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GEODYNAMIC EVOLUTION AND GEOLOGICAL MODEL OF THE SICILY CHANNEL. IDENTIFICATION AND CHARACTERIZATION OF POSSIBLE CO₂ STORAGE SITES

PhD STUDENT

MARIAGIADA MAIORANA

COORDINATOR

PROF. CHRISTIAN CONOSCENTI

TUTOR

PROF. ATTILIO SULLI

CO TUTOR

PROF. MAURO AGATE

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*Ai miei nonni,
presenti e assenti,
le cui radici profonde
hanno nutrito i miei sogni
e il cui amore infinito continua a guidarmi,
anche da lontano,
oltre il cielo.*

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Abstract

This PhD thesis, with a multidisciplinary approach, aimed to carry out a deep geological analysis of the Sicily Channel, in order to identify and characterize possible CO₂ storage sites. The project develops in a context where European policies force countries to reduce CO₂ emissions by 55% by 2050, so shall be considered the possibility of achieving this objective also through the direct trapping of CO₂ from the industrial plants through the Carbon Capture and Storage (CCS) process.

This thesis aims to achieve two main objectives: (i) to analyze the structural and geodynamic framework of the Sicily Channel and (ii) to identify suitable reservoirs and sealing formations for underground CO₂ storage through Carbon Capture and Storage (CCS) technology, a key approach to mitigating climate change.

The study utilizes an extensive dataset, including 2D seismic reflection profiles from the ViDEPI portal, exploration well data, and profiles from ENI's internal database. The findings are presented across several chapters, with key contributions documented in peer-reviewed journal articles.

The geodynamic evolution and tectonics of the Sicily Channel was examined through three articles. These focus on the construction of a Moho map correlating with volcanic and tectonic structures, an analysis of the rift zone influenced by inherited processes, and a review of the stratigraphic and tectonic framework during the Plio-Quaternary. A published study on seismo-stratigraphic and morpho-bathymetric analyses in the NW Sicily Channel, reveals in-sead fluid dynamic phenomena and leakage pathways.

The core of the thesis addresses the identification and characterization of CO₂ storage sites. Mapping criteria and statistical analyses of key parameters (reservoir depth, seal thickness, data coverage, heat flow, and proximity to seismic sources), are illustrated via pie charts. A published geological model of a promising storage site in the Gela foredeep, integrating seismic and borehole data.

Finally, is presented a basin-scale workflow for evaluating storage potential, applied to data from the Gela foredeep as a case study. This comprehensive analysis highlights the Sicily Channel's complex stratigraphy and geodynamics, integrating extensive data and methodologies to propose suitable CO₂ storage solutions.

This research represents a significant contribution to the field, underpinned by rigorous data analysis and original methodologies for CCS site identification.

CHAPTER 1

General introduction and thesis project motivations

The research topic belongs to the ‘PON Research and Innovation 2014-2020’ grant, Action IV.4 “Dottorati su tematiche dell’Innovazione-Doctorates on Innovation Topics” which aims to provide fundamental tools for the capture and geological storage of CO₂, an objective also indicated by the European Union as one of those to be achieved in the short to medium term to counter the process of global warming and the consequent harmful changes in the climate.

In this context, the PhD project involved a six-month collaboration with ENI S.p.A., which enabled to make the most of cooperation between university and industry, in this case to achieve mutual benefits in their respective fields of competence (research and higher education on the one hand, production of goods and services on the other) through the exchange of knowledge and technologies.

The main topic of this work is to develop a regional screening of the Sicily Channel area to identify potential CO₂ storage sites. Much work has been done already to find and characterize potential storage regions and to develop criteria for screening new areas (Kovscek, 2002; Hovorka et al., 2003; Bachu, 2010; Brennan et al., 2010; Blondes et al., 2013; Halland et al., 2013; Anthonsen et al., 2014; Bentham et al., 2014; Roberts-Ashby et al., 2014; DOE NETL, 2015, 2020; Raza et al., 2016; Trevino and Meckel, 2017). Generally, the screening criteria for CCS purposes are very similar to those used in the petroleum industry. A trap is identified from the identification of a potential reservoir, CO₂ containment and the presence of a covering rock, the seal. In addition, the presence of lateral terminations, and thus closures in the system, is assessed, as well as the presence of geological structures that may favour the creation of a structural trap. However, differently from the steps that are followed for oil exploration, the consideration of further factors becomes crucial.

The criteria for selecting suitable CO₂ storage sites vary based on the type of storage (EOR-Enhanced Oil Recovery, depleted fields or Saline Aquifer Storage). Most European projects follow the guidelines established by the GeocapacityProject (<http://www.cgseurope.net/Sections.aspx?section=491.492.494>), which identify key characteristics for reservoirs and seals. An ideal reservoir should exhibit high permeability, porosity and be mainly composed of sandstone. It should be located at a depth between 800 and 2500 m b.s.l., a depth that is paramount (Bachu, 2003), since CO₂ geological storage takes place in supercritical conditions ($T > 31.1\text{ }^{\circ}\text{C}$ and $P > 7.38\text{ MPa}$). In these conditions, CO₂ density is in excess of about 500 kg/m³ that provides the potential for efficient utilization of underground storage volume (U.S Department of Energy-DOE, 2010). In sedimentary basins with an average geothermal gradient of 25 to 30 °C/km, the supercritical condition is generally present at depths of about 800 m (Suekane et al., 2005).

Reservoir rocks must have adequate petrophysical properties to be suitable for CO₂ storage. As a general rule, permeability should exceed 1.97×10^{-13} (200 mD) to provide sufficient injectivity (van der Meer, 1993), however, values greater than 2.96×10^{-13} (300 mD) are preferred. Porosity should be greater than 20% (Chadwick et al., 2008), albeit lower values until 10% are acceptable.

The ideal seal should have low permeability and porosity, preferably composed of mudstone, with a thickness exceeding 50 m. In CCS projects, both primary and secondary seals are critical for preventing CO₂ leakage from underground storage. The so-called “primary seal” is the main geological barrier directly above the CO₂ storage reservoir, preventing the upward migration of injected CO₂. The “secondary seal” is an additional layer of impermeable rock located above the primary seal (not necessary directly), providing extra protection against CO₂ leakage and acting as a backup if the primary seal fails or is compromised. Identifying multiple seals (e.g., primary, secondary, etc..) is essential for maximizing storage efficiency and minimizing risk, especially in large-scale storage operations (Chadwick et al., 2008).

For this analysis, we utilized a dense grid of 2D seismic reflection profiles along with data from exploration wells, sourced from the ENI internal database. This study is also based on the analysis of a dataset that has been made available by the Ministry of the Economic Development in the framework of the project “Visibility of Petroleum Exploration Data in Italy (ViDEPI)” (<http://www.videpi.com>). This dataset includes about 1650 well data and 55,000 km of 2D multichannel seismic profiles acquired since 1957 by several oil companies for hydro-carbon exploration (mostly by ENI, the main Italian oil company). Exploration boreholes were employed to calibrate the seismic profiles. The interpretation of key horizons was conducted using the seismo-stratigraphic methods outlined by Vail et al. (1977).

The Landmark DecisionSpace Geosciences package was used to perform the seismic interpretation of key horizons and main faults, well-to-seismic tie, velocity model, depth conversion, to create depth and isopaque maps (in-depth domain) and to generate a 3D view in-depth domain.

This PhD thesis aims to explore the intricate geological evolution of the area and assess its potential for carbon dioxide (CO₂) storage developing a comprehensive screening criteria for identification of a suitable storage site both for SAS (Saline Aquifer Storage) and CSS (Carbonate System Storage) environment. Combining detailed geodynamic analysis with advanced geological modelling techniques it will unravel the tectonic history of the region and identify subsurface structures suitable for CO₂ sequestration.

Seven main chapters with connected sub-chapters, compose the work, as follows:

- ❖ Chapter 1, which explains the general motivations and purposes of the thesis.
- ❖ Chapter 2, which focuses on the geodynamic evolution and geological modelling of the Sicily Channel, a key area of the Central Mediterranean characterized by complex tectonics, diverse sedimentary basins, and active geodynamic processes. A new Moho map of the central-western Sicily Channel is presented, as well as two earthquake alignments through which two Lithospheric Seismogenic Volumes (LSVs) constructed. These results have been related with the location of the volcanoes, the tectonic structures, and the rheological profiles present in the literature. Further, to expand the limited knowledge of the geodynamic setting and lithospheric structure of the Sicily Channel presenting the results of the analysis of crustal seismic reflection profiles and velocity models from multiple databases. The tectonic setting depicted is not the result of a simple stage of passive rifting; instead, it derived from the interplay of different processes which were inherited from the complex geodynamic system of the Central Mediterranean, especially from its subduction dynamics with the fast roll-back and subsequent potential slab tear and polarity switch north of Sicily.

This chapter also presented in detail the stratigraphic architecture of the Sicily Channel and the main tectonic features that acted in this region during the Plio-Quaternary, based on an extensive review of the available literature, examined in order to understand this region's Plio-Quaternary tectonic evolution. The findings indicate that the Sicily Channel cannot be considered a simple rifted foreland zone, but rather exhibits recurrent late Neogene/Plio-Quaternary extensional and compressional pulses. This evidence suggests that distinct tectonic regimes may coexist in a foreland area, further supporting the idea that foreland basins are reactive recorders of dynamic processes governing lithosphere deformation and are susceptible to tectonic reactivation.

- ❖ Chapter 3 presents a fluids pathway model, revealing the source of fluids emissions at depth in the Adventure Plateau, and providing new insights into the identification of fluid leakage pathways. The fluid rising model proposed takes into account the geometry of sedimentary layers and the occurrence of permeable and impermeable layers derived from well-log analysis. The morpho-structural analysis showed a NW–SE oriented fault system and a string of pockmarks that follow the same trend.
- ❖ Chapter 4 introduce to a georeferenced database of sites suitable for CO₂ created by assigning classification parameters derived from literature analysis and public data. Considering the seismic and well data available in the ViDEPI database, deep and shallow tectonic structures as well as the stratigraphic context were examined in the offshore of southern Sicily to identify reservoir and seal formations and define the tectonic structure of potential sites for

investigation. Based on these correlations, the database thus created is a preliminary result within the framework of the doctoral project that provides for the creation of an atlas of sites considered suitable in the offshore of the Sicily Channel.

- ❖ Chapter 5 reveals the presence of a potential storage play within the foredeep basin-filling deposits spanning approximately 840 km² in the Gela offshore area. This was done through the interpretation of key horizons from a dense grid of 2D seismic reflection profiles, followed by well-to-seismic tie analysis and the creation of a refined velocity model. Thus, the study analyzed a potential caprock-reservoir system and its extent, age, and interaction to the tectonic structure. This provides a crucial tool for identifying relationships between tectonics and sedimentation that could generate potentially suitable sealing layers for CCS purposes.
- ❖ Chapter 6 introduces, as part of the common screening for regional-scale CCS in the Sicily Channel, a workflow that uses basin-scale geologic parameters to identify suitable rock units, then optimizes limited subsurface data to estimate storage potential. To demonstrate this approach, available data from a reservoir in the Gela Foredeep Basin were used as an example of data lean. A probability assignment was applied to each data point, which was then combined to generate a common probability map. This allowed to identify the potential and risks for injectivity (reservoir presence and quality) and containment (tightness and possible faulting).
- ❖ Chapters 7 and 8, which summarize the principal outcomes of this PhD thesis.

CHAPTER 2

Introduction to the Geology and Geodynamics of the Sicily Channel

2.1 Introduction

The knowledge of the different geological processes occurred in the Sicily Channel is challenging for conducting regional screenings for CO₂ storage purposes, where identifying and characterizing suitable subsurface storage sites is crucial. In fact, regional geological processes, such as tectonic activity, faulting, and subsurface fluid movement, could influence the long-term stability of a storage site. In this chapter, three different aspects of the Sicily Channel are investigated, from the crustal level to the carbonate layer, through to recent and active tectonics in the area.

A first study delves deep, down to the Moho, through an integrated analysis combining seismic reflection profiles with seismological data. With this study, submitted to “Scientific Reports” journal, the knowledge of the deepest layers of the Sicily Channel was investigated, in an area where several banks and volcanoes occur, fundamental elements to be considered in a CCS screening. This analysis provided instruments that can be used to understand the mechanisms influencing the variation in crustal thickness as well as the possible connection between rising deep magmatic fluids and outcropping volcanoes. With this aim, a joint analysis of multidisciplinary data was performed. Specifically, reprocessed ultra-high penetration seismic reflection profiles (Catalano et al., 2000) were interpreted to observe detailed surface geometries down to Moho depth using them to calibrate P-wave velocity (V_p) and shear wave (V_s) models extrapolated from the literature. To these data the seismological contributions were merged using earthquakes with a statistical approach and the Gaussian Kernel function to understand the connection with the deep geological structures in the area.

To investigate this topic, in the following chapter is included a paper (Maiorana et al., 2023) published in *Tectonophysics*, which aims to delineate the distribution and the chronology of the compressive and extensional events occurred along a N-S-oriented band crossing the central Sicily Channel, from the Gela Thrust System to the Linosa Graben, in order to outline the main driving forces and improve the knowledge about the geodynamic framework that shaped the study area.

The comparative analysis of several seismic lines, reaching even the crustal structure, in addition to geodetic and literature data, allowed to suggest that alternative extensional and contractional deformation located within the African Plate can be explained through the overlapping of different processes.

Integrating geological and geodynamic data, is fundamental to assess the suitability and safety of potential CO₂ storage sites, ensuring that they meet the necessary criteria for effective and long-term sequestration.

Further, to focus on the evolution of the shallowest layers, which were significantly impacted by a major post-Messinian phase of deformation, a comprehensive review of the structures occurred the Sicily Channel is presented. This study, in a paper submitted to the journal “BSGF - Earth Sciences Bulletin”, depicts the stratigraphic architecture of the Sicily Channel and the main tectonic features that acted in this region during the Plio-Quaternary, based on an extensive review of the available literature, including already-published multichannel seismic reflection profiles and structural maps. In addition, their timing was examined to acquire an exhaustive understanding of this region's Plio-Quaternary tectonic evolution.

2.2 A NEW MOHO MAP OF THE CENTRAL-WESTERN SICILY CHANNEL: CORRELATION WITH VOLCANIC AND TECTONIC STRUCTURES

A NEW MOHO MAP OF THE CENTRAL-WESTERN SICILY CHANNEL: CORRELATION WITH VOLCANOES, TECTONIC STRUCTURES AND SEISMOGENIC VOLUMES

S. Bongiovanni^{1*}, M. Maiorana¹, A. D'Alessandro², R. Martorana¹, A. Sulli¹

¹Università di Palermo, Dipartimento di Scienze della Terra e del Mare, Palermo, Italy

²Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Nazionale Terremoti, Rome, Italy

*simona.bongiovanni@unipa.it

ABSTRACT

A detailed Moho map is essential for understanding the deep structure of a given area, especially for a complex area such as the Sicily Channel, shaped by the Europa-Africa convergence. We built a new Moho map of the central-western Sicily Channel using a multidisciplinary approach, which comprises the analysis of crustal seismic reflection profiles and velocity models from multiple databases. We found two earthquake alignments that occurred in the study area from 1981 to the present that reach sub-Moho depths and through which we constructed two Lithospheric Seismogenic Volumes (LSVs). We then related these results with the location of the volcanoes, the tectonic structures, and the rheological profiles present in the literature. This work aims to expand the limited knowledge of the geodynamic setting and lithospheric structure of the Sicily Channel. Furthermore, it can constitute a starting point for future works regarding the seismic hazard of the area.

Keywords: Moho depth, Sicily Channel, Lithospheric seismogenic volume, Seismic reflection profiles

1. INTRODUCTION

The Sicily Channel is a seismically active area, characterized by moderate seismicity with a magnitude generally below 5. Unfortunately, the location of the earthquakes hypocenters in this area is poorly constrained because due to the sparse distribution of permanent seismic stations and the high attenuation [1].

As illustrated in Fig. 1a, an alignment of earthquakes with sinistral strike-slip focal mechanisms occurs in the western sector of the Sicily Channel as noted by several authors [2, 3, 4, 5].

The Sicily Channel hosts eight seismogenic sources (Fig. 1b): four with approximately N-S trends in the western sector and near the Sicilian coast (Fig. 1b within the blue dashed line) and four with N-S trends crossing the Grabens (Fig. 1b within the red dashed line). These are mapped in the DISS (Database of Individual Seismogenic Sources) [6].

The Sicily Channel has been greatly influenced by the interaction between Africa and Europe plates. Among the various deformation stages recorded, the most important one began in the Late Miocene with the formation of the Sicilian Fold and Thrust Belt (SFTB) [7]. In the Pliocene, an NNE-SSW-oriented extensional mechanism produced the Graben of Malta, Linosa and Pantelleria [8, 9, 10]; at the same time, the Gela Thrust System (GTS) emplacement occurred [11] as well as the formation of a N-S oriented left strike-slip mechanism [12], that extends from Capo Granitola-Sciacca to Linosa (CGSFZ) [5, 9] (Fig. 1c). The latter, physically separating the Graben of Pantelleria from those of Malta and Linosa (Fig. 1c), induced a different evolution between them; the earthquakes available in the area confirm that this structure is currently active and involves the lithosphere levels [9, 13]. Along this deformation belt, also a relevant magmatic activity is recorded, which was associated with the formation of magmatic manifestations, constituting several volcanoes and volcanic banks (Fig. 1a), scattered in the whole Sicily Channel [13, 14, 15, 16]. Near the coast of western Sicily, volcanic edifices of the Quaternary age were discovered by Lodolo *et al.* [17]. According to Civile *et al.* [5], in this system, the magma rises through the faults, acting as conduits, that cut across the entire lithosphere leading to a partial melting by decompression. The seismic section CROP M23 (location in Fig. 1a) of Catalano *et al.* [18] highlighted the deep structural layers of this highly deformed zone, revealing a mild Moho rising from west to east of the CGSFZ tectonic structure, and a Moho deepening beneath the Gela Thrust System. Civile *et al.* [19] also detected in the seismic line CROP M25 (location in Fig. 1a) a Moho rising under the Pantelleria Graben, probably linked to deep fluids rising causing several volcanic manifestations around Pantelleria Island (Fig. 1c). This interpretation is supported by the gravity model realized along the seismic profile showing a Moho rising to about 17 km, in the NW of Pantelleria Graben, and, to the N and S of the Pantelleria Graben, a Moho deepening at 24–25 km depth [19].

Knowledge of the Moho depth is crucial to gaining insights into the dynamics of the Earth's interior, the evaluation of geohazard, the reconstruction of the lithospheric pattern of a given area and the knowledge of deep structures. The Moho presents different characteristics and geometries depending on whether it lies in oceanic or continental region or is located in areas subjected to extensive or compressive processes [20].

The Moho is generally determined by means of seismic and/or gravimetric methods.

In the literature, many maps of Moho have been produced by different methods. Suhadolc & Panza [21] and Du *et al.* [22] generated a map of European Moho obtained from interpretations of CSS (Controlled Source Seismology) profiles.

Moho depth maps have also been created for other regions such as southern California [23], northern and northeastern China [24, 25, 26, 27], eastern Tibet [28, 29, 30] and southern China [31], using Receiver Function (RF) analysis. Teng *et al.* [32] and Reddy & Rao [33] discussed and reviewed refraction seismic profiles for Moho determination in China and

reflection seismic profiles for Indian shield Moho determination, respectively. Stankiewicz & De Wit [34] modeled the Moho below South Africa using reflection seismic profiles and RF analysis. These studies emphasize that obtaining reliable depths by using the RF method requires very accurate S-wave and P-wave velocities. Consequently, reliable results depend on velocity variations with depth, which are best constrained by seismic reflection data.

Mjelde *et al.* [35] and Aitken *et al.* [36] determined the Moho depth for South America and Australia, respectively, using gravity data from satellite observation. In addition, Aitken *et al.* [36] show a limitation of gravity inversion for crustal modeling. These authors noted the unreliability of the method, for example in areas with thick and dense crust or thin and low-density crust, adding that in such a case the method can be made reliable by defining the structure through seismic methods.

Other authors have created Moho maps by integrating data from various methods to overcome the limitations of individual techniques and to ensure better areal coverage. Grad *et al.* [37] made a Moho map of Europe using seismic and gravity data; Assumpção *et al.* [38] discussed crustal thickness models of South Africa using data extrapolated from seismic tomography, reflection seismic profiles and receiver function; Tugume *et al.* [39] made crustal thickness map in Africa and Arabia by interpolating gravity data, RF data and surface wave dispersion.

Regarding the Central Mediterranean area and the Italian region, Nicolich & Dal Piaz [40] and Scarascia *et al.* [41] produced a Moho isobath map using CSS profiles; Waldhauser *et al.* [42] and Lippitsch *et al.* [43], produced a detailed Moho map of the Alpine region using a method proposed by Waldhauser [44] and Waldhauser *et al.* [42] to determine 3-D P-wave velocity models; Pontevivo & Panza [45] used surface wave scattering to reconstruct the lithosphere-asthenosphere system of Italy; Lombardi *et al.* [46] and Piana Agostinetti & Amato [47] proposed a Moho map applying the RF method for the Italian peninsula and the central-western Alps, respectively; Di Stefano *et al.* [48] and Spada *et al.* [49] show a Moho map for the Italian peninsula using both CSS and RF data.

However, these maps either partially or completely exclude the Sicily Channel, which lies on the periphery of these models and is poorly detailed. This is primarily because they are mainly produced on a seismological basis and the seismic network in the area is not adequately distributed because stations are located only on land.

Kherchouche *et al.* [50] proposed a Moho map for the Sicily Channel using ambient noise and earthquake tomography method, but the nearly constant value of about 30 km depth is incompatible with the geological structures in the area.

Jongsma *et al.* [51], Agius *et al.* [1], and Calò & Parisi [2] report information for this area through the study of earthquakes; Civile *et al.* [8, 19], Corti *et al.* [52], and Palano *et al.* [13] describe the area focusing on the analysis of the superficial part of seismic reflection profiles.

As a result, the lithospheric knowledge of the Sicily Channel remains incomplete.

With the present work, we want to contribute to the knowledge of the deepest part of the Sicily Channel, specifically in an area where there are several banks and volcanoes, and to provide an instrument that can be used to understand the mechanisms influencing the variation in crustal thickness found in the study area and the possible connection between rising deep magmatic fluids and outcropping volcanoes.

To do this, we used joint analysis of multidisciplinary data. Specifically, we interpreted reprocessed ultra-high penetration seismic reflection profiles [18] calibrated with well-log data to observe detailed surface geometries down to Moho depth and used them to calibrate, in turn, P-wave velocity (V_p) and shear wave (V_s) models extrapolated from the literature. Further, to understand the connection with structures in the area we merged the seismological contribution using earthquakes with a statistical approach, using the Gaussian Kernel function. The location of this data is shown in Figure 1 a.

