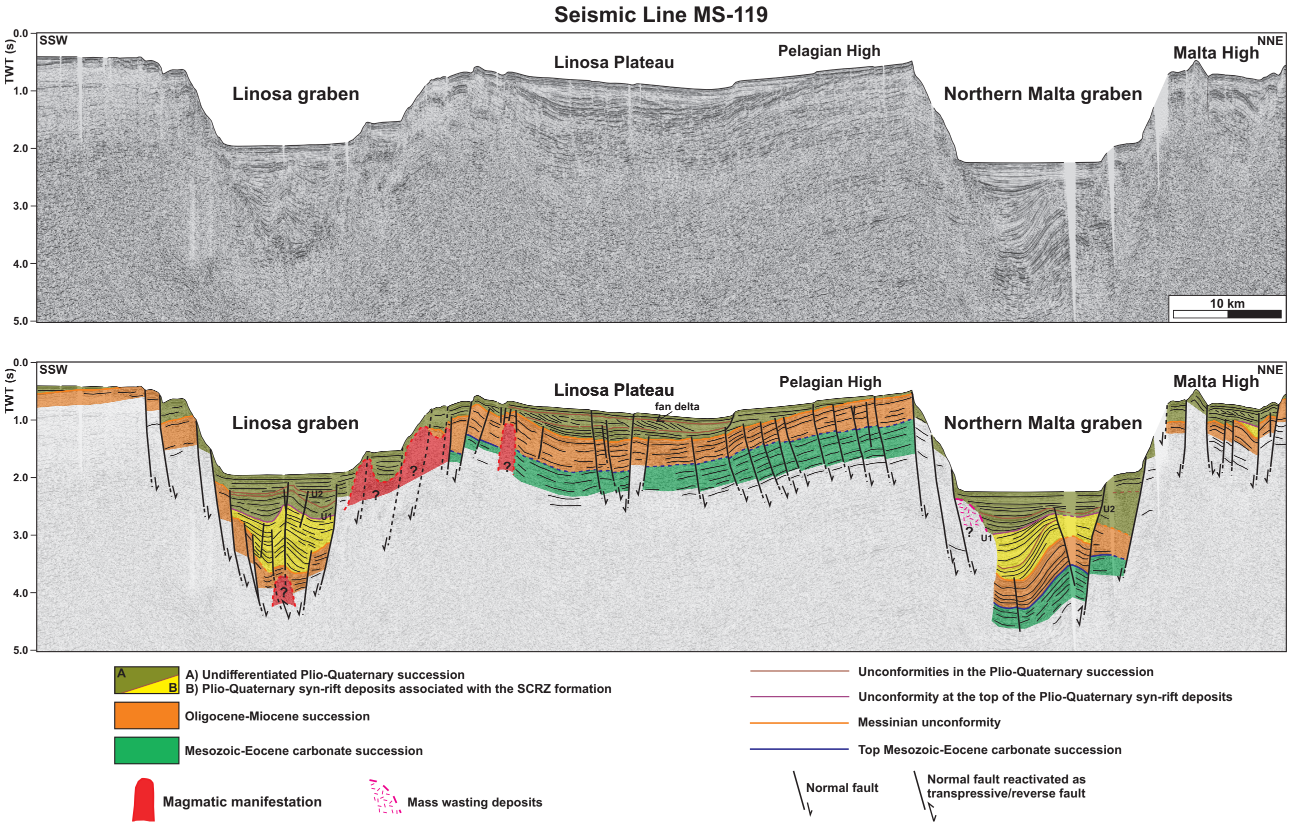

Fig. 9 - Multichannel seismic reflection profile MS-119 crossing the Linosa graben and the Northern Malta graben and interpreted line drawing showing tectonic structures related to crustal rifting process (from Civile *et alii*, 2021).

reflection studies (Fedorik *et alii*, 2018) currently document sinistral movements. East of the Gela Thrust System, the Scicli-Ragusa Fault System has acted with left-lateral strike-slip activity since the middle Pleistocene (Fig. 7; Catalano *et alii*, 2008). In the Maltese archipelago, the focal mechanisms of recent earthquakes show evidence of right-lateral strike-slip faulting (Micallef *et alii*, 2019).