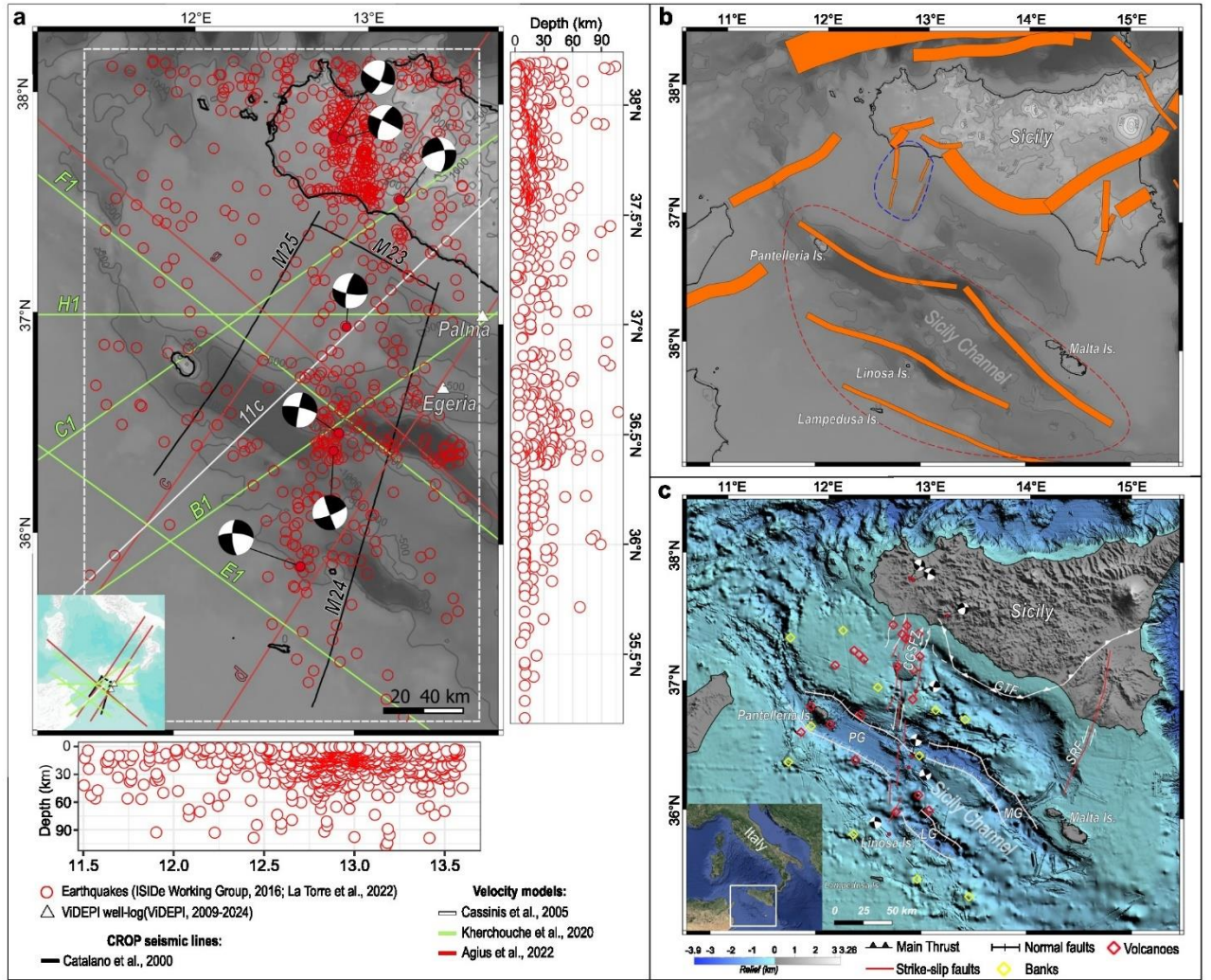


Figure 1. a – Location of the dataset available for the study area. Focal mechanisms of the major events present in the Time Domain Moment Tensor (TDMT) database are also reported [53]; b - The seismogenic sources detected in the DISS (Database of Individual Seismogenic Source) [6] are shown in orange. The red and blue dashed lines contain the seismogenic sources located in the Sicily Channel; c - Geological and morpho-structural map of the study area. GTF (Gela Thrust Front) [54], LG (Linosa Graben), MG (Malta Graben), PG (Pantelleria Graben), CGSFZ (Capo Granitola-Sciacca fault zone) [5], SRF (Scicli-Ragusa Fault) [5]. Focal mechanisms of the major events present in the Time Domain Moment Tensor (TDMT) database are also reported [53]. The location of banks and volcanoes is derived from Aïssi *et al.* [15] and Lodolo, *et al.* [17].

2. RESULTS

2.1 SEISMO-STRATIGRAPHIC INTERPRETATION

We interpreted CROP seismic profiles M23, M24, and M25 to determine the thickness and the geometries of the main units and structures. On each seismic line, we projected V_p profiles from Cassinis *et al.* [55] and Agius *et al.* [56]. Key reflectors, limiting the main layers from Moho to the seabed, have been identified based on their amplitude, lateral continuity, and velocity variation. The correlation with well data (Egeria and Palma) (location in Fig. 1c) and literature data [5, 18, 57, 58] allowed us to characterize the shallower levels and attribute them to the respective age and feature. The deep layers were identified based on seismic reflection characteristics and velocity variation (Figs. 2),

From the seabed to the horizon corresponding to the Top of Miocene a wide Plio-Pleistocene sedimentary filling is observed; its maximum thickness (1.8 s/TWT) is reached in front of the GTS wedge (Fig. 2a). The reflectors show medium amplitude, high frequency, and parallel geometry, with onlap termination on the GTS and CGSFZ. This unit is composed of pelagic marls and marly limestones of the Zanclean Trubi Fm., and of the Piacenzian-Pleistocene shelf clayey deposits with sandy intercalations of the Ribera Fm. [5, 9].

In the northern sector of the study area, the GTS chaotic reflectors, dissected by different S-vergent thrust faults, exceeding 2 s/TWT of thickness, are observed (Fig. 2a).

Underneath this unit, the Miocene deposits are present, consisting of shelf siliciclastic deposits of the Terravecchia Fm. and evaporitic sediments of the Messinian Gessoso-Solfifera Group [5, 9]. The seismic signal is characterized by a high amplitude reflector, and medium frequency, with locally transparent zones (Fig. 2a).

Underlying these, the Mesozoic carbonates are observed; these are composed of: the Upper Triassic (Sciaccia Fm.) and Lower Jurassic (Inici Fm.) deposits consisting of a carbonate platform succession overlain by Jurassic-Eocene pelagic limestones with marly and clayey intercalations (Buccheri, Chiamonte, Hybla and Amerillo Fms.). Horizons show high lateral continuity, medium frequency, and a sub-parallel configuration (Fig. 2a).

Volcanic manifestations are widespread in the entire study area (Fig. 1a), and volcanic intrusions are visible in all the analyzed seismic lines (Figs. 2a and b). Those are characterized by wide diffraction hyperbolae zones and chaotic facies, sometimes reaching the seafloor.

The deep layers include the units occurring below 5 s/TWT. The crystalline basement is the top of the upper crust, the shallowest of the deep layers, and is identified by a discontinuous and strong reflector lying at an average depth of 6 s/TWT (10 km) in all the study area [18] and by a Vp velocity variation that goes above 6 km/s at it (Figs. 2a and b).

The top of the lower crust was identified below this, with numerous horizontal (near flat) and gently dipping reflections characterized by low continuity and medium amplitude, locally interrupted by wide diffraction hyperbolae zones). The velocity here increases to more than 7 km/s up to the Moho (Figs. 2a and b). A double laminated, laterally discontinuous reflector occurs at its base; this, according to Catalano *et al.* [18] interpretation, is assumed to be the Moho horizon.

In seismic profiles M23, M24 and M25, the signal shows high amplitude, low frequency, and it is locally interrupted by diffraction hyperbolae (Figs. 2). The most prominent double reflection is visible in M24 and M25 (Fig. 2c). In proximity to the assumed Moho, the velocity increases up to 8 km/s.

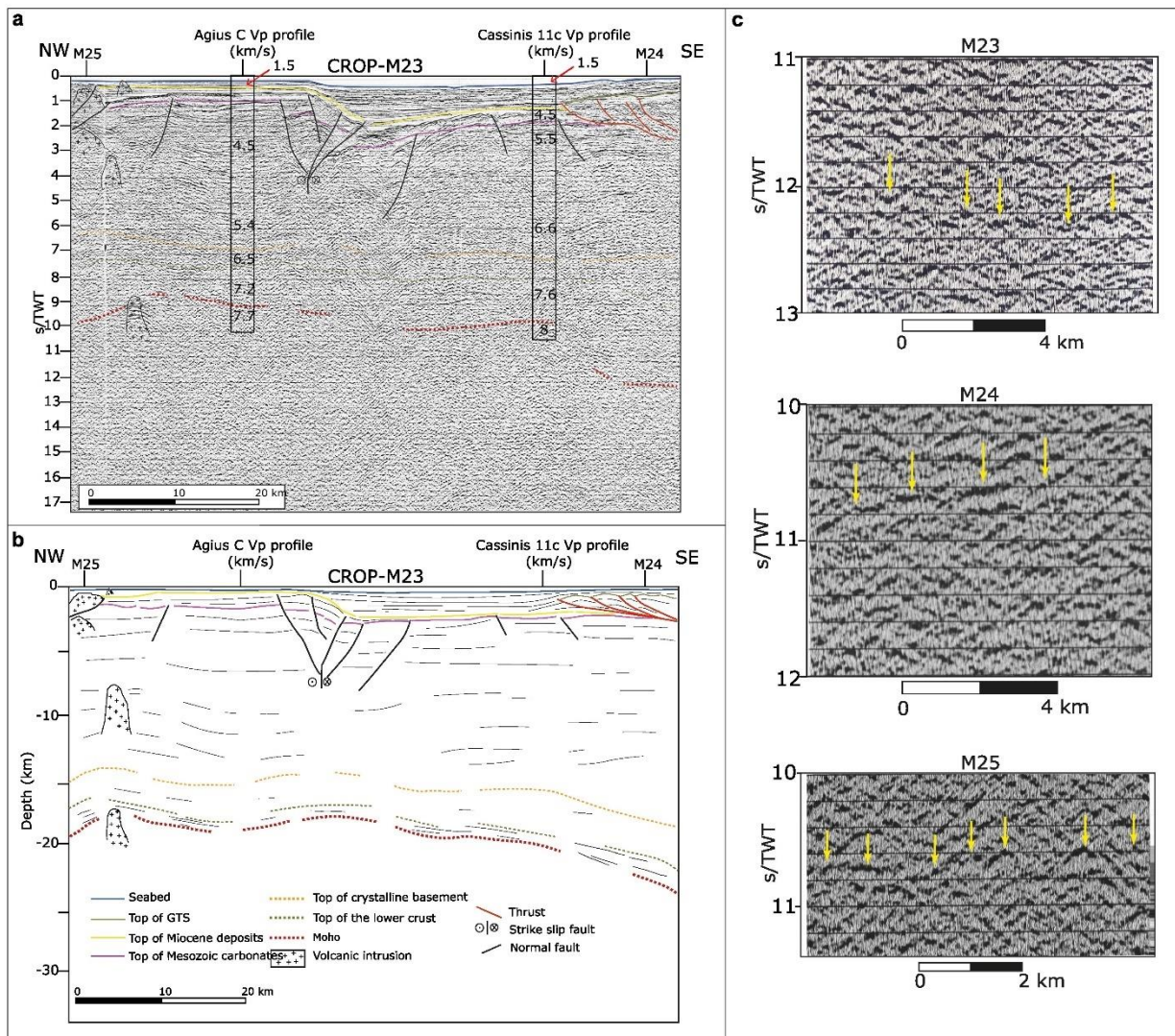


Figure 2. a - M23 seismic line interpretation after Catalano *et al.* [18] in time (TWT); b - Line drawing in depth (km). Crossing Vp profiles by Cassinis *et al.* [55] and Agius *et al.* [56] have been represented; c - Moho reflection characteristics (indicated by yellow arrows) in M23, M24 and M25 CROP profiles.

2.2 MOHO SURFACE IN TIME (S/TWT) AND IN DEPTH (KM)

From the Vs models of Agius *et al.* [56] and Kherchouche *et al.* [50] (location shown in Fig. 1a) we obtained Vp values for the Moho surface, which are respectively 8 km/s and 7.7 km/s.

The velocity models of Kherchouche *et al.* [50] were not used to construct the Moho surface as they did not align well with the other data used.

The obtained Moho surface in time ranges from ~6.7 to ~12.6 s/TWT (Fig. 4a). The lowest values are found beneath the Pantelleria Graben (6.7 s/TWT); there, the contour lines follow the trend of the tectonic structures, which are normal faults at the rims of the Graben (Fig. 1a). Otherwise, between the Pantelleria Graben and the Linosa Plateau sector, the concavity of the contour lines shows a constant NW trend; and, on the contrary, in the proximity of the GTS and in the southern Linosa Graben, a variation in the concavity of the contour lines is observed (Fig. 3a).

The Moho surface in depth shows strong lateral variation, with depths ranging from ~16.8 km to ~27.2 km (Fig. 3b).

In the Pantelleria Graben, the Moho reaches 16.8 km depth, maintaining a shallower trend than in the surrounding areas. Near the Linosa and Malta rims, it reaches depths of around 20 km (Fig. 3b).

Additionally, a Moho deepening is observed along the M23 profile from west to east. At the point where it intersects the orogenic wedge of the GTS, the Moho reaches ~27 km depth (Fig. 3b).

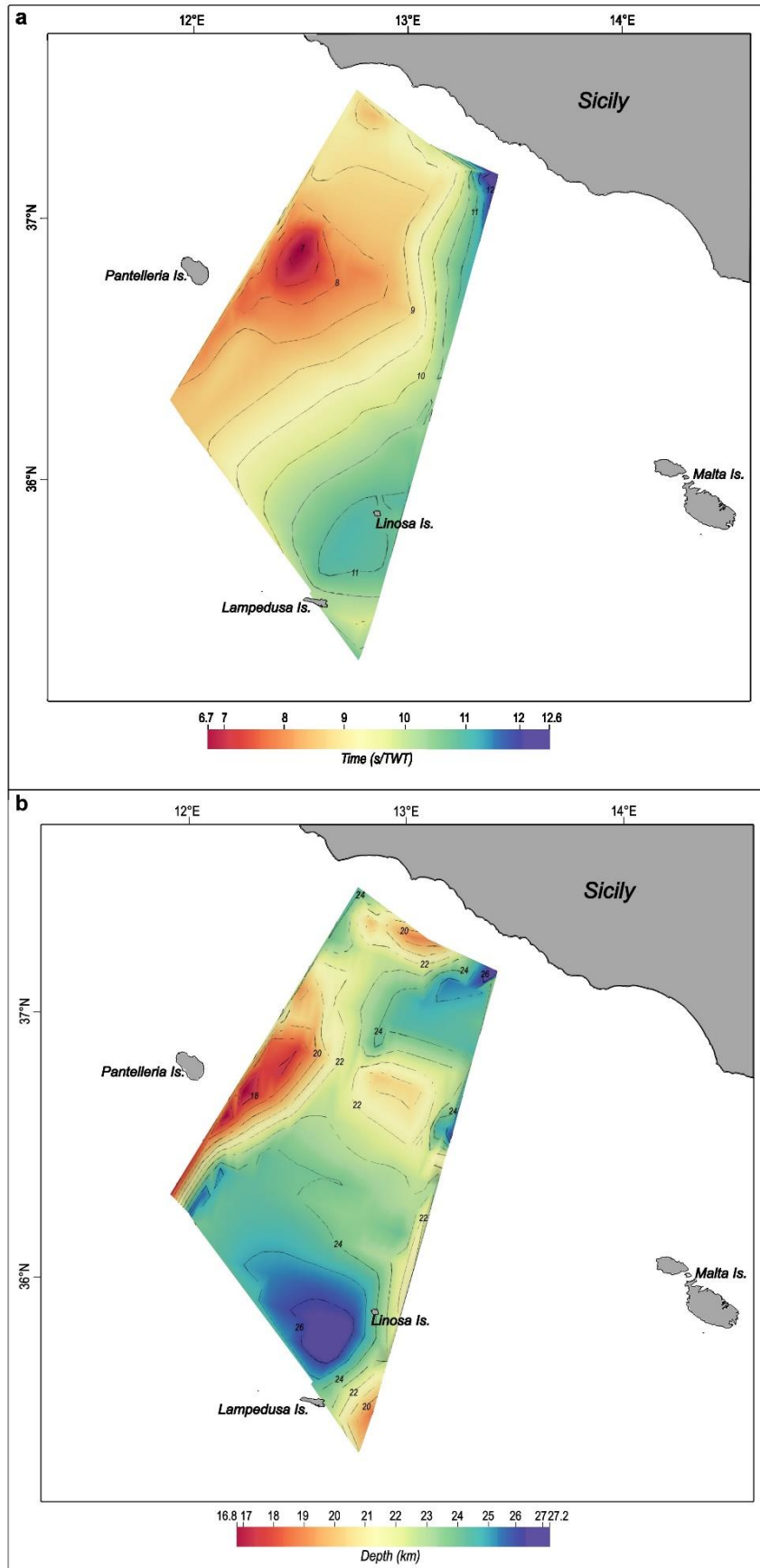


Figure 3. Moho map in time (a) and in depth (b) of the central western sector of the Sicily Channel.

2.3 LITHOSPHERIC SEISMOGENIC VOLUMES (LSVS)

From the statistical analysis of each dataset of earthquakes divided into depth ranges, we obtained density plots on which we calculated gradients (example in Fig. 4) and maximum gradient values. Using the isolines, obtained from the maximum density gradient values for each depth range, we determined two pairs of surfaces perpendicular to each other bordering two LSVs also perpendicular to each other: one with N-S trend (blue scale in Figs. 5) and one with E-W trend (red scale in Figs. 5).

It is observed that the N-S-oriented LSV follows the trend of the tectonic structures located within the CGSFZ. Otherwise, the E-W volume shows a trend concordant with the normal faults bordering the Pantelleria, Malta, and Linosa Grabens.

In Fig. 5, the geometry of the N-S-trending LSV's bounding surfaces is well illustrated to the west and east. The volume extends from the northern coast of Sicily to the island of Linosa for about 240 km and from 5 km to about 60 km depth. In particular, the northernmost sector of the volume is present from a depth of 5 km to about 25 km; from the island of Pantelleria southward, the volume deepens to a depth of 60 km.

To the south of the Sicily coast, the volume decreases vertically and is only present from about 20 km depth to about 35 km depth. The minimum, average and maximum distance between the two surfaces, and thus the minimum, average and maximum value of the volume thickness are 35 km, 48 km and 55 km, respectively. The two surfaces also exhibit concavity facing toward the inside of the volume (Figs. 5b and d). The central sector of the NS-trending LSV perpendicularly intersects the EW-trending LSV (red scale in Figs. 5).

The latter extends from a depth of 50 km to 60 km and a length of 100 km. The minimum, average and maximum distance between the two surfaces and thus the minimum, average and maximum volume thickness are 50 km, 70 km and 90 km, respectively. The two surfaces bordering the volume exhibit a concavity facing toward the inside of the volume (Figs. 5a and c).

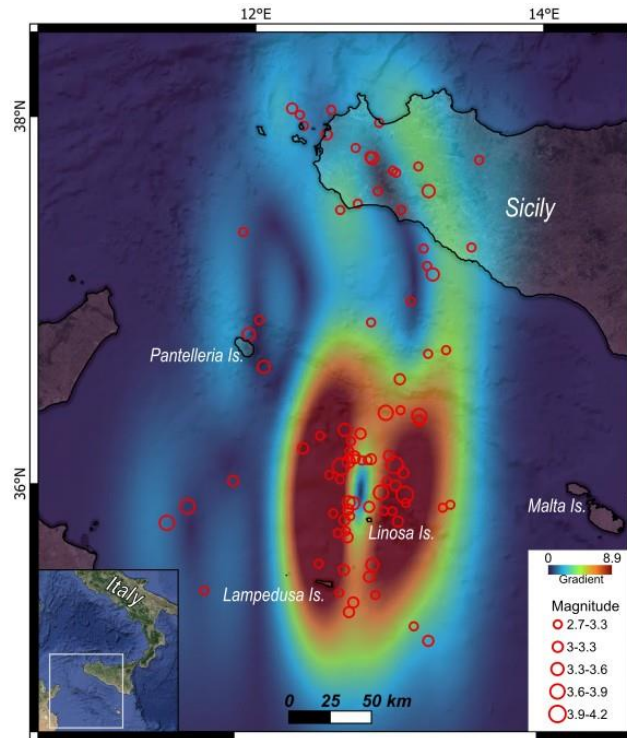


Figure 4. An example of the density gradient (color scale) obtained from the density of earthquakes (red dots) located between 5 and 15 km depth.

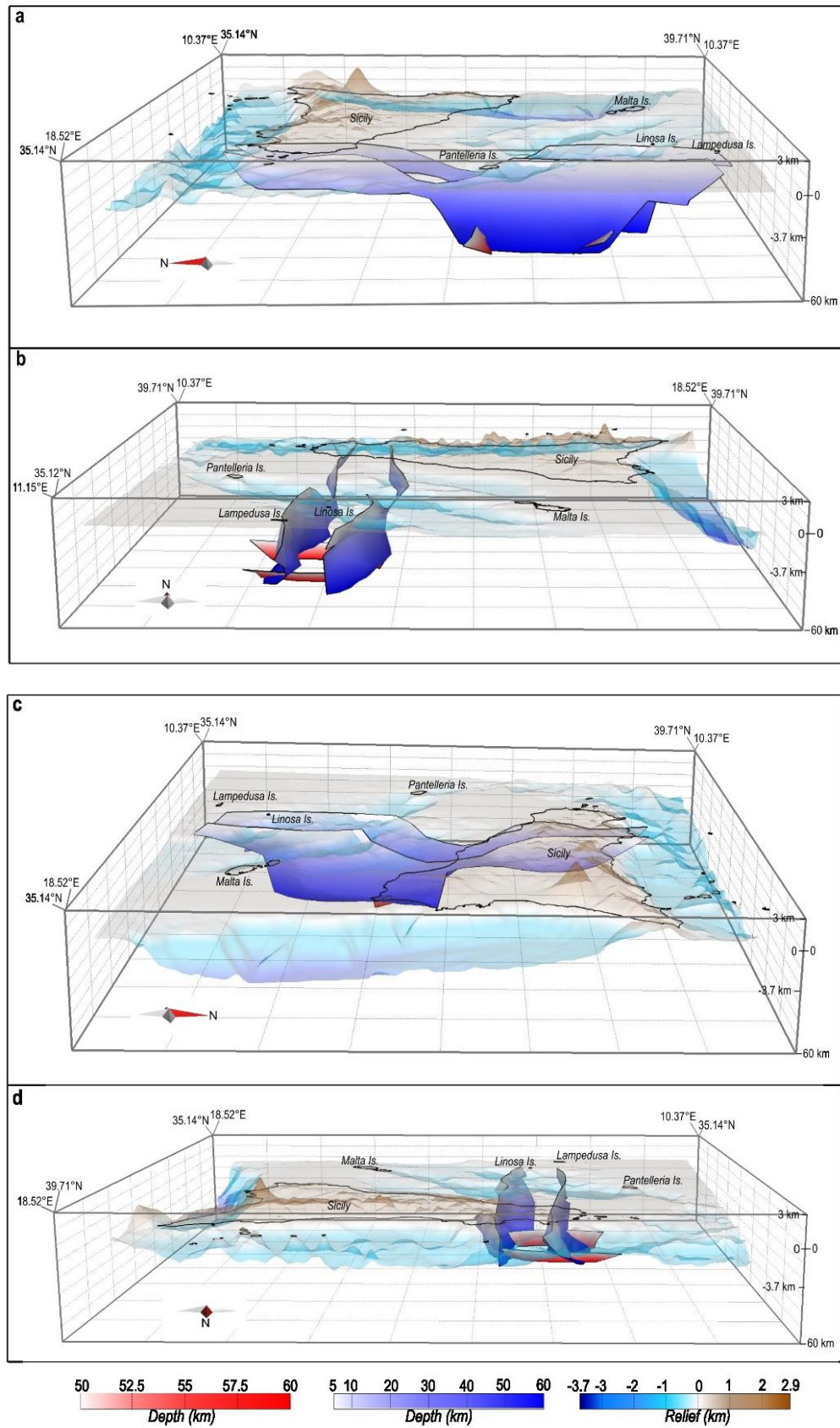


Figure 5 a, b, c, d. Different views of the LSV. Topography (exaggeration x8) is represented in blue-brown color scale; in blue scale the LSV with NS trend, in red scale the LSV with EW trend.

3. DISCUSSION

A new, reliable, high-resolution Moho map of the central-western sector of the Sicily Channel, realized using a multidisciplinary approach, fills in the gaps in the Moho maps produced for the Italian peninsula that mostly excluded the Sicily Channel sector [41, 43, 46, 47, 48, 49].

Considering that this new map covers a smaller study area and was made using a wide dataset, it exhibits a higher resolution comparatively to other Moho maps of the Mediterranean and the Italian peninsula [55, 57, 59].

Moreover, the map reveals strong lateral variations (the depth ranges between 16.8 km and 27.2 km, see Fig. 3b) conversely to the map proposed by Kherchouche *et al.* [50] which shows a constant trend in Moho depth within the Sicily Channel, probably due to a not well-distributed seismic network in the area.

Furthermore, our map exhibits a strong correlation with the tectonic structures found in the literature and shown in Fig. 1c (e.g., Pantelleria, Malta, and Linosa Grabens) and with the location of volcanoes; in fact, a shallower Moho (16.8 km depth) is observed in correspondence with the Capo Granitola-Sciaccà offshore, around the Pantelleria, Lampedusa, and Linosa islands and near the volcanoes (Fig. 6).

The two constructed LSVs, if compared with the other data analyzed, are a fundamental tool for understanding the lithosphere structure variation of the study area. Fundamental evidence is that both the N-S and the E-W LSVs show a concordant trend with both tectonic structures (Fig. 1c) and seismogenic sources from the DISS database (Fig. 1b).

Specifically, these LSVs exhibit (i) a NNE-oriented trend (in agreement with Calò & Parisi [2]; Di Stefano *et al.* [3]; Spampinato *et al.* [4]; Civile *et al.* [5], which follows the structures of the CGSFZ, interpreted by Civile *et al.* (2018) as lithospheric faults favoring the rise of magmas to the surface, and (ii) an EW-oriented trend, concordant with the normal faults delineating Pantelleria, Malta, and Linosa Grabens (Fig. 7).

Furthermore, the E-W alignment of seismic events, which has not been widely discussed by other authors, is supported by the presence of an E-W seismogenic source identified in the DISS database.

In detail, the N-S LSV extends from 5 km to 60 km depth, except in the northernmost region where it lies at a depth between 20 km and 35 km depth (Figs 5a and c). In this sector, morpho-bathymetric and seismic data from the literature [5, 15, 17, 60] indicate a high concentration of volcanoes, located outside the LSV. Conversely, some volcanoes are observed within the LSV, particularly around Linosa and Pantelleria Islands (Fig. 6). Hence, it is not possible to derive a direct relationship between the location of volcanoes and LSVs.

Viti *et al.* [61] suggest, in the rheological profiles realized for the Sicily Channel, an alternation between viscous and brittle behavior at various depths down to approximately 35 km; down to this value, they observe a predominantly viscous behavior, in agreement with the maximum Moho depth reconstructed in this work (see Fig. 3b).

Analysis of a large earthquake dataset, linked to the reconstruction of a detailed Moho map, has identified sub-moho earthquakes.

The sub-Moho earthquakes are rare, and their existence is sometimes debated [62, 63], otherwise, they are observed in various parts of the world and across different tectonic regimes [64, 65, 66, 67]. Therefore, we hold that the finding of the two seismic alignments that reach greater depths than the Moho is not unusual, especially in an area where ongoing geodynamic processes are observed, as reported by Corti *et al.* [52] and Maiorana *et al.* [10].

The presence of such sub-Moho events would suggest also the presence of a mantle-like rheological variation, which should however be further investigated with supplementary rheological data.

However, if we consider the absence of a shallow LSV in the north of the Pantelleria volcanic island (Figs. 5 a and c) and the absence of it at great depth near to the Linosa volcanic island (Figs. 5 b and d), we see that the absence of LSV also gives important information about the mantle rheological nature.

In the first case, the absence of a shallow LSV to the north is in an area where a shallow magma chamber is present, at a depth of about 6 km, also inferred from a significant positive gravimetric anomaly in the complete Bouguer map [17, 68]. In contrast, the absence of a continuous LSV at depth around Linosa is related to the presence of deep magmatic intrusions as indicated by seismic reflection data [10] and to the absence of evolved rocks on Linosa Island indicating a deep magma reservoir [69].

Considering our results, optimizing the localization of earthquakes would be beneficial, thereby improving the accuracy of seismogenic volumes such as those we have produced. Extending the seismic network to include offshore areas could help achieve this goal.

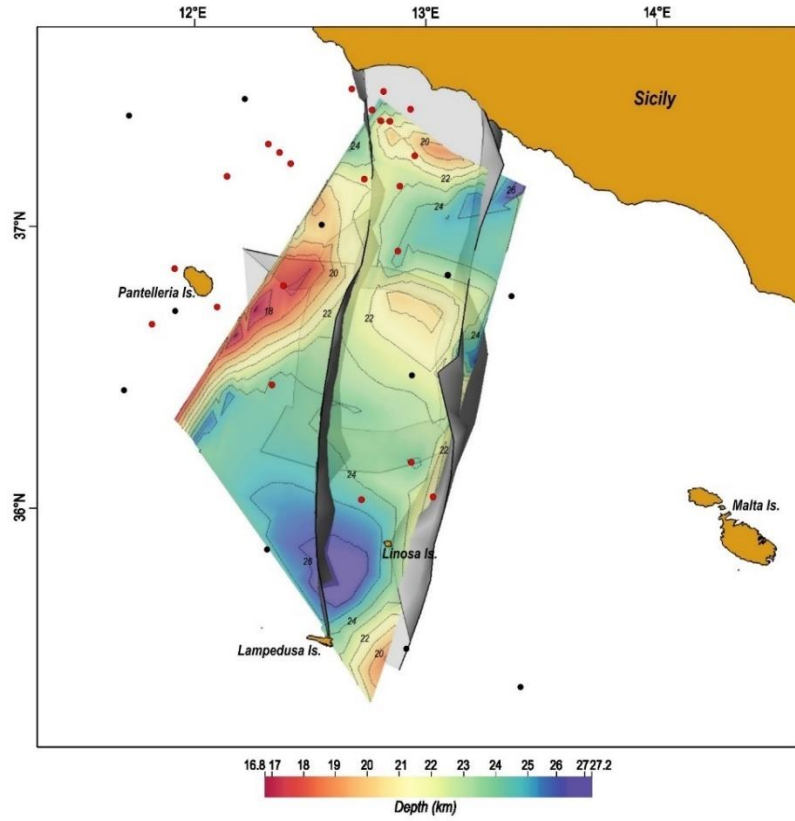


Figure 6. Moho map in depth (color scale) and the LSVs (in grey scale) obtained. The red and black dots represent volcanoes and banks, respectively.

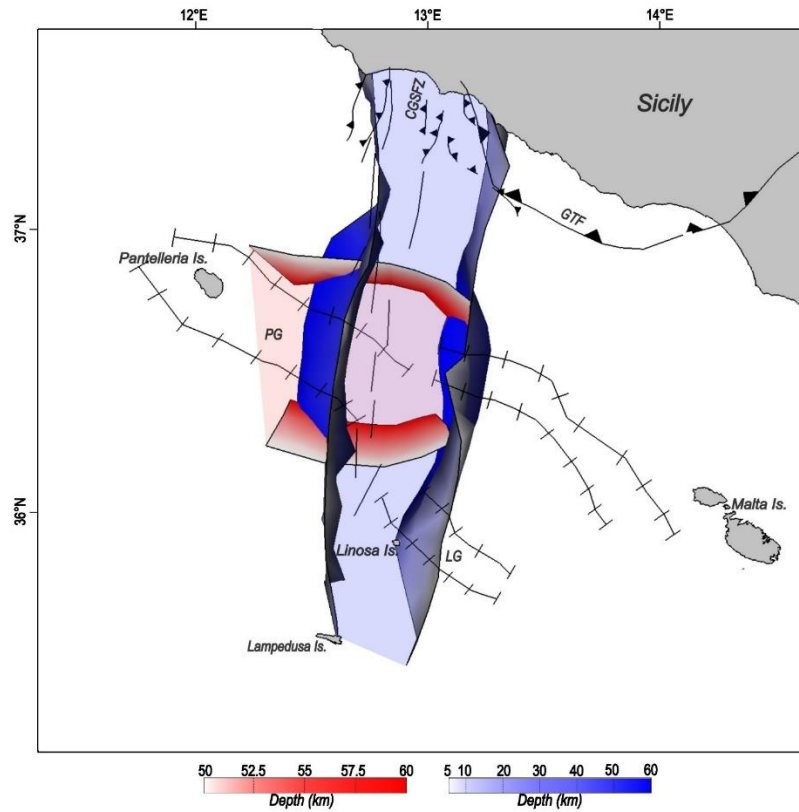


Figure 7. LSVs in plan. LSV with N-S trend, in red scale the LSV with E-W trend. PG (Pantelleria Graben), MG (Malta Graben), LG (Linosa Graben), CGSFZ (Capo Granitola-Sciaccà Fault Zone) [5], GTF (Gela Thrust Front) [54].

In conclusion, our Moho map of the west-central sector of the Sicily Channel represents a fundamental tool for constraining velocity models useful for earthquake localization. This is particularly important because, currently, earthquakes in the Sicily Channel are localized using a single velocity model that covers large areas with varying structural characteristics. Given the difficulty in determining earthquake hypocenters using the current onshore seismic network, one potential solution could be extending the offshore network. Doing so may also provide valuable insights into understanding the mechanisms of formation of sub-Moho seismic events. Moreover, since the E-W trending seismogenic sources extend farther east than the sector we analyzed, it is necessary to extend the analysis to obtain a complete overview of the entire Sicily Channel.

Finally, based on our results, we suggest updating the rheological models proposed in the literature for the Sicily Channel to improve our understanding of the geodynamics and lithospheric structure, which remains still unclear.

4. METHODS

4.1 INTERPRETATION OF SEISMIC REFLECTION PROFILES AND WELL-LOG DATA

We analyzed intermediate to ultra-high penetration seismic reflection profiles and well-logs data derived from ViDEPI (<https://www.videpi.com/videpi/videpi.asp>) and CROP databases [18] (Fig. 2). The CROP (CROsta Profonda) project (<http://www.crop.cnr.it/>) interpreted the deep crust reflection seismic profiles to map the deepest crustal reflectors. The seismic reflection profiles were acquired in collaboration with CNR-ENI and CNR-ENEL from 1988 to 1995 by the RV OGS-Explora using an Airgun array and a 4500 m long and 180-channel streamer. This represents a multidisciplinary geophysical research project aimed at understanding geodynamic processes, assessing geological hazard, and exploring energy resources in Italy. Approximately 10000 km of seismic reflection were acquired (about 1250 km on land and about 8700 km at sea). The dataset is publicly available for consultation (www.videpi.com/videpi/videpi.asp).

The interpretation of the dataset was carried out through a seismo-stratigraphic and structural analysis, applying Vail [70]'s method, and implementing a 2.5D geological model using MOVE Software (Midland Valley). The interpretation of the seismo-stratigraphic horizons was compared with the analysis of the seismic profiles by various authors [18, 71, 72].

Literature data on the localization of volcanic banks [15, 17] were projected on a DEM downloaded from EMODnet (<https://emodnet.ec.europa.eu/geoviewer/#>) (Fig. 1c).

4.2 VELOCITY DATA AND TIME TO DEPTH CONVERSION

We digitized and analyzed, through the 3D modeling software MOVE Software (Midland Valley Ltd.), 5 shear velocity models (V_s) obtained from ambient noise and earthquake tomography method by Kherchuche *et al.* [50], 3 shear velocity models (V_s) inferred from seismic surface waves by Agius *et al.* [56] and a P-wave velocity model inferred from the WARR (Wide-Angle Reflection-Refraction) profiles by Cassinis *et al.* [55] (Fig. 1a).

Initially, we converted shear velocity models (V_s) to P-wave velocity models (V_p) using the relationship between V_p and V_s proposed by Menichelli *et al.* [74] for the study area. Subsequently, we converted these velocity models from depth-to-time through the 3D Time Conversion Tool. In particular, we used the Database method where rock properties, such as the velocity and velocity decay with depth, are assigned to each layer.

We calibrated the P-wave velocity models with seismic reflection profiles. To construct the Moho surface in times (s/TWT), we interpolated- the recognized Moho horizon on each individual profile by Delaunay triangulation method. This method offers the advantage of creating a uniform grid of triangles for better model computation quality, without adding or removing data points from the original dataset. A grid with 4 km x 4 km cells was used for resampling the interpolated surfaces and simplifying it.

For the construction of the Moho surface in depth, we converted velocity models and reflection seismic profiles from time to depth using the 3D Depth Conversion tool and Database method. Velocity values (Tab. 1) extrapolated from literature [18, 41, 72] were used to depth-convert the reflection seismic profiles.

We realized a Moho surface in depth (km) with the same method used for the construction of the surface of the Moho in times (s/TWT).

	M23			M24			M25		
	MIN (m/s)	AVE (m/s)	MAX (m/s)	MIN (m/s)	AVE (m/s)	MAX (m/s)	MIN (m/s)	AVE (m/s)	MAX (m/s)
Water	1500	1500	1500	1500	1500	1500	1500	1500	1500
Seabed	1574	1659,57	1887	1615	1983,93	2718	1770	2032,14	1977
GTF	4036	4036	4036	4036	4036	4036	N.A.	N.A.	N.A.
Oligo-Miocene	1160	1851,33	2545	1657	2094,92	2859	1618	2104,93	3290
Meso-Cenozoic	5300	5600	5800	2030	2879,45	3966	1997	2975,91	3951
Upper Crust	6000	6000	6000	6000	6000	6000	5788,94	6090,47	6392
Lower Crust	6800	7100	7400	7000	7000	7000	7000	7000	7000
Crust/mantle discontinuity	7700	7922,67	8068	8000	8000	8000	8000	8000	8000

Table 1. Velocity values obtained for each layer detected in the CROP seismic reflection profiles. Values derive from sonic logs (Egeria and Palma) analysis, interval velocities tables of the seismic profile, and Vp velocities from Cassinis *et al.* [55] and Agius *et al.* [56].

4.3 ANALYSIS OF EARTHQUAKES

We considered seismic events from 2005 to 2023 extrapolated from the ISIDe [75] database, which contains the parametric data of all seismic events localized by the INGV. To extend the dataset's temporal range, we also included earthquakes from 1981 to 2018, extrapolated from the CLASS (Catalogo delle Localizzazioni ASSolute) catalog [76], which contains earthquakes with optimized localizations. For this reason, we removed from the ISIDe catalog those earthquakes with the same ID as the events from 2005 to 2018 in the CLASS catalog.

Our research was conducted in the area between latitudes between 35.2° and 38.2° N and longitudes between 11.5° and 13.6° E. The location of epicenters on a horizontal plane and vertical planes of this dataset that we created is shown in Figure 1a. The same figure also shows focal mechanisms of the major events, extrapolated from Time Domain Moment Tensor (TDMT) dataset [53].

At first, we calculated the magnitude of completeness (Mc) of the dataset created using the MAXimum Curvature method (MAXC) [76] implemented in the Tremors software-app [77] and we captured STAI (Short-term aftershock incompleteness) periods using the same software-app to avoid overestimation of Mc.

We implemented a MATLAB code to organize the obtained database of earthquakes into 10-km depth ranges with a 50% overlap. We then analyzed these data through a statistical approach using the R statistical software [78], a language and environment for statistical processing and graphics. We chose this open-source software because it allows processing a large set of data, it is possible to customize packages, it has a wide range of libraries, it can be easily run on Windows, Linux, and Mac, and it is an evolving programming language.

We implemented a code on R statistical software using a Kernel smoothed intensity function from a point pattern with 0.01 x 0.01-pixel grid to obtain a density plot of the seismicity for each of these depth ranges.

The Kernel smoothing estimator for intensity is a valid approach for modeling a highly heterogeneous spatial distribution. Intensity is a function of spatial location, and this is the expected number of random points per unit area. The intensity estimate has been computed with a *Gaussian* Kernel function and bandwidth chose with the rule of thumb by Scott [79]. The latter determines the width of the window within which the points affecting the calculation of the intensity estimate are located.

In addition, in the computation of density plots, we assigned weights to each seismic event based on magnitude. Specifically, since the energy of an earthquake increases exponentially as the magnitude increases, we assigned an exponentially increasing value for each increasing value of magnitude.

The functions employed here are found in the *raster* [80] and *spatsat* [81] packages of the R statistical software.

For each density plot calculated for each depth range, we obtained the density gradient. Finally, we extrapolated the isolines of the maximum values of the density gradient, interpolated them using the Delaunay triangulation method, and obtained two perpendicular pairs of vertical surfaces bordering two Lithospheric Seismogenic Volumes (LSVs).

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AUTHOR CONTRIBUTIONS STATEMENT

S.B, M.M.: data analysis and interpretation of results, review of literature data, preparation of the figures, writing the main text of the manuscript; A.S.: interpretation of results, initial idea, work planning and review of the manuscript; R.M, A.D.: work planning and review of the manuscript.

DATA AVAILABILITY

The source of the datasets used in this paper are cited in the paragraph ‘Data and Methods’.

ADDITIONAL INFORMATION

Competing Interests: All authors declare that they have no conflicts of interest.

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2.3 IS THE SICILY CHANNEL A SIMPLE RIFTING ZONE? NEW EVIDENCE FROM SEISMIC ANALYSIS WITH GEODYNAMIC IMPLICATIONS



Is the Sicily Channel a simple Rifting Zone? New evidence from seismic analysis with geodynamic implications

Mariagiada Maiorana^{a,*}, Andrea Artoni^b, Eline Le Breton^c, Attilio Sulli^a, Nicolò Chizzini^b, Luigi Torelli^b

^a Department of Earth and Marine Sciences, University of Palermo, Via Archirafi 22, 90123 Palermo, Italy

^b Department of Chemistry, Life Sciences and Environmental Sustainability University of Parma, Parco Area delle Scienze, 157/A, Parma, Italy

^c Department of Geosciences, Freie Universität Berlin, Berlin, Germany

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ABSTRACT

The Sicily Channel is characterized by the presence of prominent WNW-oriented grabens (Pantelleria, Malta, Linosa Graben) which would point out a main extensional phase within this part of the northern African plate. However, the analysis of both seismic and wells data shows evidence of tectonic reactivation and contractional events in a N-S oriented band crossing the Gela Thrust System and the Malta and Linosa Grabens. We present and discuss the timing of the different deformation phases and their potential geodynamic framework with regard to the regional Africa and Europe convergence. We suggest four main deformation phases affecting the Sicily Channel in Neogene time: 1) a contractional phase, related to the thrusting of the Sicily Fold-and-Thrust Belt in the Upper Miocene, related to the evolution of the regional Western Mediterranean Subduction Zone, 2) an extensional phase with the opening of the main grabens in Lower Pliocene, related to the fast rollback of the Calabrian Slab to the East-Southeast of the Sicily Channel, 3) a Plio-Pleistocene contractional phase with inversion structures within the grabens and onset of transpressive deformation along the Capo Granitola-Sciacca Fault Zone (CGSFZ) and Scicli Ragusa Fault System (SRFS), related to the advance of the Gela Thrust System, and 4) a presently active, mild contractional phase affecting the area between the CGSFZ and SRFS, in particular the Malta and Linosa Graben, which might be related to a regional plate reorganization and potential subduction polarity switch north of Sicily.

1. Introduction

The “Sicily Channel Rift Zone” (SCRZ; [Finetti, 1984](#)) is considered a great example of passive rifting that occurred during the Lower Pliocene ([Reuther and Eisbacher, 1985](#); [Boccaletti et al., 1987](#); [Cello, 1987](#); [Civile et al., 2010](#)) in the Mediterranean area. It is widely known that crustal thinning and the formation of the WNW-oriented graben of Pantelleria, Linosa and Malta, which form the SCRZ, here coexist with the Sicilian Fold and Thrust Belt (Gela Thrust System), an expression of the Africa-Europe convergence ([Fig. 1](#)). The presence of both extensional and contractional structures has been demonstrated and analyzed by several authors (e.g., [Finetti, 1984](#); [Civile et al., 2010](#); [Civile et al., 2021](#); [Sulli et al., 2021](#)). The Sicily Channel is therefore a key area to study coexisting, diverse tectonic and geodynamic processes.

The convergence of the European and African plates was associated with southward roll-back of the African slab in the Western-Central

Mediterranean, causing the opening of the Tyrrhenian back-arc basin in the overlaying plate ([Faccenna et al., 2001a, 2001b](#); [Corti et al., 2006](#)) contemporaneously with the formation of several extensional structures in the Sicily Channel ([Argnani, 1990](#)) in Mio-Pliocene times. A passive rifting process is widely accepted to explain the extensional structures and the local crustal thinning of the Sicily Channel but in the frame of not complete coverage of seismic crustal data ([Finetti, 1984](#); [Civile et al., 2010](#); [Civile et al., 2021](#)). Many authors suggest that the extension was induced by two dextral strike-slip faults, which led to the formation of pull-apart basins ([Jongsma et al., 1985](#); [Reuther and Eisbacher, 1985](#); [Boccaletti et al., 1987](#); [Catalano et al., 2009](#)). Instead, [Argnani \(1990\)](#) and [Argnani \(2009\)](#) suggested that the rifting process was triggered by mantle convection developed during the roll-back of the African slab beneath the Tyrrhenian Basin. In particular, they considered the crustal stretching of the SCRZ to be caused by slab-pull forces, the consequent trench retreat and roll-back, and, ultimately, the break-off of the slab.

* Corresponding author.

E-mail address: mariagiada.maiorana@unipa.it (M. Maiorana).