West Sardinia offshore

The West Sardinian margin, in continuity with the West Corsican margin, has a regional N-S orientation, locally affected by a more complex physiography. In particular, up to the Gulf of Oristano (Fig. 10b) there are north-western fault alignments of the Late Miocene - Plio-Quaternary Campidano Graben extension in the Sardinia onshore during the Tyrrhenian Sea opening (Casula *et alii*, 2001). The Gulf of Oristano is partially separated from the continental margin through the threshold shaped by the Sinis and Capo Frasca Peninsulas. The continental shelf ranges in width from 25 km in front of the Gulf to 50 km in the northern and southern sectors (Fig. 10b). The shelf exhibits a flat seabed, connected to the topset of a variously developed clinoform system locally intruded by Plio-Quaternary volcanics (Fig. 10c). The outer shelf and uppermost slope are incised by canyon systems (Fig. 10c) which cut orthogonally the shelf break.

The continental slope represents the most complex sector of the margin with an irregular morphology due to erosion, normal faults and volcanic structures. The transition from the lower slope to the abyssal plain is locally marked by the presence of some imposing volcanic structures (Fig. 10a,b). The flat abyssal plain reaches a depth of approximately 2,800 m. In the lower slope and deep basin salt diapirs deform the overlying Plio-Quaternary sediments into circular structures having a diameter of a few kilometers and become more numerous toward the north-west, where the original salt thickness increases. The Plio-Quaternary thickness also increases in the same direction as a consequence of the large sedimentary contribution of the rivers that flow into the NW Mediterranean Sea (in particular the Rhône and Ebro rivers).

To the west of Sardinia the passive margin represents the inheritance of the late Oligocene/Early Miocene opening of the Liguro-Provençal Basin (Fig. 5) (Rehault *et alii*, 1984). This extensional phase is linked to the westward subduction of the Tethys below the European/Iberian margin, which produced