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Furthermore, among the most recent hypothesis, Arab et al. (2020) linked the extension of the Sicily Channel to the presence of a subduction transform edge propagation (STEP) fault or eastward slab tearing within the African continental lithosphere (Tunisian-Atlas Tear) segmenting the northward subducting African slab and facilitating the slab-retreat (Govers and Wortel, 2005; Rosenbaum et al., 2008). Other authors, such as Corti et al. (2006), consider however the accretion of the Sicilian Maghrebian chain and rifting in the Sicily Channel as two independent tectonic processes acting simultaneously.

In addition to the various hypotheses proposed to explain the extension in the Sicily Channel, local variations of the African continental crust thickness need to be considered. The latter shows a medium

value of 25–30 km in the Mediterranean area (Finetti, 1984; Finetti and Del Ben, 2005; Micallef et al., 2019) and it decreases to 12–15 km at the current Gela Front, which is more advanced than the surrounding areas due to a less thick crust (Catalano et al., 2000; Civile et al., 2008). Seismic and gravimetric data also shows that the crust is less than 20 km (with local Moho's rising) in the Pantelleria, Linosa, and Malta basins (Scarascia et al., 1994; Finetti and Del Ben, 2005; Agius et al., 2022). Much uncertainty in this area relates to the timing and the causes of positive inversions in the Sicily Channel area (Civile et al., 2008). In the onshore sector, the presence of an active convergence between Europe and Africa has led to the development of north-verging thrusting in the northern Sicily continental margin (Sulli et al., 2021). Instead, in the

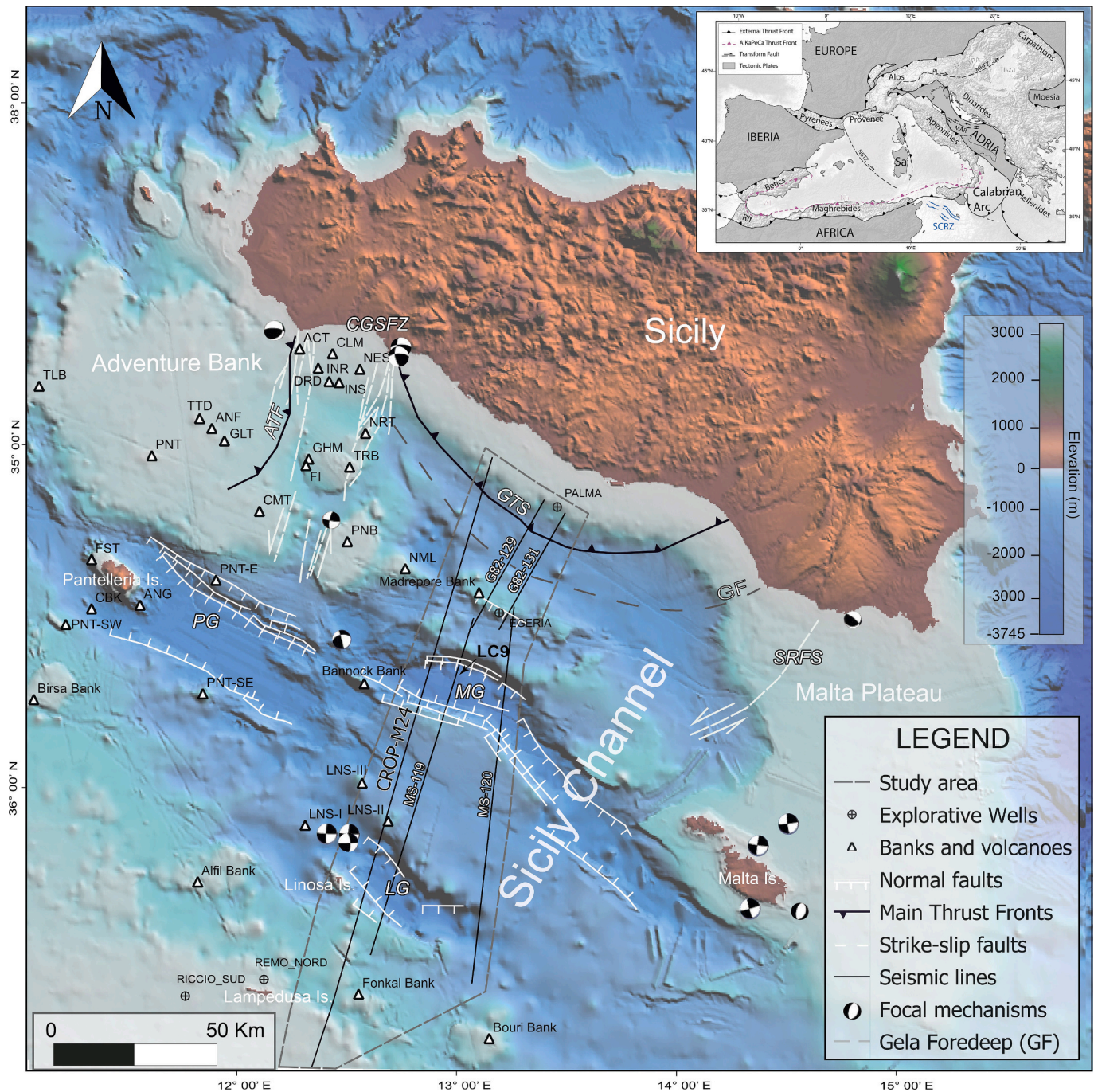


Fig. 1. Bathymetric data from GEBCO (<https://www.gebco.net/>) showing the main morphological and structural elements. 1: Adventure Bank; 2: Graham Bank; 3: Pantelleria Bank; 4: Talbot Bank; 5: Birsa Bank; 6: Alfil Bank; 7: Fonkal bank; 8: Bouri bank; 9: Malta Plateau; 10: Madrepore Bank; 11: Falda di Gela; 12: Gela Basin; 13: Malta Graben; 14: Linosa Graben; 15: Pantelleria Graben; 16: Nameless Bank; 17: Linosa Plateau.

offshore sector, [Cavallaro et al. \(2017\)](#) linked the evidence of a positive tectonic reactivation in this area to the onset of a complex poly-phasic advancing of the Gela Thrust System whose deformation extends to the north-central sector of the Sicily Channel. But it has not been detected how far in the Sicilian offshore this compression extends. This work aims to delineate the distribution and the chronology of the compressive and extensional geological events along a N-S-oriented band crossing the central Sicily Channel, from the Gela Thrust System to the Linosa Graben ([Fig. 1](#)) in order to outline the main driving forces and improve the knowledge about the geodynamic framework that shaped the study area.

2. Geological setting

2.1. Tectonic setting

The Sicily Channel area ([Fig. 1](#)) is located in the foreland area of the Sicilian Fold and Thrust Belt which formed due to the convergence between the European and African Plates. For a better understanding of the geodynamic setting of the Sicily Channel, it is necessary to consider the tectonic evolution of the Central Mediterranean area. A phase of divergence between Europe and Africa led to the opening of the Alpine Tethys Ocean in the Mesozoic ([Catalano and D'Argenio, 1982](#); [Jongsma et al., 1985](#); [Stampfli, 2005](#); [Handy et al., 2010](#); [Van Hinsbergen et al., 2020](#); [Le Breton et al., 2021](#)). This event was followed by the closure of the Alpine Tethys, starting in Cretaceous time, which caused the dissection of the preexisting domains ([Catalano and D'Argenio, 1982](#); [Casero et al., 1984](#); [Antonelli et al., 1988](#); [Catalano et al., 2000](#); [Basilone, 2009](#)). A second extensional event characterized by a diffuse extension in the Sirte and Tripolitania Basin of Tunisia occurred in the Lower Cretaceous and was related to a major rifting event in Central Africa ([Stampfli et al., 2001](#)). In the Upper Cretaceous-Middle Eocene, the Central Mediterranean was dominated by a NW-SE-oriented compressive stress field ([Antonelli et al., 1988](#); [Torelli et al., 1995](#)) coeval to a change in African Plate motion that started to move towards the North, due to the opening of the South Atlantic ([Stampfli and Borel, 2002](#); [Stampfli, 2005](#); [Handy et al., 2010](#); [Van Hinsbergen et al., 2020](#); [Le Breton et al., 2021](#)). During the Upper Oligocene-Lower Miocene, the rollback of the Western Mediterranean subduction resulted in upper-plate extension, opening of the Liguro-Provençal Basin and counter-clockwise rotation of the Sardinia-Corsica, coevally to the accretion of the Sicilian Fold and Thrust Belt ([Speranza et al., 2018](#)). The evolution of the Mediterranean area was abruptly marked in the Late Messinian by the isolation of the Mediterranean basin from the Atlantic; this event was called the "Messinian Salinity Crisis" ([Hsü et al., 1973](#); [Butler et al., 1995](#); [Andreotto et al., 2021](#)). The sedimentation of considerable width and locally very thick, up to 3 km, of evaporative deposits, allows us to have a seismic marker of the Messinian age in the entire Mediterranean basin ([Lofi et al., 2011](#); [Roveri et al., 2014](#); [Haq et al., 2020](#)). During the Messinian Salinity Crisis, most of the banks/seamounts of the Sicily Channel emerged and underwent a diffuse erosion ([Civile et al., 2015](#)). Later, during the Lower Pliocene, an extensional event led to the formation of the Malta, Linosa, and Pantelleria WNW-ESE-oriented depressions ([Grasso and Torelli, 1999](#); [Carminati and Doglioni, 2005](#); [Civile et al., 2010](#); [Ghielmi et al., 2012](#); [Civile et al., 2021](#)) ([Fig. 1](#)). The closeness of the Sicilian Fold and Thrust Belt is considered to be the cause of the local superposition of contractional structures on the pre-existing extensional system in the north-central sector of the Sicily Channel ([Cavallaro et al., 2017](#)). However, even in inland Sicily and inside the fold-and-thrust belt, north-verging thrusts and double-verging thrust systems have been recently evidenced and documented as back-thrusting ([Sulli et al., 2021](#)).

2.2. Morphostructural setting

Within the Sicily Channel, several morphostructural highs and basins

can be observed ([Fig. 1](#)). Offshore Sicily, the first morphological element is the Adventure Bank to the west ([Fig. 1](#)), which is a wide shallow platform occupied by the outermost front of the Sicilian Fold and Thrust Belt, called the Adventure Thrust Front (ATF in [Fig. 1](#); [Argnani, 1990](#)) and its foredeep, the Adventure Foredeep (AF in [Fig. 1](#); [Antonelli et al., 1988](#); [Argnani, 1990](#)). The AF is affected by a regional tectonic structure named the Capo Granitola-Sciacca Fault Zone (CGSFZ in [Fig. 1](#)). The CGSFZ is a wide structure developed in the Lower Pliocene that shows a left-lateral kinematic movement active in the Quaternary period ([Civile et al., 2018](#)). To the East, the Gela Foredeep (GF in [Fig. 1](#)) is a Plio-Quaternary foredeep developed in front of the south-verging Plio-Pleistocene Gela Thrust System (GTS; [Argnani, 1990](#); [Butler et al., 1992](#); [Catalano et al., 2013](#); [Lickorish et al., 1999](#)). East of the GTS, the Malta Plateau forms another shallow shelf zone ([Todaro et al., 2021](#)), which hosts the Scicli Ragusa Fault System (SRFS in [Fig. 1](#)), a wide structure showing also a left-lateral movement in the last 0.85 Ma ([Catalano et al., 2008](#)). In the central part of the Sicily Channel, the Pantelleria (PG), Malta (MG), and Linosa (LG) grabens form distinct WNW-ESE-oriented narrow (c. 10–25 km wide) and elongated (c. 50–120 km long) morphostructural features. Spread throughout the area, extending to the limit to the Tunisian continental shelf, several small seamounts and seamount-like structures are observed ([Fig. 1](#); [Aissi et al., 2015](#)).

2.3. Magmatism

Throughout the Sicily Channel, magmatic manifestations are widespread ([Fig. 1](#)) and have long been investigated through seismic reflection profiles and bathymetric data. The oldest magmatic activity is registered by [Beccaluva et al. \(1981\)](#) in the Nameless Bank (NML in [Fig. 1](#)) in the late Miocene (9.5 ± 0.4 Ma). The main volcanic manifestations of the Sicily Channel that occurred in the Plio-Pleistocene during the Sicily Channel's extension are registered in the Graham and Terrible Bank (GHM and TRB in [Fig. 1](#)). Volcanism is mainly concentrated in Pantelleria and Linosa islands ([Lodolo et al., 2012](#)). In fact, the Pantelleria island consists of a volcanic building that develops partly above sea level. Some volcanic seamounts (e.g. Angelina, ANG in [Fig. 1](#)) extend around the Pantelleria Graben axis suggesting a volcano-tectonic origin ([Civile et al., 2010](#); [Lodolo et al., 2012](#)). The Linosa island, which emerged in the Quaternary age, shows volcanic activity dated from 1.06 to 0.5 Ma ([Lanzafame et al., 1994](#)) with an alkaline composition on the outcropping rocks ([Romagnoli et al., 2020](#)). and a main NW-SE trend. Near Linosa several volcanic centers occur, e.g. Linosa I, II, III (LNS I, II, III in [Fig. 1](#); [Lodolo et al., 2012](#)). Indeed, recent bathymetric data reveal that the emergent part of Linosa represents only about 3.6% percentage of the entire volcanic complex (about 165 km²). This shows how much uncertainty there still is about the submarine extension of the volcanic product of the area ([Tonielli et al., 2019](#)). Among the most recent magmatic manifestations, six volcanic edifices were formed following a tectonic event that occurred near the CGSFZ ([Fig. 1](#)). Their magmatic activity is dated pre-Last Glacial Maximum (LGM, ca. 20 ka B.P.), except for Actea volcano (ACT, [Fig. 1](#)), which shows post-LGM volcanism ([Lodolo et al., 2019](#)). Other important and recent eruptions are the ones that occurred in 1831 in the Graham Bank of Ferdinanda Island (FI in [Fig. 1](#)) and in 1981 near Pantelleria Island, approximately 5 km NW of the island ([Washington, 1909](#)).

2.4. Seismicity

The Sicily Channel's seismicity has been generally related to the several tectonic processes coexisting in the area, in particular to the Europe-Africa convergence. Seismic activity in the Sicily Channel area is considered moderate, despite the complex setting. Different focal mechanisms available by the INGV database ([ISIDE Working Group, 2007](#); https://emidius.mi.ingv.it/CPTI15-DBMI15/query_place/) highlight a widespread strike-slip type of movement ([Palano et al., 2012](#); [Fig. 1](#)). Seismological studies show the presence of two main seismic

fault zones in Sicily, respectively to the east and the west of the Gela Thrust System, extending offshore into the Sicily Channel. The first to the west has a NNE-SSW direction, from Sciacca to Linosa island, and corresponds to the CGSFZ (Fig. 1; Civile et al., 2018; Ferranti et al., 2019; Civile et al., 2021). In this sector, it is also documented the presence of several earthquakes with a left-lateral strike-slip deformation, volcanic manifestation and high heat flow (Palano et al., 2020). Geochemical and seismic evidence shows that this system develops down to the upper mantle (70 km depth), involving a lithospheric discontinuity that could not be related to a rifting process (Caracausi et al., 2005; Calò and Parisi, 2014). The other fault zone to the east of the Gela Thrust System, is the Scicli Ragusa Fault System (SRFS), which develops from the southeastern sector of Sicily, from Ragusa to the Sicily Channel offshore, with an undetermined length (Fig. 1). A left-lateral strike-slip activity has been detected in the whole fault zone (Catalano et al., 2008), and is related to the development of both restraining and releasing bends geometries between the distinct en-echelon segments (Grasso and Reuther, 1988). Moreover, in the Maltese archipelago focal mechanisms of recent earthquakes show evidence of right-lateral strike-slip faults (Fig. 1) (Micallef et al., 2019).

2.5. Geodetic data

The convergence between Africa and Europe, based on GPS measurements, has an average rate of 4–5 mm/yr (Sulli et al., 2021). The available data of the different GPS stations of Sicily (Fig. 2) show a higher velocity in the SE, at the NOTO station, with an average value of

4.7 mm/yr and a NNW direction. In the NW sector of Sicily, the MILO station, shows an average velocity of 3.6 mm/yr, with a NNW direction (Hollenstein et al., 2003; D'Agostino and Selvaggi, 2004; Serpelloni et al., 2005; Devoti et al., 2011; Palano et al., 2012; Sulli et al., 2021). GPS data acquired in the Sicily Channel indicate that Pantelleria (PZIN) moves towards SSE with a 2.95 mm/yr medium rate and Lampedusa (LAMP) moves towards SSE with a 1 mm/yr velocity (Fig. 2). Malta (MALT) moves towards NNW (Fig. 2) with an average rate of 1.5 mm/yr (Palano et al., 2012). These movements imply an ongoing convergence between the two islands with a NW-SE convergence and a NE-SW stretching direction between Lampedusa and Malta (Meccariello et al., 2017).

2.6. Gravimetric anomalies

The highest positive anomaly in the Sicily Channel was detected near the Pantelleria depression, with a value of +70 mgal (Fig. 2) (Sandwell et al., 2013). Other highest values, +60, and +65 mgal (Fig. 2), are recorded in the areas of Nameless Bank, Graham Bank and Adventure Bank (Sandwell et al., 2013). Those anomalies, also linked to magnetic anomalies, have been associated to the presence of buried magmatic bodies (Lodolo et al., 2012) which has been linked to a Moho's rising at relatively shallow depths below them, up to 17–18 km (Finetti and Del Ben, 2005; Civile et al., 2008). Negative values of Bouguer's anomaly, −40 mgal, are recorded in correspondence to the Gela Thrust System (Sandwell et al., 2013) (Fig. 2). This has been related to a Moho deepening up to 36 km depth beneath the Gela Thrust System (Finetti and Del

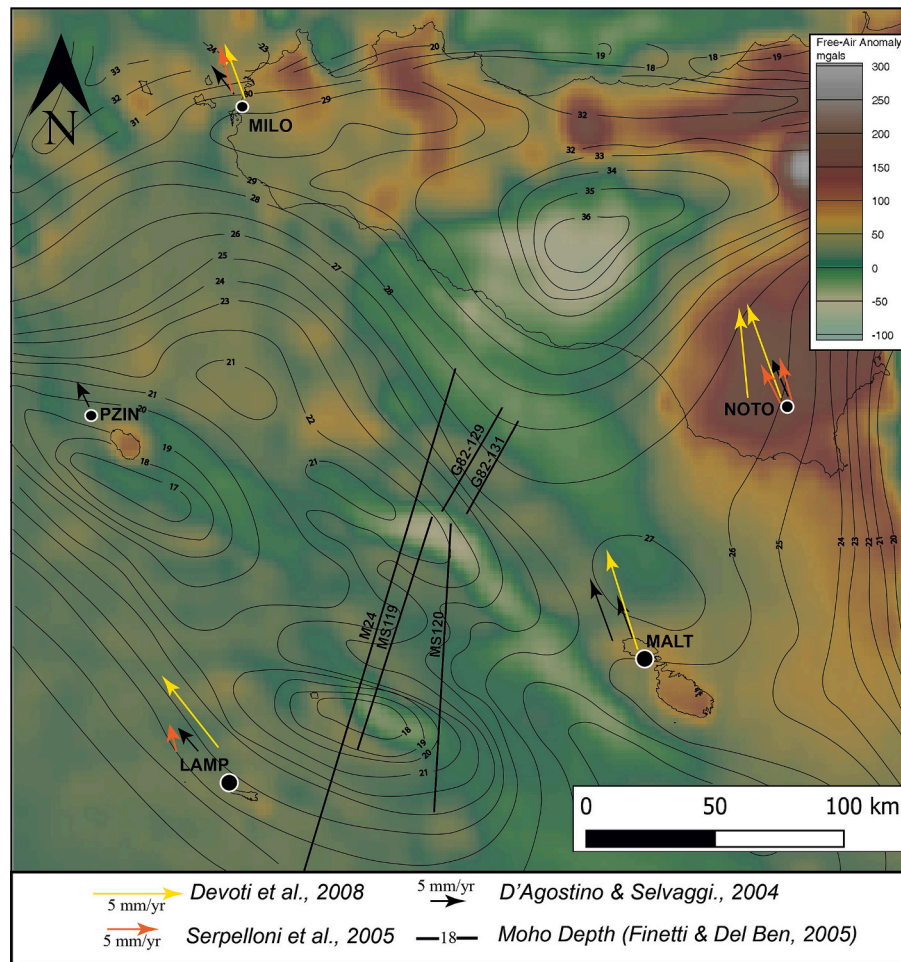


Fig. 2. Map showing gravimetry model from Sandwell et al. (2013), Moho contour lines, and available data of the different GPS stations of the study area GPS velocity vectors with respect to Eurasia according to different authors; the location of the analyzed seismic reflection profiles is also reported.

Table 1

Recording parameters for MS119, MS120, G82–131 01–04, G82–129, M24 lines.

Lines	MS 119,120
Recording date	Aug.-Sep. 1980
Sample rate	4 ms
Tape format	SEG-B/9 TRACKS
Filters	Low cut 8 Hz
	High cut 62 Hz
	Notch IN
Gain	Alias 62 Hz
	IFP
Streamer	Contant 24 dB
Gable length	Seco-multidyne
Number of traces	2350 M
Group interval	48
Hydrophone group	50 m
	46
Group length	100 m
Deep of streamer	20 m
Energy source	Flexotir
Filter	8/12–62 Hz
Coverage	1200 x

Line	M24
Recording date	November 1993
Sample rate	4 ms
Shot interval	50 m
Recording length	1700 ms
Filters	High cut 77 Hz
Group interval	25 m
Group	120
Depth	8 m
Energy source	Air Gun
Coverage	30-fold

Lines	G82–131 01–04, G82–129
Recording date	May 1982
Sample rate	2 ms
Tape format	SEG-B/9 TRACKS
Filters	Low cut 8 Hz
	High cut 128 Hz
	Notch IN
Group interval	25 m
Group	96
Depth	6.5 m
Energy source	Air Gun
SP interval	8/12–62 Hz
Coverage	1200 x

Ben, 2005).

3. Materials and methods

3.1. Materials

To achieve the goals of this study, data collected by the ViDEPI (Visibility of petroleum exploration data in Italy) Project have been analyzed (<https://www.videpi.com/videpi/videpi.asp>) where well-logs and reflection seismic data are available. More specifically, we used seismic data from the CROP Project (Deep Seismic Exploration of the Central Mediterranean and Italy; <http://www.crop.cnr.it/>) and from reconnaissance seismic campaigns of Italian offshore areas (Zone G) acquired by AGIP, on behalf of the Italian State. The CROP marine dataset was performed from 1988 to 1995 by the RV OGS-Explora with an Airgun array and a 4500 m long and 180-channel streamer (Finetti and Del Ben, 2005). The profiles of the G dataset were acquired with the Airgun with a sampling interval of 4 ms (250 Hz), a 6–7 s acquisition

Table 2

Processing parameters for MS119, MS120, G82–131 01–04, G82–129, M24 lines.