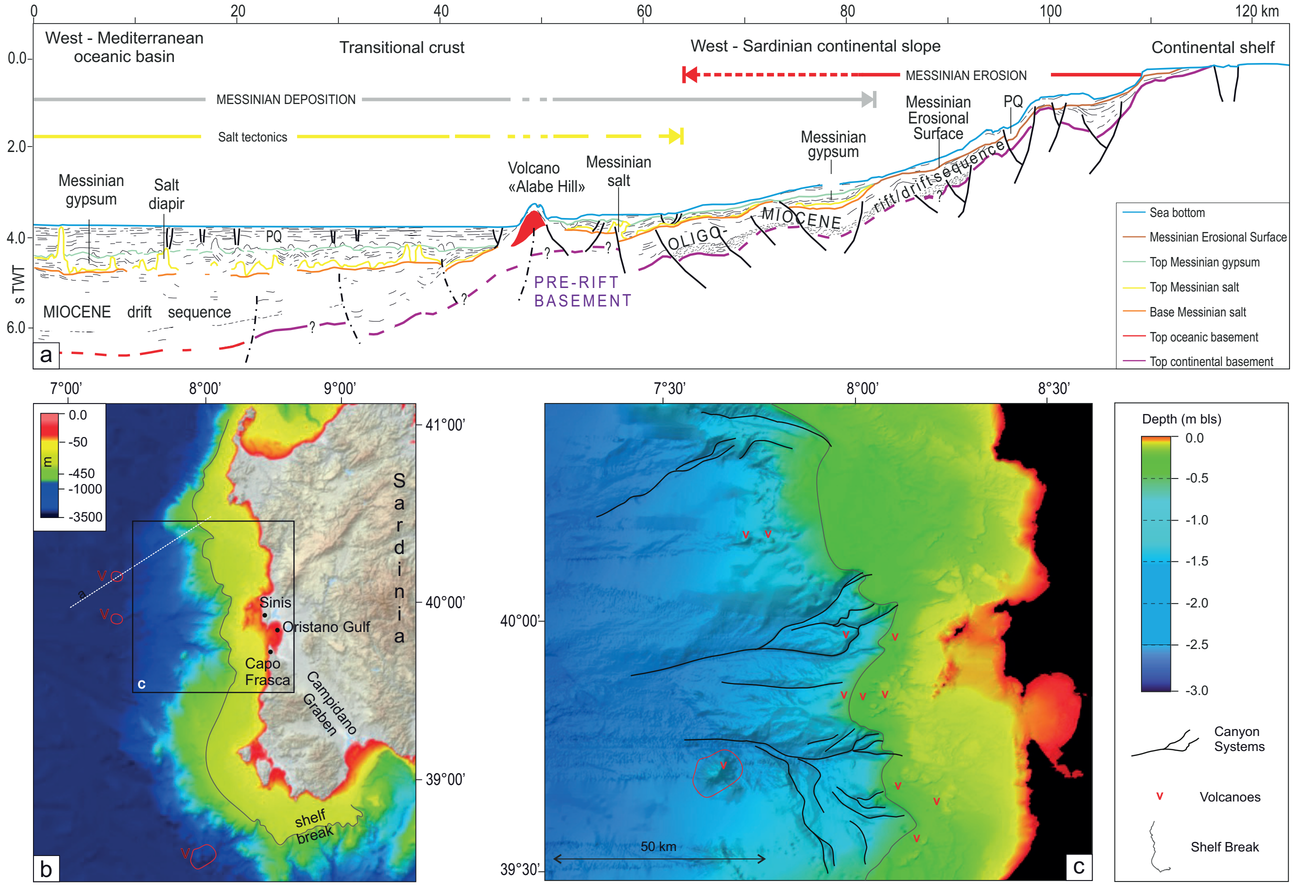

Fig. 10 a) Line drawing of a seismic profile crossing the West Sardinian continental shelf and slope, and the eastern Liguro-Provençal Basin. b) Location of the profile and the main toponyms and structures mentioned in the text; the onshore Campidano Graben, connecting the Oristano and Cagliari Gulfs, is evidenced. c) Detail on the West Sardinian Canyon Systems.

several back-arc basins of the western Mediterranean Sea (REHAULT *et alii*, 1984; CHERCHI & MONTADERT, 1982). Opening of the Liguro-Provençal Basin resulted from the counterclockwise rotation of the Sardinian-Corsican plate, which detached from the European plate during the Aquitanian and continued until the Burdigalian (GATTACECA *et alii*, 2007). After that, thermal subsidence started and has continued to the present. In the Late Miocene, the Messinian Salinity Crisis occurred with a sharp drop in sea level, deposition of evaporites on the deeper region and erosion on the continental slope (CLAUZON *et alii*, 1996; LOFI *et alii*, 2008) (Fig. 10a). Unloading of the lithosphere by water would have caused uplift which, in turn, could have reactivated some of the normal faults produced by the previous extensional phase. Subsequent re-connection with the Atlantic Ocean and flooding of the West Mediterranean Sea must have produced a water re-load, resulting in regional subsidence.

With the exception of DSDP sites 133 and 134 in the southern edge of the lower continental slope, the sedimentary succession of the area has not been documented. The two DSDP sites intersect Plio-Pleistocene marine calcareous oozes and reach the Messinian upper evaporite beds and the underlying metamorphic rocks of the Paleozoic basement (RYAN *et alii*, 1973). The Paleozoic rocks crop out mainly in the east Sardinian onshore, but are locally cropping out or anyway buried below a thin sedimentary cover also in the western onshore. A late Oligocene-Early Miocene clastic succession commonly infills and covers the horst and graben structures (Fig. 10a), which characterize the metamorphic basement of the West Sardinian margin that originated during rifting (FAIS *et alii*, 1996; GELETTI *et alii*, 2014). It is covered by a marine sedimentary succession, bounded at the top by a marked erosional surface or covered by Messinian deposits. These last are evaporites typically subdivided into three units (Messinian trilogy, REHAULT *et alii*, 1984): the intermediate unit related to salt, and the upper and lower units related mainly to gypsum. On the West Sardinia margin the salt and upper gypsum are generally well recognizable in seismic profiles, allowing to evaluate their extensive volume deposited in a very (geologically) short time. Numerous volcanoes have been interpreted based on their shape and seismic facies: some enormous edifices are present at the boundary between the lower continental slope and the deep basin (red circles in Fig. 10b) and are interpreted as being caused by the extensional phase of the late Oligocene-Early Miocene, as are also some buried volcanic bodies on the slope. Other smaller volcanoes, totally or only partially buried under the Plio-Quaternary sediments, are present on the continental shelf and interpreted as post-Miocene in age.