Lines	MS120, MS122
Processed length	10–12 s
Sample rate	4 ms
Pre-processed	CDP GATHER
T.V. deconvolution	3 zones
Velocity A.N. location	N.M.O. corr. and 12-fold stack
Display	Wiggle V.A. 2.5 in./s. 25 traces

Lines	G82–131 01–04, G82–129
Trace merging	5/4
Resample	4 ms
Air gun delay	51 ms
Length	200 ms
Stack	4800
Time variant filters	12/65 Hz
	4/98 Hz
Traces	80/km

Line	M24
Resample	8 ms
Channel reduction	To 90
F-K Filter	2–12 ms
Analysis interval	15 km

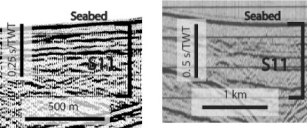
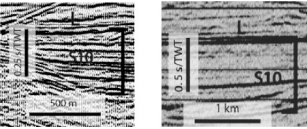
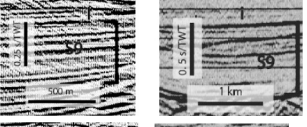
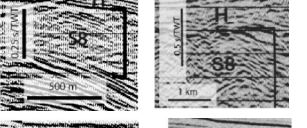
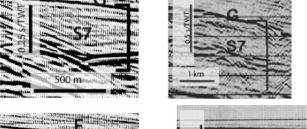
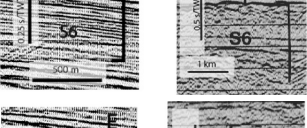
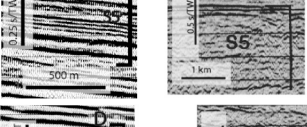
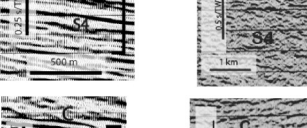
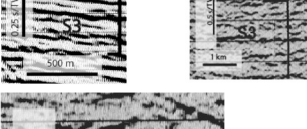
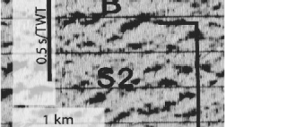
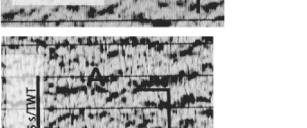
window and 4800% coverage and 1:25000 scale (ViDEPI). Data derived also from the Mediterranean Sea project (MS) that covered extensive areas of the Mediterranean Sea, performed by the Osservatorio Geofisico Sperimentale (OGS) of Trieste from 1969 to 1982 were also analyzed (Finetti and Morelli, 1973a, 1973b). In order to improve the quality of some seismic reflection profiles, we realized a conversion from ViDEPI PDF seismic profile to SEG-Y format by using Tif2seggy tool. Further, migration has been applied through SeisUnix software, to reduce diffraction hyperbolae zones. The seismic reflection profiles presented in this work (location on Fig. 1) and their recording and processing parameters are reported and Table 1 and Table 2. CROP M24, a high penetration seismic reflection profile has been analyzed to constrain the crustal setting of the area. The wells Egeria and Palma were used to constrain the stratigraphy of the northern part of the study area. Otherwise, Riccio Sud and Remo Nord wells were analyzed to constrain the stratigraphy of the southern part of the study area. The LC9 sampling (Fig. 1), by Reeder et al. (2002), defines the characteristics of the shallow filling of the Malta Graben, up to 26 m b.s.l.. In detail, it shows the presence of volcanic tephra at about 9 m deep, and the presence of faults from 15 to 18 m deep.

3.2. Methods

3.2.1. Interpretation of seismic reflection profiles: Seismo-stratigraphic and structural analysis

An interpretation of the seismic reflection profiles has been carried out using dedicated graphic design programs. Different seismic facies have been identified by reflection attributes such as amplitude, frequency, and lateral continuity as well as their lateral terminations (onlap, downlap, toplap) and reflection patterns following the seismic reflection profile interpretation technique (Vail, 1987; Hart, 2010). The most continuous and geologically meaningful, as derived after well-log calibration, reflectors have been mapped and the units have been correlated with the Egeria, Palma, Riccio Sud, and Remo Nord wells. The seismic stratigraphic analysis has been based on the identification of different characteristics of the reflections; namely amplitude, frequency, continuity, and configuration patterns (parallel, divergent, etc.) according to the procedure described in Mitchum et al. (1977). Different

Table 3Seismic facies and topping horizons definition and description of the main seismic lines based on [Vail \(1987\)](#) method.

Seismic Facies/ Topping horizon	Description	Seismic signal
S11/Seabed	Reflectors with high amplitude, low frequency, and parallel (locally chaotic) geometry, with onlap termination on S10 facies.	
S10/L	Reflectors with medium amplitude, medium/low frequency, and parallel geometry, with onlap termination on S7 facies. In the Linosa Plateau sector, the reflectors show high amplitude, low frequency, and an oblique parallel reflection configuration with a downlap termination on the S9 facies.	
S9/I	Reflectors with medium amplitude, low frequency, and parallel geometry, with onlap termination on S7 facies.	
S8/H	Chaotic reflectors with a transparent signal upwards. This facies shows a convergent geometry in the Malta Graben, Linosa Graben.	
S7/G	Reflectors with high amplitude and low frequency, with a locally chaotic configuration interrupted by semi-transparent zones.	
S6/F	Facies with high frequency, low amplitude and a parallel configuration. Locally interrupted by diffraction hyperbola zones. Locally it shows an erosive truncation.	
S5/E	Reflectors with high-medium amplitude, high continuity, high frequency and a parallel configuration. Frequently interrupted by diffraction hyperbola zones and dissected by several normal faults.	
S4/D	Reflectors with high amplitude, high continuity, medium frequency, and a subparallel configuration. Locally with chaotic configuration. Frequently interrupted by diffraction hyperbola and dissected by normal faults.	
S3/C	Layered signal, with high-medium amplitude, medium continuity, low frequency, and a subparallel configuration, frequently interrupted by diffraction hyperbola zones.	
S2/B	Poorly layered signal, with medium amplitude, low continuity, low frequency, and a subparallel configuration, locally interrupted by diffraction hyperbola zones.	
S1/A	Discontinuous signal, with high amplitude, low frequency, and a chaotic configuration; topped by double high-amplitude reflections, locally interrupted by diffraction hyperbola arranged in a mound-shaped body.	

seismic facies, bounded by 11 key reflections named A-L and including seafloor reflection, have been identified in the analyzed seismic profiles. These seismic facies are reported in Table 3. The key reflectors are used as markers to identify structural features deforming the Sicily Channel.

3.2.2. Depth-to-time conversion of selected well-logs

In order to constrain the seismo-stratigraphic interpretation, the Egeria and Palma wells were projected onto the closest seismic reflection profiles (G82–131, G82–129, M24; Fig. 1). The wells could be projected in time because of the sonic log velocities reported in the final log. In Tables 1–4 of Suppl. Mat., the well-logs data of thickness, lithology, and depth for each lithological unit and the interval velocity obtained from the average microsec/ft. in the sonic log are reported. Instead, Riccio Sud and Remo Nord, with no sonic log, were depth-converted using standard velocities for each lithology (Christensen and Mooney, 1995) (Suppl. Mat., Table 5) and then projected onto the CROP M24 seismic lines.

3.2.3. Seismic reflection profiles calibration and well-tie

The reflectors with the highest contrasts in acoustic impedance were compared to the major lithological contacts/changes reported in the well-logs. This comparison allowed us to verify the corresponding position of the main stratigraphic contacts in the time domain. This step was needed to calibrate the seismo-stratigraphic units and the main horizons identified in the seismic lines. The well-logs calibration was integrated with literature data and the lateral variability of the stratigraphic units was evidenced by stratigraphic correlations among the four wells available after establishing a comparative table of stratigraphic successions known on the Tunisian margin and in inland Sicily (Table 6 in Suppl. Mat.). The seismic calibration was mainly based on the stratigraphic logs of the Palma, Egeria, Riccio Sud, and Remo Nord's wells (Fig. 3). Once the wells were located on the closest seismic reflection profiles, each horizon was identified and traced in the profiles and over the maximum extent of the survey (Fig. 4).

4. Results

The recognized seismic facies (Table 3), well-log stratigraphic correlation (Fig. 3), well-log tied to seismic reflection profiles, seismo-stratigraphic and structural interpretation (Figs. 4–11) are presented below. The shallow portions (down to ~3 s) were calibrated with the well-log data, while the interpretations of the deep portions are mainly based on the M24 seismic line and the literature data (Finetti and Del Ben, 2005).

4.1. Seismic facies, seismo-stratigraphic units, and well-tie

The lowermost seismic facies (S1) detected in the CROP M24 seismic line, is marked at the top by double high-amplitude reflections (A) (Table 3). Horizon A shows low continuity and high reflectivity, it is located at an average depth of 11.4 s/TWT (Table 3, Figs. 4, 5). The seismic facies S1 shows widespread hyperbolae zones with a mound-shaped body arrangement that is concentrated in correspondence of the Linosa and Malta Grabens, interrupting the lateral continuity of the signal (Table 3, Figs. 4, 5). There the Horizon A also shows a mild rising to 10 s/TWT and it deepens towards the Gela Thrust System down to 12.8 s/TWT (Fig. 4). The overlying seismic facies (S2) appears poorly layered and topped by the Horizon B, which shows high amplitude and discontinuous reflector (Table 3, Figs. 4, 5). It appears at an average depth of 6 s/TWT and deepens to 11 s/TWT towards the Gela Thrust System (Fig. 4). Like the previous seismic facies, it is locally interrupted by a mound-shaped body rich in hyperbola, attributed to fluid rising based on similar signals highlighted in literature data (ex. Tonga Trench, Bally, 1983). Reflector A has been identified as the Moho surface while the Horizon B (Table 3, Figs. 4, 5) has been attributed to the top of the Upper Crust; as deep drills and logs are missing, this attribution was

based on literature data (Finetti and Del Ben, 2005; Scarascia et al., 1994) and seismic attributes analysis. The following seismic facies have been calibrated with well-log data (Suppl. Mat. Table 1–4) and projected onto the seismic lines. The S3 facies is bounded at the top by the Horizon C, which corresponds to the top of the Jurassic formations (Buccheri Fm., Nara Fm., Sidi Kralif Fm.) (Fig. 3 and Table 6 Suppl. Mat.). Horizon C appears to be affected by several normal faults and is locally interrupted by diffraction hyperbola mounds, attributed to magmatic intrusions based on the seismic signal and the Egeria's well-log evidence (Fig. 3).

The facies S4 is topped by Horizon D which is a high amplitude reflector (Table 3) dissected by several normal faults. The S4 facies corresponds to the Early Cretaceous Formations (Sidi Kralif Fm., Hybla Fm., Gebel Nehal Fm., Bou Hedna Fm., Sidi Aich Fm., Serd J Fm., Hammeima Fm., Fadhene Fm.) (Suppl. Mat.) that appears locally interrupted by diffraction hyperbola that has been still associated with magmatic intrusions, although no evidence of igneous rock has been detected in the analyzed well-logs (Figs. 3, 4, 5).

The facies S5, topped by Horizon E (Table 3), appear highly affected by faulting. It locally shows the presence of diffraction hyperbola attributed to magmatic intrusions, based on the Remo Nord well-log. This facies S5 has been interpreted as the Paleocene-Eocene units (Amerillo Fm.) (Fig. 3 and Suppl. Mat. Table 6). The facies S6 is topped by the Horizon F and corresponds to the Oligocene-Lower Miocene formation (Ragusa Fm.) (Figs. 4, 7). Horizon F is a discontinuous reflector that marks an erosional truncation, it is highly interrupted by normal faults and diffraction hyperbola. Facies S7 is topped by the Horizon G (Table 3, Figs. 4–10) corresponding to the top of the Messinian evaporites which, in the whole Mediterranean area, identifies a marker locally associated to erosional phases (Lofi et al., 2011). Horizon G, also known as the "M-reflector", forms a typical seismic signal throughout the entire region, characterized by a high acoustic impedance contrast with high amplitude and a relatively high continuity (Lofi et al., 2011). Upward, according to biostratigraphic analysis (Di Stefano et al., 1993a), three main horizons are visible in the Plio-Pleistocene succession. They have been identified and are all related to transgressive and regressive phases (Cavallaro et al., 2017). Respectively, they are the base of Zanclean (5.33 Ma - Top of Messinian evaporites, Horizon G), the base of Gelasian (Horizon H), a 1.2 Ma unconformity (Horizon I), and a 0.8 Ma unconformity (Horizon L). The corresponding seismic facies are respectively the facies S8–S11 (Table 3), showing medium amplitude and parallel geometries, limited to each other by onlap and downlap terminations and with a progressive higher frequency upward (Table 3).

4.2. The deep crustal horizons

The M24 seismic line is a high penetration seismic profile that allows us to recognize the structures of the deep crust's layers underneath the Sicily Channel. A key element to investigate is the tracking of the Moho surface. The seismo-stratigraphic interpretation allows us to identify a maximum Moho's rise to 10 s/TWT in correspondence with the Fonkal Bank, with another possible rise in correspondence of the Linosa Graben up to 8 s/TWT (Figs. 4–6). The presence of several diffraction hyperbolae causes signal anomalies that have been linked to a rise of deep-origin fluids. In the northern part of the Sicily Channel, under the Gela Thrust System, the Moho's deepens to 11.8 s/TWT (Fig. 6 a, b). WARR (Wide Angle Reflection Refraction) velocities (Scarascia et al., 1994) allow us to carry out a depth conversion of the identified units. The calculated Moho's depth ranges from a minimum of 20 km under the Fonkal bank to a maximum of 36 km under the Gela Thrust System. The deep layers were mainly defined after the analysis of Moho's reflection characteristics. In the southernmost sector of the M24 line, the Moho rises from 11 to 10 s/TWT and is abruptly interrupted by a wide diffraction hyperbolae zone extended from 8 to 13 s/TWT underneath the Fonkal bank (Figs. 4, 5). Moho is also interrupted below the Linosa

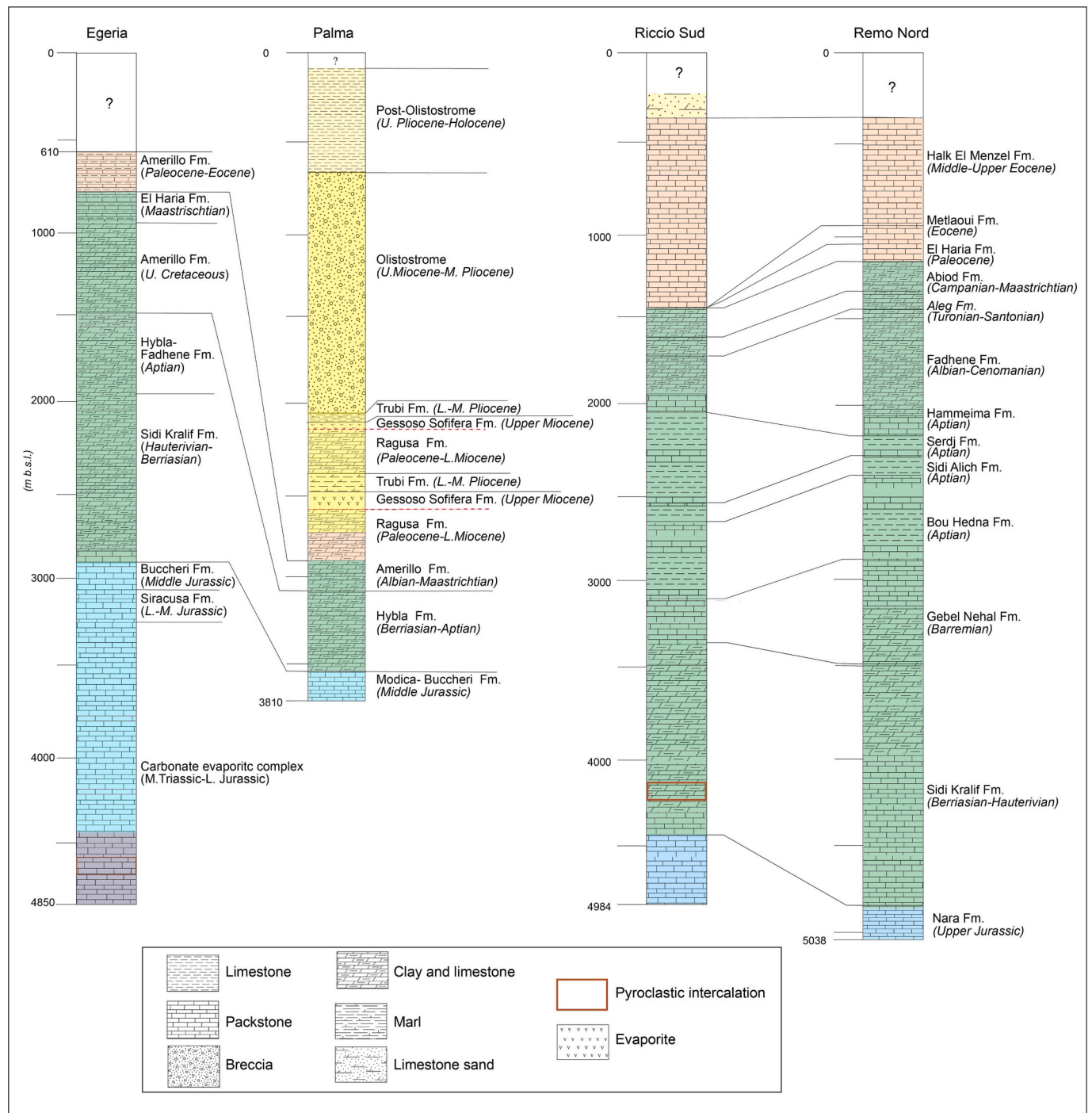


Fig. 3. Lithostratigraphic correlations of the wells respectively near the northern (Egeria and Palma, see Fig. 1) and the southern (Riccio and Remo, see Fig. 1) sector of the CROP M24 seismic line.

Graben by two wide zones rich in hyperbolae extended from 9 to 15 s/TWT (Figs. 4–6). Other Moho's interruptions are in correspondence of the Malta Graben, which extended from 8 to 14 s/TWT (Fig. 4) and under the northernmost sector where this reaches 13 s/TWT (Fig. 5 a, b). The top of the Upper Crust is located at 6 s/TWT in the southern sector of the line and deepens down to 9 s/TWT from the Linosa Plateau to the Gela Thrust System (Figs. 4–5).

4.3. The shallow structural framework

The shallow portion analysis has been divided along the main

structural domains observed in the seismic data. Three main different regions have been distinguished in our study area (Fig. 1): 1) Offshore southern Sicily and the Gela Thrust System, further subdivided into the Gela Thrust System and the Madrepore bank; 2) the Central sector-Malta Graben; and 3) the Linosa-Lampedusa Sector.

4.3.1. Offshore southern Sicily and Gela Thrust system

a) Gela Thrust System

The offshore domain of southern Sicily was investigated with the

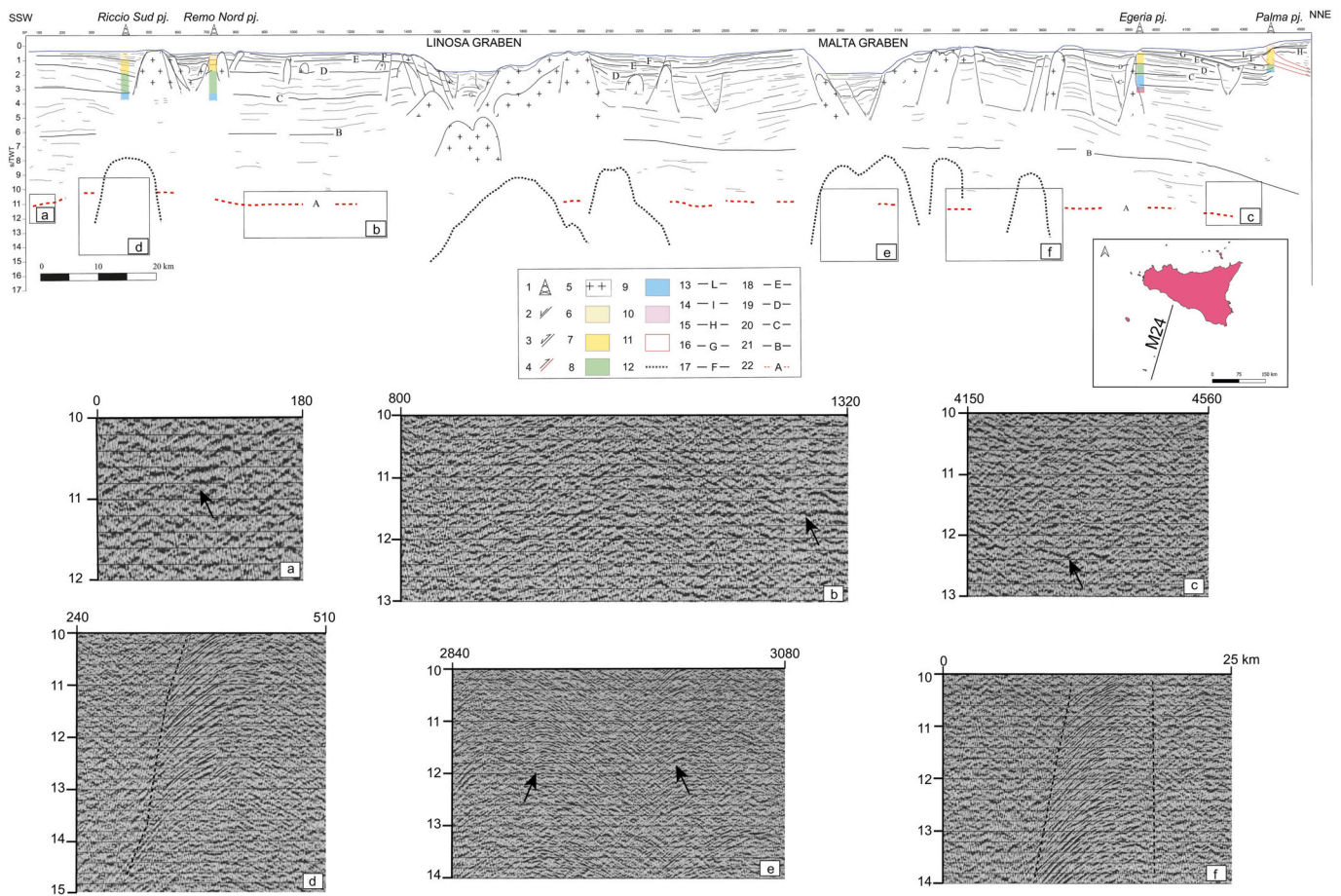


Fig. 4. Line drawing of CROP M24 seismic line with wells correlation. In the boxes below from (a) to (f) are indicated the main reflection characteristics of the deepest sectors, which show diffuse diffraction hyperbolae and high amplitude reflections. 1: well location; 2: normal fault; 3: thrust; 4: crossing seismic line; 5: volcanic intrusion; 6: Plio-Pleistocene unit; 7: Eocene-Miocene unit; 8: Cretaceous units; 9: Jurassic unit; 10: Triassic unit; 11: magmatic levels; 12: possible magmatic intrusion; 13: 0.8 Ma unconformity; 14: 1.2 Ma unconformity; 15: Base Gelasian; 16: Top Messinian Evaporites; 17: Top Oligocene unit; 18: Top Eocene unit; 19: Top Cretaceous unit; 20: top Jurassic; 21: upper crust; 22: Moho.