Several extensional faults are present in the West Sardinian margin. They originated during the late Oligocene-Early Miocene producing block tilting and horst-and-graben structures affecting the basement and the deep clastic continental sediments. Some of these faults, especially the west-verging ones, were reactivated during the subsequent Plio-Quaternary thermal subsidence, often allowing rising of magma and fluids to the seabed. Local extensional faults verging to the east close to the NNW the Campidano Graben and separate the Gulf of Oristano from the continental shelf. Furthermore, the halokinetic tectonics, due to the presence of the Messinian salt, gave rise to short, concentric, normal faults above the salt diapirs in the deep basin (Fig. 10a) and to rollover structures and listric normal faults which flatten and converge with the salt base in the lower slope (Fig. 10a).

Currently, the Sardinia region is among the most stable in the Mediterranean Sea and in west Sardinia no major seismic events have been recorded, neither in historical nor in recent times.

FINAL REMARKS

The collection of existing data regarding tectonics, volcanoes and earthquakes in seas surrounding Italy, carried out in the frame of the EMODnet Geology Project, complemented by information on their geodynamic evolution allowed to elaborate an update of the Structural Model of Italy concerning submerged areas. Data were implemented by new acquisitions and were critically revised on the base of the last thirty years of marine geological surveys which were boosted by improvements in technology.

The Italian peninsula and islands represent the outcropping part of complex geodynamic structures developed mainly in the subsurface of the surrounding marine domains. These domains are composed of three very deep, partly oceanic basins (Ionian, Liguro-Provençal and Tyrrhenian), as evidenced by the minimum values of the Moho depth and high heat flow, and of two main shallow seas (Adriatic and Sicilian Channel) and other developed shelves, as evidenced by the depth of the Moho that progressively deepens and by the heat flow which is much lower than in deep basins.

The Ionian Basin is the remnant of an ancient, very large portion of oceanic crust, most of which was subducted before and during the collision between the Eurasian and African plates. As a result of its west-northwestward subduction, two back-arc basins opened up: the Liguro-Provençal Basin, during the Late Oligocene-Early Miocene, to the west of the Sardinian-Corsican plate, and the Tyrrhenian Basin, since the Middle Miocene, between the Sardinian-Corsican plate and the Apennine-Maghrebian Chain. These three deep basins of different ages are therefore closely interconnected.

The Adriatic, Ionian and Sicilian Channel marine areas represent the foreland of the chain, where the frontal thrusts often generate high seismicity (northern Adriatic and western Ionian), while the most recent foredeep basins are evidenced by the thickness of the Plio-Quaternary succession.

High seismicity, generally ascribed to the collision of the Eurasian and African plates, is also recognised in the Adriatic Sea, between Croatia and the Gargano peninsula, in the Ionian Sea, along the Malta Escarpment, and in the southern Tyrrhenian Sea, north of Sicily and west of Calabria. The latter is also associated with the Aeolian volcanic arc that characterizes the Tyrrhenian Basin, together with several very huge volcanoes (such as Marsili and Vavilov) associated with the Tyrrhenian opening.

Similarly, extensional tectonics, that occurred to the west of the Sardinian-Corsican plate, produced Late Oligocene-Early Miocene volcanic edifices at the foot of the continental slope, while more recent smaller edifices on the continental slope and shelf appear to be of Plio-Quaternary age.

In the Ligurian Sea, where seismicity seems to be linked to a complex interplay between the Alps and the Apennines, the morphostructural setting was generated primarily by the aforementioned extensional tectonics and its interaction with regional tectonic inversion episodes during the Middle–Late Miocene and from the Plio–Pleistocene onward.

At the same time, an extensional domain produced a crustal rifting also in the Sicilian Channel, through characteristic NW-SE grabens and several outcropping (Linosa and Pantelleria) or submerged volcanic structures.

The Structural map of seas surrounding Italy describes the geodynamic evolution of the subsequent back-arc-arc-trench systems. Future investigations might improve the structural geology knowledge, particularly concerning sea sectors not yet fully understood and active tectonic structures which need to be further investigated to assess their potential to generate marine geohazards. The geodynamic model generally accepted today will be further updated by future observations, starting from the results recently obtained by the IODP Expedition 402 conducted in the central Tyrrhenian Basin. However, this map represents an accurate and updated collection of the submerged tectonic structures identified so far in the seas surrounding Italy.

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MAP DATABASE

doi: https://www.openaccessrepository.it/record/212660/

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