G82–129, G82–131, and M24 seismic profiles, where the outermost thrust of the Gela Thrust System (Gela Thrust Front) is observed (Figs. 1, 6, 7). The latter is a tectonic wedge well defined by the presence of a basal thrust that tips out towards SSW. In all the analyzed seismic lines, three key horizons, which mark the main deformation events, have been identified, respectively named H, I, and L (Figs. 6, 7). The Thrust System advancement appears to be not homogenous along strike, as testified by the presence of a more advanced thrust towards the South in the central part of the wedge also sealed by Horizon L on the G82–129 line (Fig. 7 c, d) but not on the G82–131 line (Fig. 7 a, b).

b) Madrepora bank

The southern sector of the Gela Thrust System is occupied by the associated foredeep and by the Madrepora Bank (Fig. 1). Locally reactivations of older normal faults NW-SE trending are reported in this region (Antonelli et al., 1988; Corti et al., 2006; Cavallaro et al., 2017). In the southern sector of the bank, two normal faults separate the Madrepora Bank from a depression here named Madrepora Graben (Figs. 4, 5, 8). This extends for about 9 km and shows an anticline structure, whose geometry is the result of the reactivation of pre-existing normal faults (Fig. 8 a-d), and, in line with Cavallaro et al. (2017)'s interpretation, may be affected by a positive flower structure. So far, in the Madrepora Graben two extensional phases, separated by a positive reactivation phase, have been identified on the basis of the main recognized horizons and unconformities. An old extensional phase was

identified on the basis of the Horizon G displacement by normal faults. It follows an inversion phase testified by *syn*-inversion deposits (see red square focus on Fig. 8 d) onlapping against the hinge zone of the anticlines (Fig. 8 b, d). A third event of renewed extension is observed by the presence of a mild seafloor displacement on the northernmost edge of the Madrepora Graben (Fig. 8 a-d). In the whole area, volcanic intercalations occur, detected in the Palma and Egeria well-logs and in the seismic profile, where the presence of diffraction hyperbola highlights the possible occurrence of volcanic intrusions (Figs. 3, 8).

4.3.2. Central sector-Malta Graben

In the central sector of the study area, an extensional structure called Malta Graben is observed. This is highlighted in the MS 119, MS 120, and M24 seismic lines (Figs. 4, 9 a-d). The graben's margins show chaotic/hyperbolae signals; since the evidence of volcanic tephra at 9 m b.s.l. recorded in the LC9 core by Reeder et al., 2002 (Fig. 1), and the records of similar signals along the M24 seismic line (also showing Moho rising in correspondence of these), these signals have been assumed to be magmatic intrusions with no shallow manifestation (Fig. 9 a-d), differently from Civile et al. (2021) that assumes that mass wasting deposits. Different deformation phases have been distinguished through the identification of three main unconformity surfaces (U1-U3) (Fig. 9 b, d). The Malta Graben records a younger extensional event, highlighted by the *syn*-rift geometry of the unit between U1 and U2 in both MS and CROP seismic lines (Fig. 9 a, b). A second event, that caused an inversion of the pre-existing structures, has been identified in the M24 and MS-119

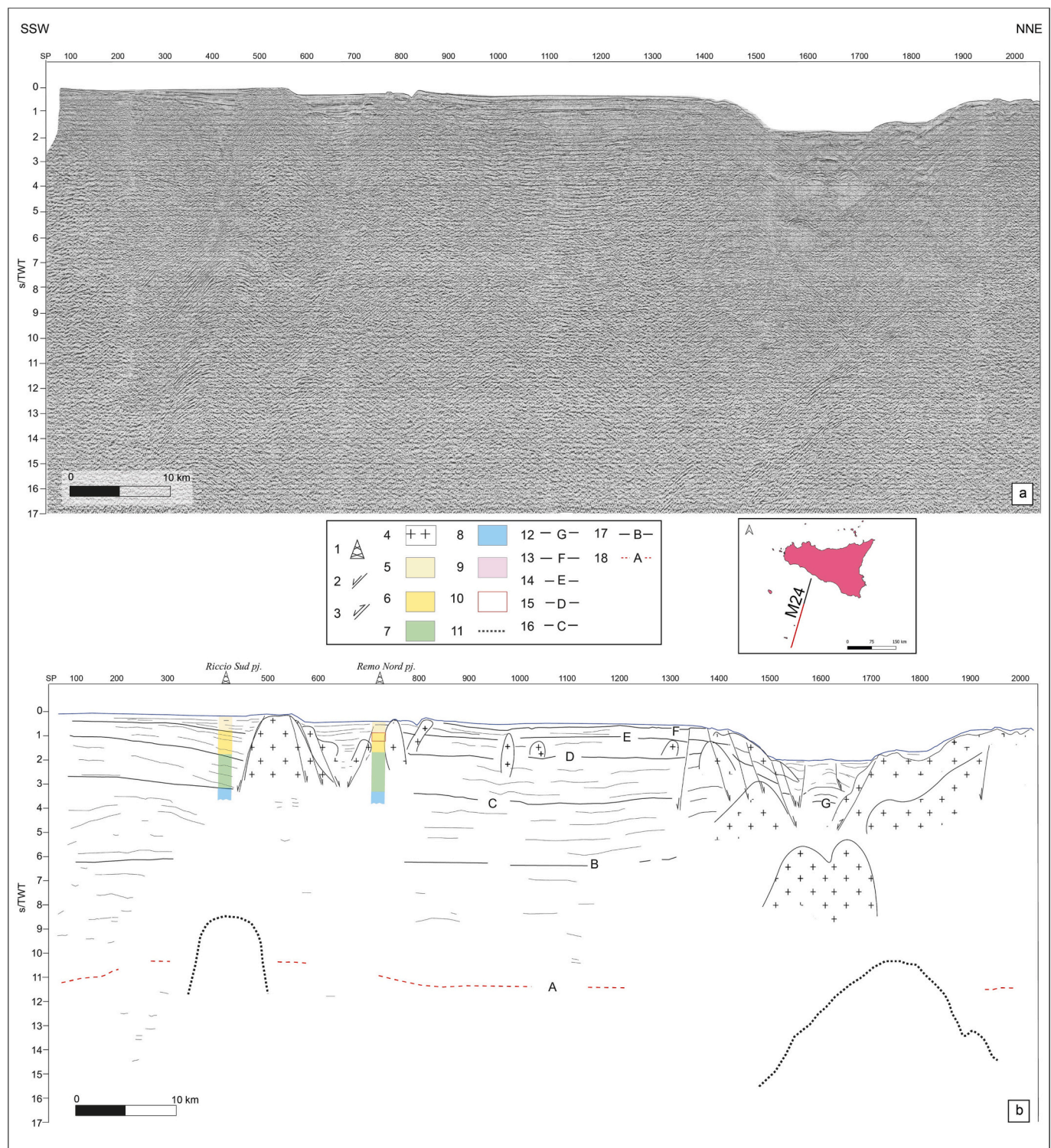


Fig. 5. (a) M24 seismic line, from the Fonkal Bank to the Linosa Graben (shown in Fig. 1) and (b) relative line drawing. 1: well location; 2: normal fault; 3: inverted fault; 4: volcanic intrusion; 5: Plio-Pleistocene unit; 6: Eocene-Miocene unit; 7: Cretaceous units; 8: Jurassic unit; 9: Triassic unit; 10: magmatic levels; 11: possible magmatic intrusion; 12: Top Messinian Evaporites; 13: Top Oligocene unit; 14: Top Eocene unit; 15: Top Cretaceous unit; 16: Top Jurassic; 17: Top upper crust; 18: Moho.

seismic lines, between the U2 and U3 unconformities. It follows a renewed extension, highlighted by the presence of normal faults intersecting the recent deposits, but only in the M24 and MS-119. However, the MS-120 shows a positive relief affecting the seabed which is uplifted of at least 500 m high (Fig. 9 a, b). The internal geometry of the Malta Graben is characterized by a roll-over anticline structure formed during

an extensional phase, its antithetic fault was inverted causing the folding of the deposits overlying the Horizon G and of the seafloor of the central Malta Graben (Fig. 9 b, d).

4.3.3. Linosa-Lampedusa Sector

Interpretation of the M24, and MS119 lines shows the presence in the

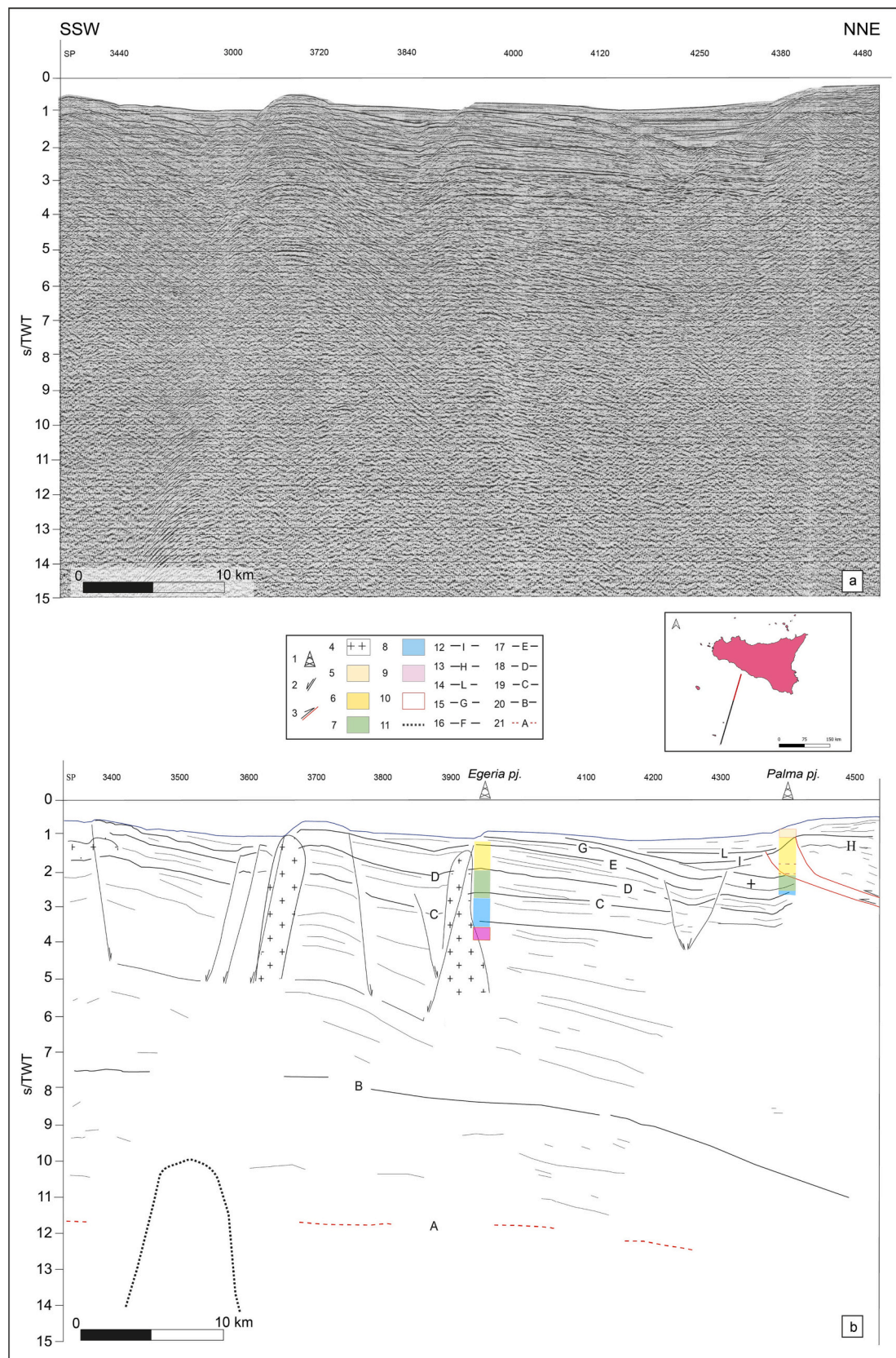


Fig. 6. (a) M24 seismic line showing the Falda di Gela sector (showed in Fig. 1) and (b) relative line drawing. 1: well location; 2: normal fault; 3: inverted fault; 4: crossing seismic line; 5: volcanic intrusion; 6: Plio-Pleistocene unit; 7: Eocene-Miocene unit; 8: Cretaceous units; 9: Jurassic unit; 10: Triassic unit; 11: magmatic levels; 12: possible magmatic intrusion; 13: 0.8 Ma unconformity; 14: 1.2 Ma unconformity; 15: Base Gelasian; 16: Top Messinian Evaporites; 17: Top Oligocene unit; 18: Top Eocene unit; 19: Top Cretaceous unit; 20: top Jurassic; 21: upper crust; 22: Moho.

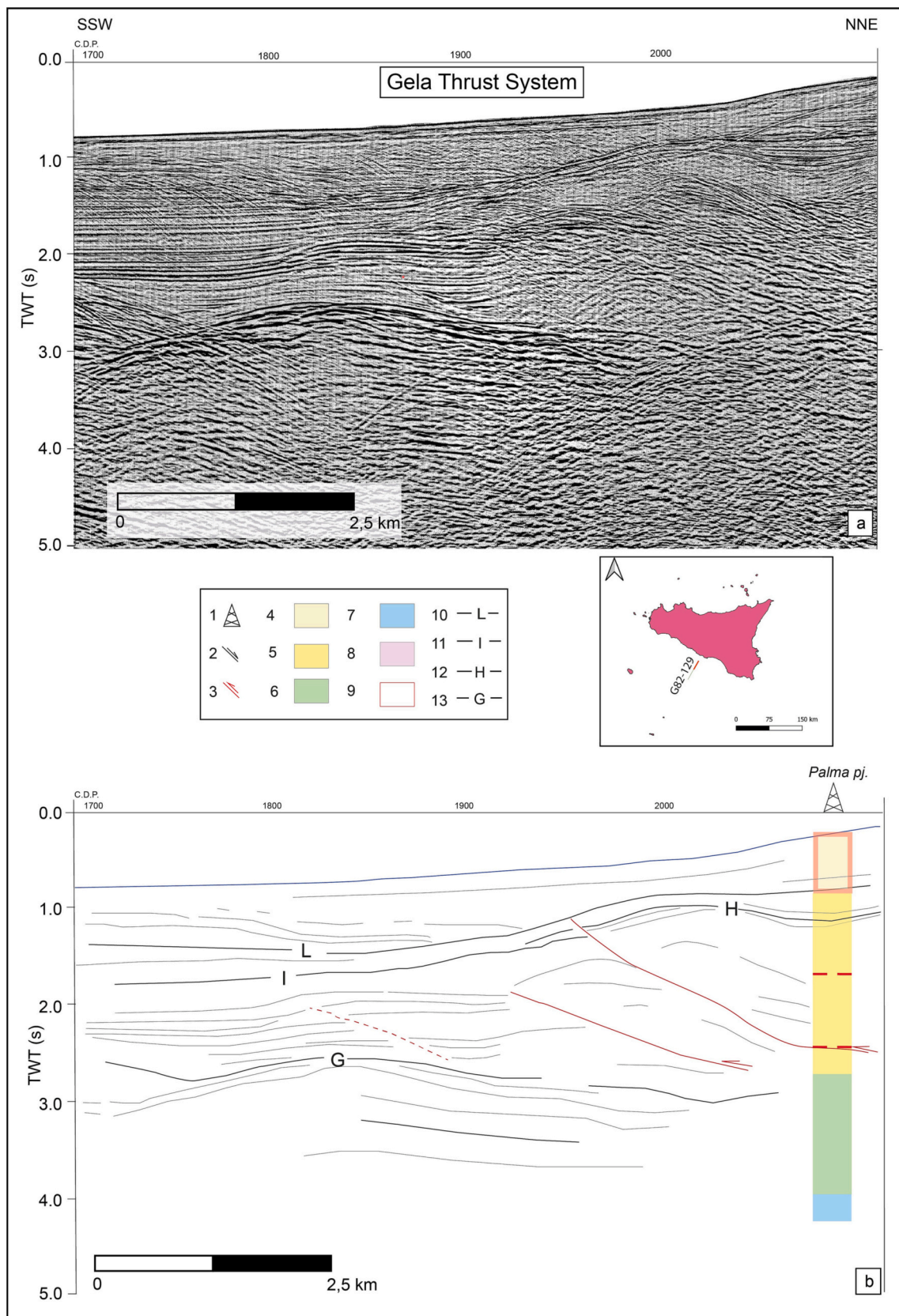


Fig. 7. (a) G82 129 seismic line showing the Falda di Gela (shown in Fig. 1), and (b) the relative line drawing with Palma well log's correlation. (c) G82 131 seismic line showing Falda di Gela structure, (d) relative line drawing and correlation with Palma well log. 1: well location; 2: normal fault; 3: thrust; 4: Plio-Pleistocene unit; 5: Eocene-Miocene unit; 6: Cretaceous units; 7: Jurassic unit; 8: Triassic unit; 9: magmatic levels; 10: 0.8 Ma unconformity; 11: 1.2 Ma unconformity; 12: Base Gelasian; 13: Top Messinian Evaporites.

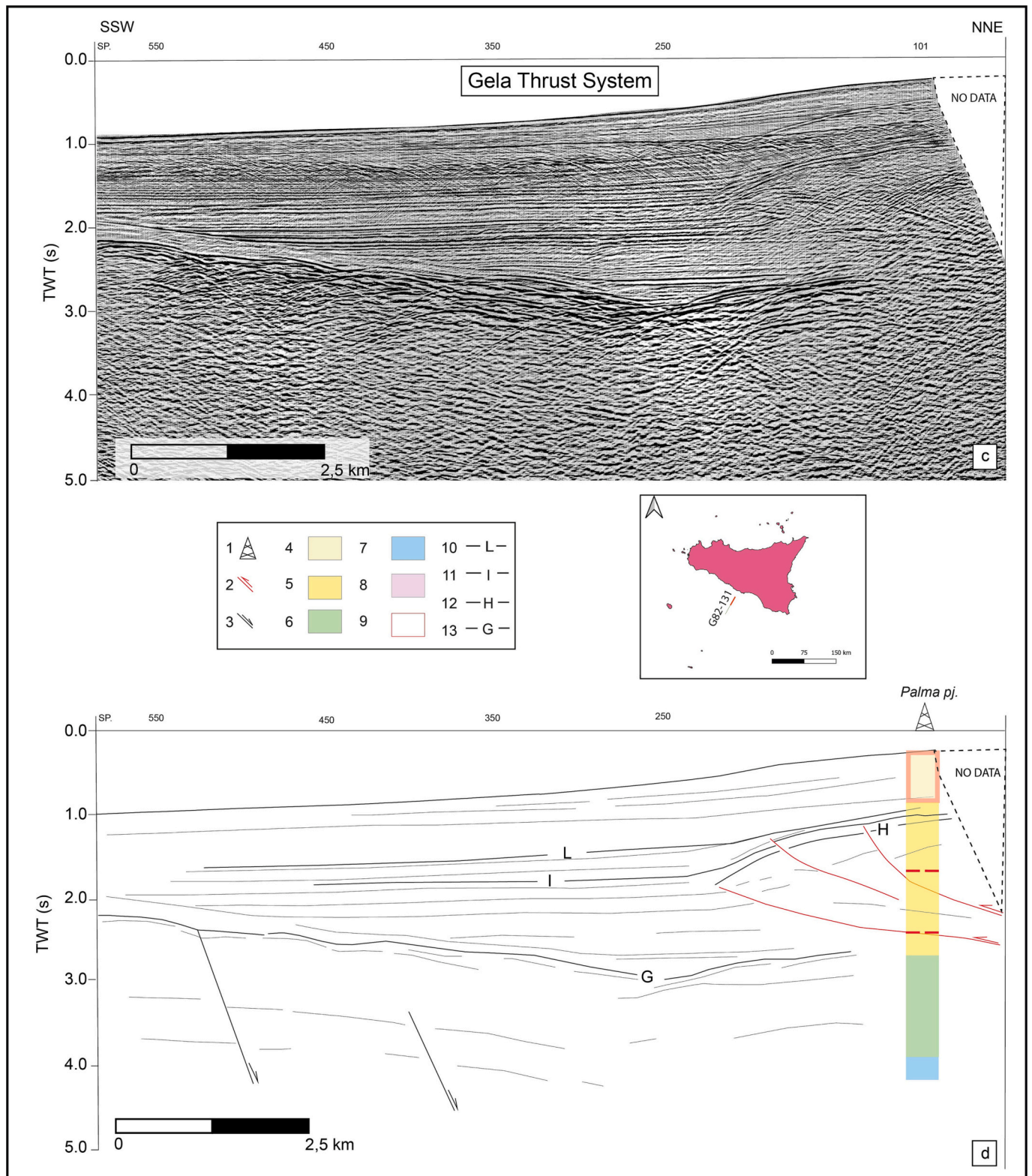


Fig. 7. (continued).

Lampedusa sector of a bank called Linosa Plateau and a tectonic depression named Linosa Graben (Figs. 1, 10). The Linosa Plateau is a 50 km wide bank that separates Malta and the Linosa grabens (Fig. 1). According to the seismo-stratigraphic interpretation, the G horizon appears affected by several normal faults that cause a moderate bending of the whole plateau (Fig. 10 b). These are covered by horizon I and are

overlaid by a series of prograding wedges topped by the horizon L (Fig. 10 b). The top of the wedges is 0.8 s/TWT, which is about 600 m deep, assuming an average velocity of 1550 m/s. The Linosa Graben is the southernmost analyzed basin, and it is the richest, among the analyzed basins, in magmatic intrusions, with a shallow manifestation in the northern rim (Fig. 11 b) attributed to Linosa II volcano (location in

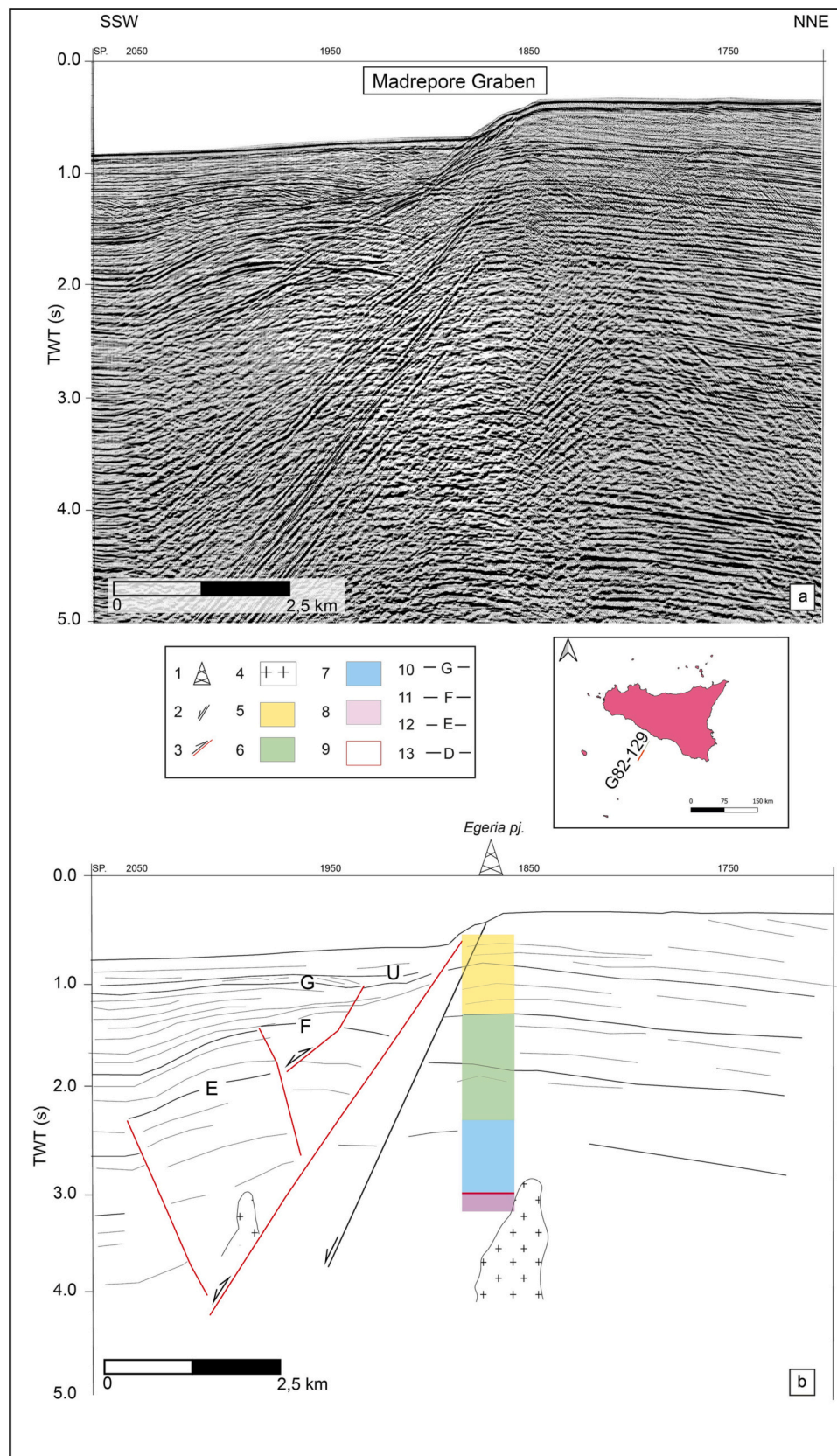


Fig. 8. (a) G82 129 seismic line showing Madrepore Graben structure (showed in Fig. 1), and (b) the relative line drawing and correlation with Egeria well-log. (c) G82 131 seismic line showing Falda di Gela (11 in Fig. 1), and (d) the relative line drawing and correlation with Palma well-log. 1: well location; 2: normal fault; 3: inverted fault; 4: crossing seismic line; 5: volcanic intrusion; 6: Plio-Pleistocene unit; 7: Eocene-Miocene unit; 8: Cretaceous units; 9: Jurassic unit; 10: Triassic unit; 11: magmatic levels; 12: possible magmatic intrusion; 13: 0.8 Ma unconformity; 14: 1.2 Ma unconformity; 15: Base Gelasian; 16: Top Messinian Evaporites; 17: Top Oligocene unit; 18: Top Eocene unit; 19: Top Cretaceous unit.

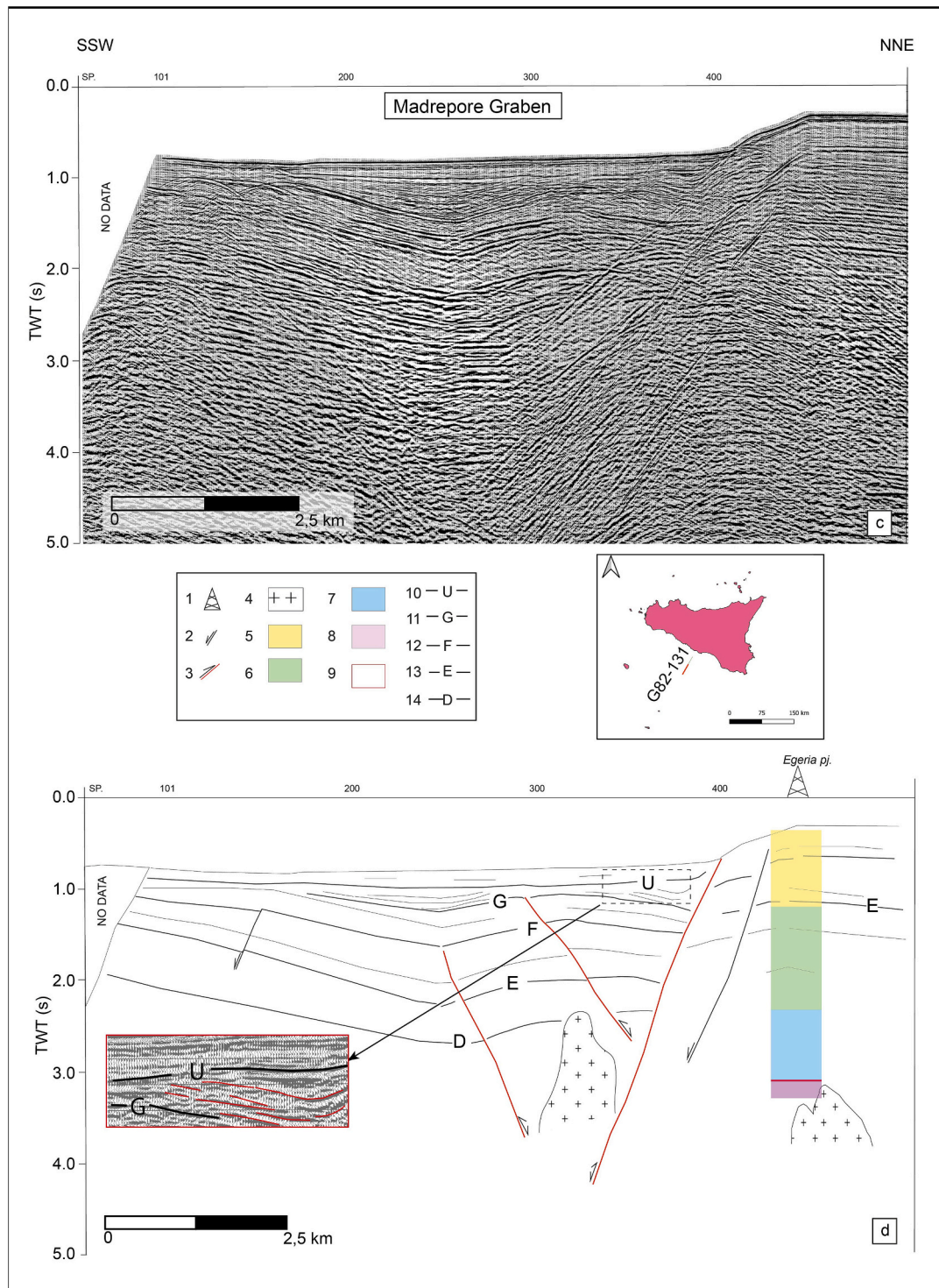


Fig. 8. (continued).

Fig. 1). An extensional phase is detected by the *syn-rift* geometry of the unit between U1 and U2 in both MS 119 and CROP M24 seismic lines (Figs. 4, 11). The internal geometry of the Linosa Graben also shows the presence of a rollover anticline that involves the G and F horizons (Fig. 11 b). Even in this graben, a positive inversion shortens the rollover anticline which appears sealed by the U3 unconformity. In a similar way to the Madrepore Graben, the northern edge of the Linosa Graben is affected by a normal fault reaching the seafloor in the MS 119 (Fig. 11 b) but not in the M24, where instead a folded seafloor creates a positive relief of ~400 m. This necessarily implies that within the Linosa Graben,

there is a local variation of the deformation in a few km of distance.

5. Discussion

5.1. Timing of the observed deformation phases

The seismo-stratigraphic interpretation allowed us to identify the chronology of the deformations occurred in an N-S-oriented band in the Sicily Channel. For the Madrepore, Malta, Linosa Graben, and the Linosa Plateau, the ages of the deformation stages have been derived by

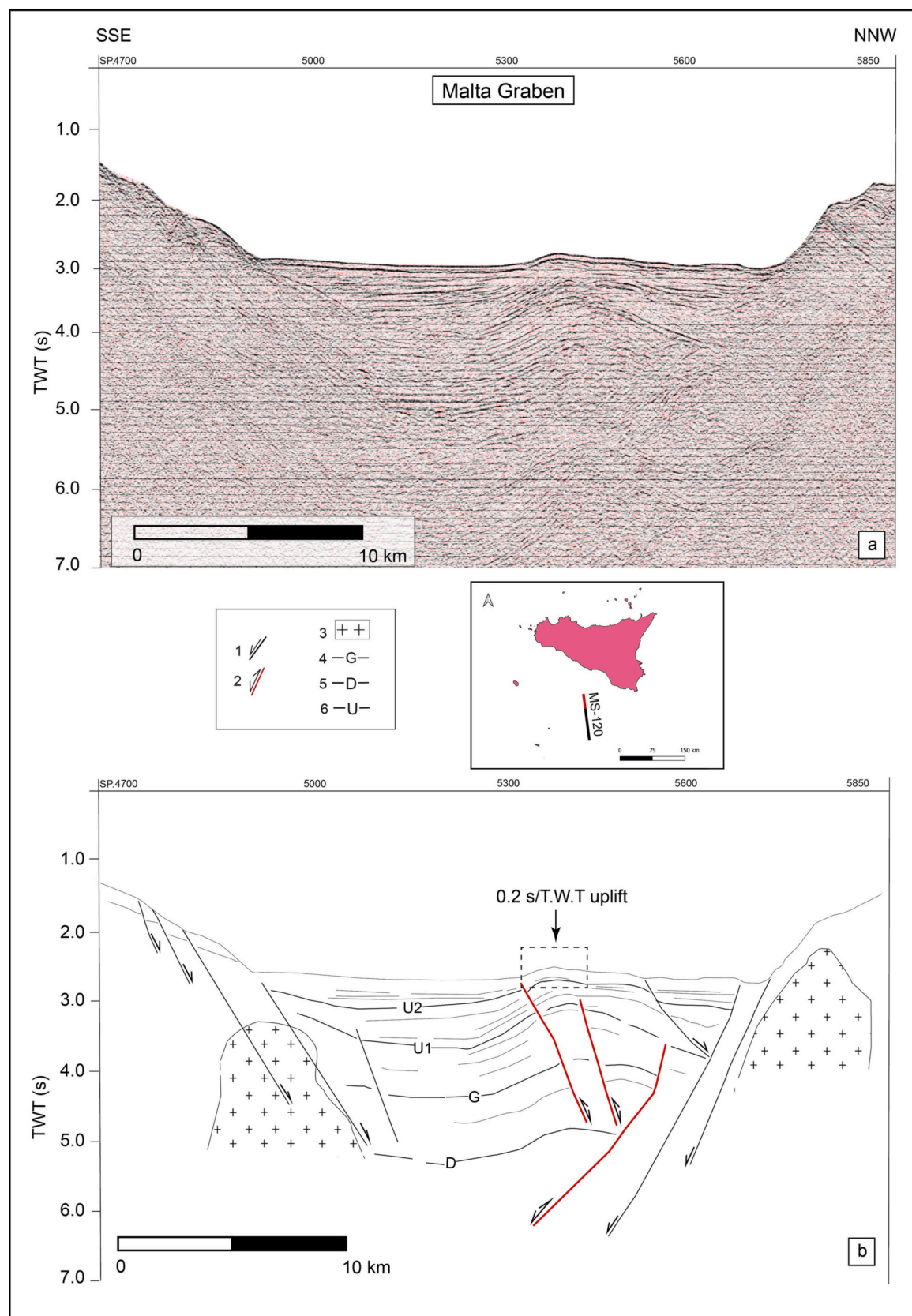


Fig. 9. (a) MS 120 line showing a positive relief of the seafloor in correspondence of Malta Graben (showed in Fig. 1), with (b) relative line drawing. The positive relief is absent in the (c) MS 119 seismic line and in the relative line drawing (d). Fig. 9 (e) shows a model of the positive inversion highlighted in Fig. 8 (b). 1: normal fault; 2: inverted fault; 3: volcanic intrusion; 4: Top Messinian Evaporites; 5: Top Cretaceous unit; 6: unconformity surface.

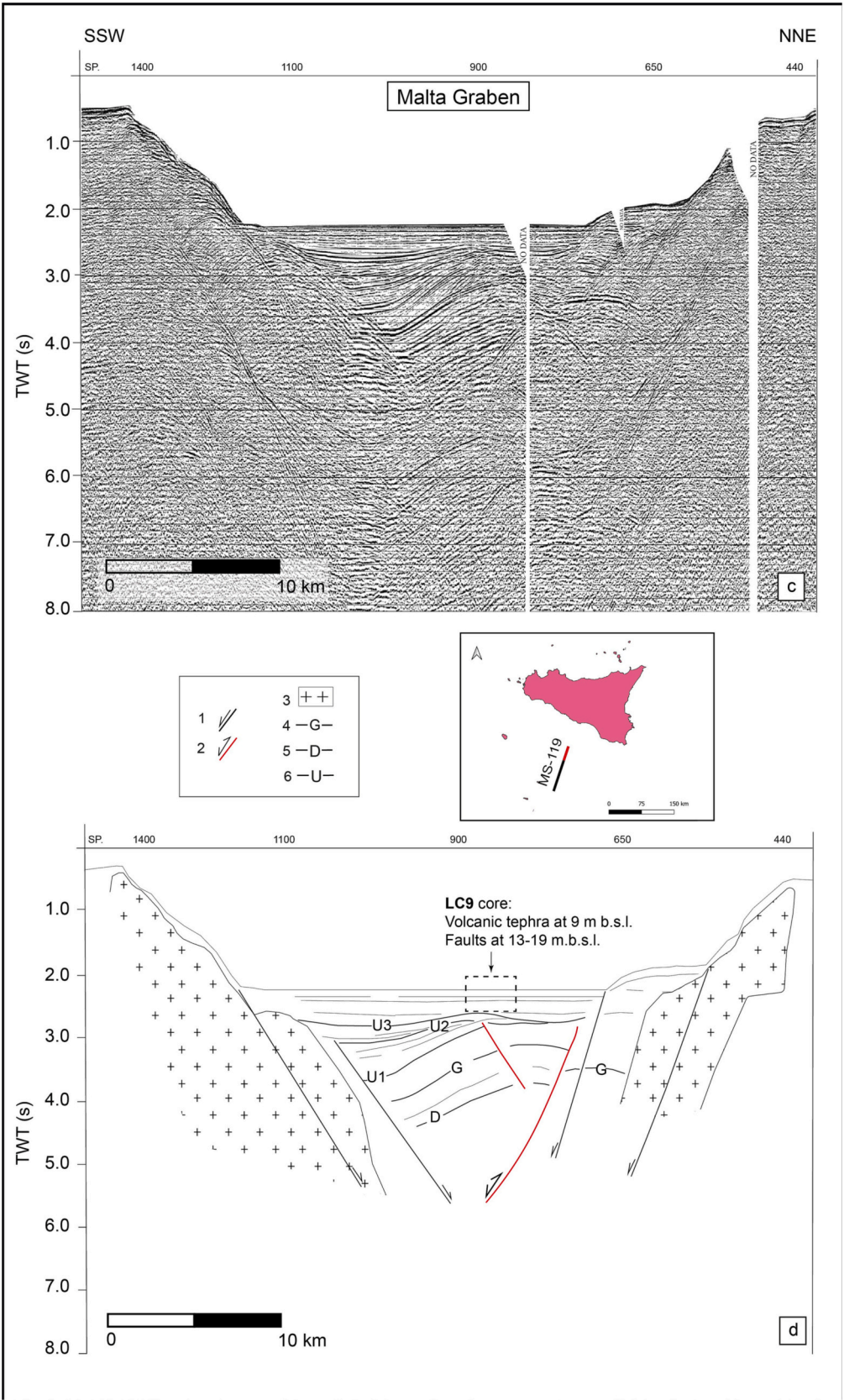


Fig. 9. (continued).

calculating the sedimentation rates for each level (Table 4) and by seismo-stratigraphic interpretation and well-tie. New constraints on the evolution of the different sectors investigated are presented below:

(a) Gela Thrust System: according to the Palma well-log analysis (Fig. 3), it involves deposits from the Paleogene to the Quaternary period. The seismo-stratigraphic analysis highlighted three main

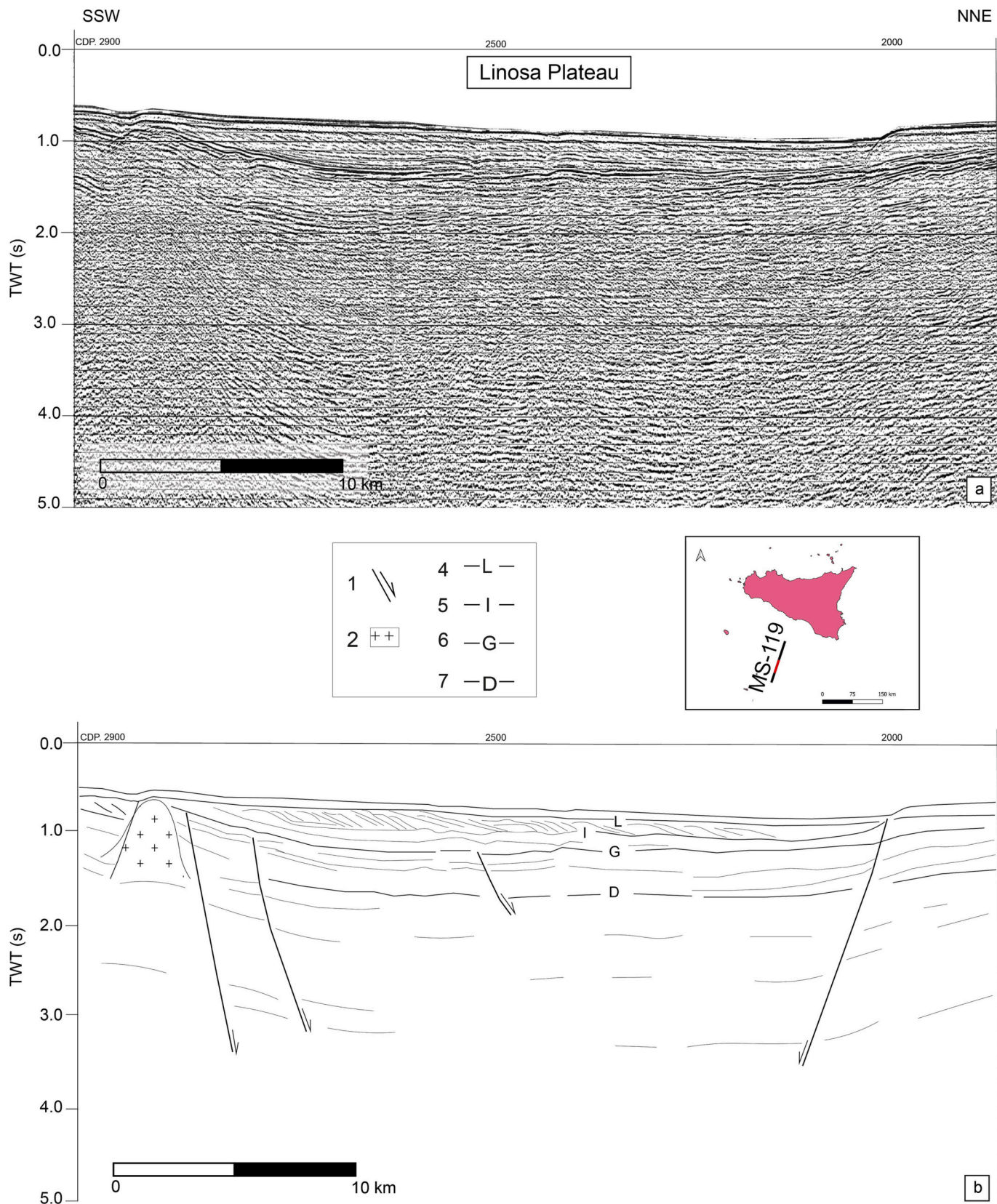


Fig. 10. (a) MS 119 seismic line showing prograding wedges in the Linosa Plateau and (b) relative line drawing. 1: normal fault; 2: volcanic intrusion; 3: 0.8 Ma unconformity; 4: 1.2 Ma unconformity; 5: Top Messinian Evaporites; 6: Top Cretaceous unit.

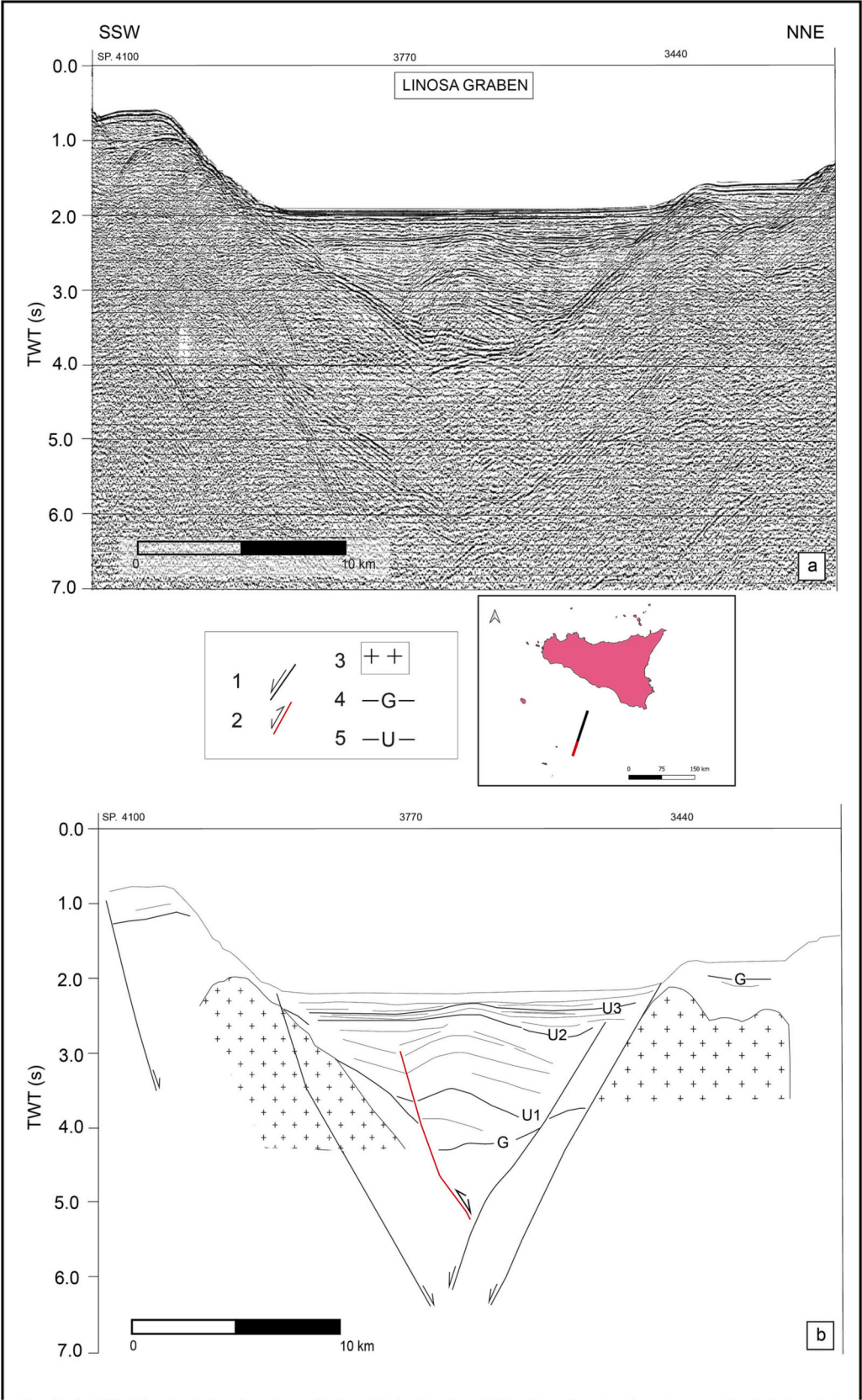


Fig. 11. (a) MS 119 seismic line the Linosa Graben (showed in Fig. 1) and (b) relative line drawing. 1: normal fault; 2: inverted fault; 3: volcanic intrusion; 4: Top Messinian Evaporites; 5: unconformity surface.

Table 4

Obtained sedimentation rate and age of main deformation events detected in Malta, Linosa and Madrepore Graben.

Line	Process	Thickness (s)	Thickness (mm)	Age (Ma)		Sedimentation rate	Area
MS-119	Extension (Seabed)	0,4	400,000	0,03	Calabrian-Chibanian	0,3 mm/yr	Malta Graben
	Inversion (top U3)	0,15	150,000	1,23	Calabrian		
	Extension (top U2)	0,8	800,000	1,63	Calabrian		
	Post-Messinian (top U1)	0,4	440,000	4,03	Zanclean		
MS-120	Inversion (top U3)	0,3	300,000	0,33	Chibanian	0,4 mm/yr	
	Extension (top U2)	0,6	660,000	1,33	Calabrian		
	Post-Messinian (top U1)	0,6	660,000	3,33	Piacenzian		
	Extension (seabed)	0,4	400,000	0,03	Calabrian-Chibanian		
M24	Inversion (top U3)	0,2	200,000	1,28	Calabrian	0,3 mm/yr	
	Extension (top U2)	0,5	500,000	1,83	Gelasian-Calabrian		
	Post-Messinian (top U1)	0,4	440,000	3,93	Zanclean		
	Inversion (Seabed)	0,3	300,000	0,04	recent		
M24	Extension (top U2)	0,35	385,000	1,34	Calabrian	0,24 mm/yr	
	Post-Messinian (top U1)	0,5	550,000	2,94	Piacenzian		
	Extension (Seabed)	0,3	300,000	0,03	Chibanian		
	Inversion (top U3)	0,2	200,000	0,86	Calabrian		
MS-119	Extension (top U2)	0,9	990,000	1,41	Calabrian	0,36 mm/yr	
	Post-Messinian (top U1)	0,4	440,000	4,11	Zanclean		
	Inversion (Top U)	0,16	160,000	3,13	Piacenzian		
G82-131	Inversion (Top U)	0,16	160,000	3,13	Piacenzian	0,7 mm/yr	Madrepore Graben

unconformity surfaces (H, I, L) that have been attributed to the main stages of deformation, respectively Zanclean (5.33 Ma), Piacenzian (3.6 Ma) and top of Calabrian (0.8 Ma), in agreement with literature data (Catalano et al., 1993; Cavallaro et al., 2017). Since the wedge appears sealed by 0.8 Ma unconformity (Horizon L) we suggest that its advancement is no longer active, in agreement with Di Stefano et al. (1993a)'s interpretation.

(b) Madrepore Graben: in the Madrepore Graben a Zanclean (5.33 Ma) extensional phase has been identified on the basis of the Horizon G displacement, dated back to the Messinian through the well-tie analysis. The observed *syn*-inversion deposits (Fig. 8 d) have been dated back to Piacenzian (3.13 Ma). The timing has been estimated considering 0.7 mm/yr of sedimentation rate for the units between G and U horizons, while the sedimentation rate was obtained by considering the maximum thickness of the units overlying the Messinian deposits (Horizon G) (Table 4). A third event of a recent, renewed, extensional phase (Post Piacenzian) was identified by a seafloor displacement (Fig. 8 a-d).

(c) Malta Graben: we identified three different deformation phases (U1-U3) (Fig. 9 b, d, e). The ages have been obtained by different sedimentation rates for each seismic line (M24, MS-120, MS-119) which consider the maximum thickness of the units overlying the post-Messinian deposits (Horizon G), dated back to 5.33 Ma (Table 4). The younger extensional event (between U1 and U2) has resulted to be: Piacenzian-Calabrian (3.33–1.33 Ma) in the MS-120 (using a sedimentation rate of 0.4 mm/yr); Zanclean-Calabrian (on average 3.9–1.7 Ma) in the M24 and MS-119, assuming a sedimentation rate of 0.33 mm/yr (Table 4). The second identified event (U2-U3) is an inversion phase that, with a sedimentation rate of ~0.35 mm/yr, has been dated in MS-119 and M24 to the upper Calabrian (1.2 Ma) (Table 3). The followed renewed extension is testified only in the M24 and MS-119 by recent normal faults intersecting the seafloor. Instead, the MS-120 shows a positive relief affecting the seabed which is uplifted at least 500 m high (Fig. 9 a, b); this implies that a contractional phase was or is still active in recent times and is mainly localized in the central Malta Graben.

(d) Linosa Plateau: according to the seismo-stratigraphic interpretation, the post-Messinian units appear affected by several normal faults that cause a moderate bending of the whole plateau (Fig. 10 b). This implies that an extensional phase took place during the deposition of the Messinian unit. These are covered by the 1.2 Ma unconformity (horizon I) and are overlaid by a series of prograding wedges topped by the 0.8 Ma unconformity (horizon L) (Fig. 10 b).

(e) Linosa Graben: an extensional phase is detected by the *syn*-rift deposits between U1 and U2 in both MS 119 and CROP M24 seismic lines (Figs. 4, 11). This event has been dated from Zanclean (4.11 Ma) to Calabrian (1.41 Ma) in the MS 119, assuming a sedimentation rate of 0.36 mm/yr; while in the M24 has been dated to Piacenzian (2.94 Ma)-Calabrian (1.34 Ma) (Table 3). The internal geometry of the Linosa Graben also shows the presence of a rollover anticline that involves the Messinian and Post-Messinian deposits (Fig. 11 b). Even in this graben, in the MS-119, a positive inversion shortens the rollover anticline which appears sealed by the U3 unconformity dated to upper Calabrian (0.86 Ma) (assuming a sedimentation rate of 0.24–0.36 mm/yr) (Table 3). While, in the M24, the inversion affects the seabed, which creates a positive relief of ~400 m, suggesting a more recent age. In a similar way to the Madrepore Graben, the northern edge of the Linosa Graben is affected, in the MS-119, by a normal fault reaching the seafloor suggesting a post-Calabrian deformation (Fig. 11 b). This necessarily implies that within the Linosa Graben, there is a local variation of the deformation in a few km of distance.

5.2. Magmatic intrusions

Several magmatic intrusions have been detected in the shallow layers, some of which have been calibrated with well-logs data (Egeria and Riccio Sud) (Fig. 8) and sampling (e.g. LC9 for Malta Graben). Shallow volcanic intrusions have been recognized in the seismic lines along Malta Graben and Linosa Graben, where there are also recorded outcropping volcanoes (Figs. 9 a-d, 11). In the deep layers, in correspondence with several Moho's interruptions, we observed the presence of diffraction hyperbolae causing signal anomalies linked to deep-origin fluids rising (Figs. 4, 12). This is suggested by the associated upwards occurrence of numerous volcanic bodies in the whole area, such as, for example, the Linosa II volcano, whose edifice outcrops at the rims of the Linosa graben (Fig. 11). Near Malta Graben, there is no gravimetric anomaly detected (Della Vedova et al., 1987), but it cannot be excluded an absence of a Moho's rising since the evidence of volcanic manifestations. Since the magmatic manifestations are concentrated along the main graben's margins, we suggest a relationship between extension and magmatism.

5.3. Constraints on the geodynamic evolution of the Sicily Channel

The response of continental forelands to subduction/collision is a widely investigated topic in the Mediterranean region (Maesano et al.,

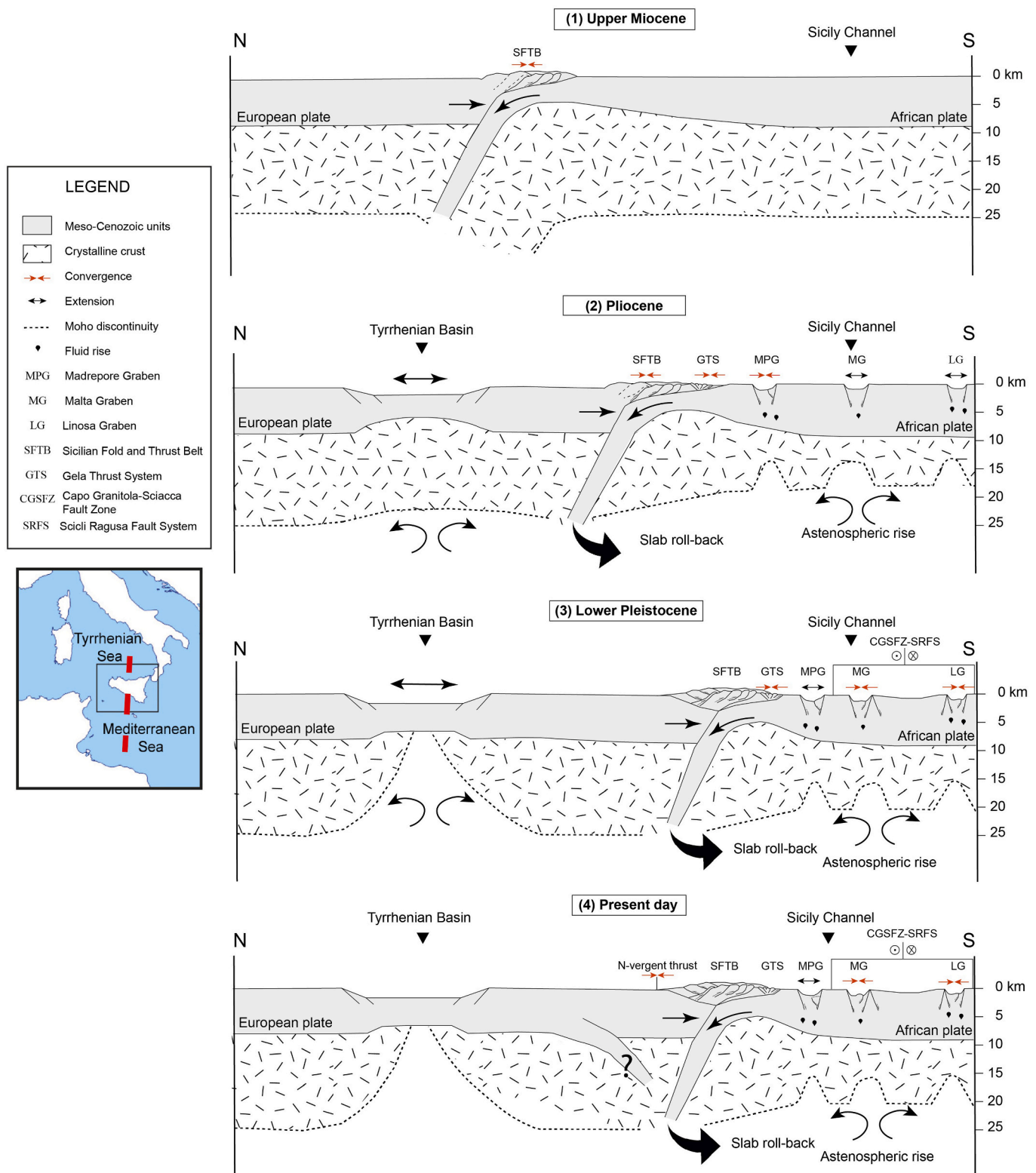


Fig. 12. Schematic representation showing the events that occurred in the Sicily Channel from Lower Pliocene to Present day after the slab roll-back of the African plate (modified after Argnani, 1990). In the bottom left corner is the rough location (red line) of the model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2020). As already known by literature, and as confirmed by our seismic interpretation, the Sicily Channel is characterized by both extensional and contractional deformation. This is a typical feature of the Central Mediterranean region, such as for the nearby southern Adria plate, whose evolution since the late Neogene is characterized by extensional

and compressional/transpressional pulses related to the alternation/coexistence of different tectonic processes (Chizzini et al., 2022).

However, the processes related to these deformation phases that affected our Sicilian foreland study area are still poorly defined, as well as how they acted during the geological time.

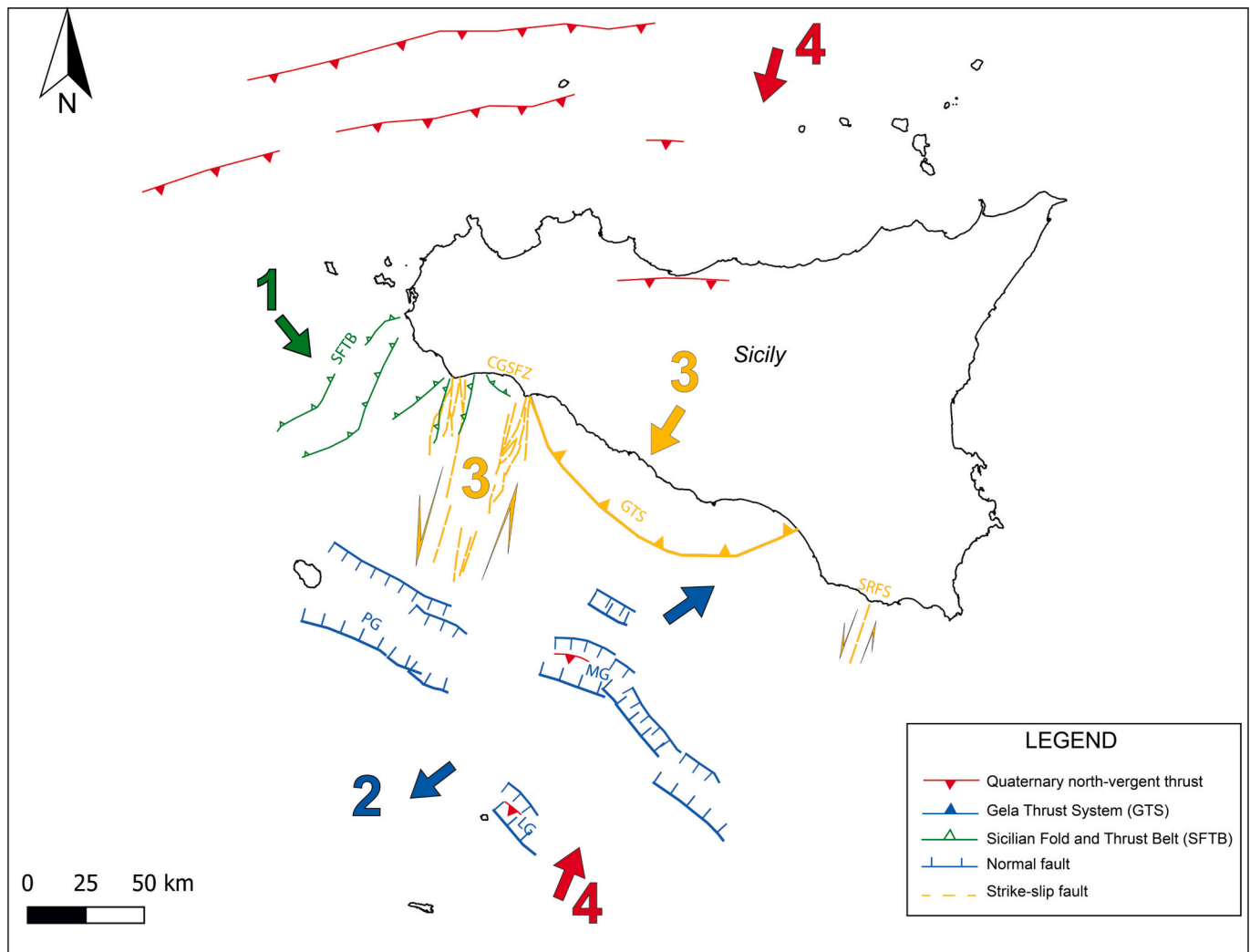


Fig. 13. Simplified plan representation of tectonic phases occurred in the Sicily Channel from the Late Miocene onwards. PG: Pantelleria Graben; MG: Malta Graben; LG: Linosa Graben; CGSFZ: Capo Granitola-Sciacca Fault Zone; SRFS: Sicily Ragusa Fault System.

In this section, we aim to discuss the relation of the observed extensional and contractional deformation with the regional geodynamic setting. We propose the following sequence of four tectonic events and main driving forces (Figs. 12, 13) as follows:

1. In the Upper Miocene, a regional contractional deformation occurred due to the convergence between Africa and Europe (Bellon & Letouzey, 1977; Dercourt et al., 1986; Dewey et al., 1989) producing the collisional Sicilian Fold and Thrust Belt (SFTB) and the Ionian-Tyrrhenian arc-trench complex (Sulli et al., 2021) (Figs. 12, 13).
2. In the Lower Pliocene, the foreland area of the African Plate, localized in the Sicily Channel, has been subject to a NW-SE oriented extension since 5.33 Ma ago (Zanclean) (Figs. 12, 13). The opening of the Pantelleria, Linosa and Malta grabens took place, potentially with a dextral strike-slip component (Catalano et al., 2009), especially in Malta and Linosa grabens. The extension was accompanied by changes in the asthenospheric flows, which led to the Moho (and magma) rising detected in the M24 seismic line under the main grabens and accompanied by local volcanic manifestation along the grabens' margins (Figs. 4, 12 b). These events could be related to the fast slab retreat of the Calabrian Arc (Faccenna et al., 2001a, 2001b), potential slab tearing (Arab et al. (2020) and the independent motion and rotation of the Adriatic Plate relative to Africa and Europe (Le

Breton et al., 2017). This is also supported by GPS data, which shows that the Africa-Europe convergence rate decreased by about 25–55% (Calais et al., 2003; Meccariello et al., 2017; Palano et al., 2020) from Oligocene to the present. Moreover, in the last 3 Ma, the African Plate rotates counterclockwise 20° relative to Eurasia, and Adria rotates $5^\circ \pm 3^\circ$ counterclockwise relative to Europe in the last 20 Ma (Dewey et al., 1989; Torelli et al., 1995; Calais et al., 2003; Le Breton et al., 2017). This caused a divergence between Africa and Adria of about 60 km, which seems to be accommodated by extension in the Sicily Channel (Le Breton et al., 2017).

3. In the Lower-Upper Pliocene, the Gela Thrust System (GTS) advance induced a positive reactivation phase in the Madrepore Graben (Fig. 12) dated to the Piacenzian age (3.13 Ma), which is in agreement with the first stage of advancement of the GTS dated by , and with the ages of tectonic reactivation detected by Cavallaro et al. (2017) and Civile et al. (2021) in the same area.

In the Lower Pleistocene, the last stage of advancement of the GTS is recorded at 0.8 Ma (upper Calabrian), in accordance with the seismostratigraphic interpretation of Cavallaro et al. (2017). At this stage, the Madrepore graben returns to register an extensional phase, no longer subjected to the compression given by the GTS advancement. However, an inversion of previously formed normal faults occurred between 1.8 and 0.7 Ma (Calabrian) and is registered in the Malta and Linosa graben (in line also with Civile et al., 2021), which

after 0.7 Ma, (upper Calabrian) show again an extensional phase. Contemporaneously, a transpressive activity of the lithospheric discontinuities CGSFZ and SRFS is registered (Civile et al., 2021), probably responsible for the inversion and contraction deformation observed in the grabens.

4. Today, conversely to other studies, a recent inversion has been detected in the Malta and Linosa Grabens, not caused by the advance of the Gela Thrust System (no longer active) but most likely caused by a response to a possible plate re-organization and change of subduction polarity (Sulli et al., 2021). A link between the recent positive inversions and the plate re-organization comes from a recent study (Sulli et al., 2021) on the Sicilian compressional structures. They identified a shift of the deformation to the north, from the Gela Thrust System to the inner sector in the southern Tyrrhenian Sea that is consistent with the recent theories of a change in the subduction polarity in the central Mediterranean orogens (Mauffret et al., 2004; Billi et al., 2011; Roure et al., 2012; Arab et al., 2016; Hamai et al., 2018; Sulli et al., 2021). We believe that this compressive stress field triggers the localized reactivations of pre-existing zones of weakness such as the extensional faults, especially in the Malta Graben but also in the Madrepore and Linosa Graben (Figs. 12, 13). This last stage is also accommodated by sinistral transcurrent zone (CGSFZ in particular), which today is seismically active and subdivides the Sicily Channel into a westward and eastward sector (Civile et al., 2021), as testified by focal mechanisms in the area (Fig. 1).

6. Conclusions

The comparative analysis of several seismic lines, reaching even the crustal structure, in addition to geodetic and literature data, allowed us to suggest that alternative extensional and contractional deformation located within the African Plate can be explained through the overlapping of different processes, as follows:

- I. In the Upper Miocene a regional contractional deformation occurred due to the regional convergence between Africa and Europe producing the Sicilian Fold and Thrust Belt;
- II. After the Messinian (post 5.33 Ma), in the Lower Pliocene, the fast rollback of the Calabrian slab caused a NW-SE oriented extensional phase that induced the formation of the main grabens;
- III. This extensional phase appears partly contemporary with the advance of the Gela Thrust Front (GTS) that caused the Madrepore Graben positive reactivation in the Zanclean time (3.9 Ma). This is followed in the Lower Pleistocene, between 1.8 and 0.7 Ma (Calabrian), by a contractional phase, caused by the further activity of the GTS and onset of transpressive activity of the CGSFZ and SRFS, induced fault reactivations and inversion in Malta and Linosa Grabens;
- IV. Today, the Malta Graben and Linosa Graben appear indeed affected by a recent contractional phase which caused positive reliefs of the seabed; this phase has been related to the potential change in the subduction polarity of the Africa plate suggested by geodetic and previous work in Sicily (Sulli et al., 2021). This recent plate re-organization seems not only to affect the northern part of Sicily and the southern Tyrrhenian Sea sectors but also the Sicily Channel.

We depict a tectonic setting in the Sicily Channel that is not the result of a simple stage of passive rifting. The Sicily Channel structural setting resulted indeed from the interplay of different processes which derive from the complex geodynamic system of the Central Mediterranean, especially from its subduction dynamics with the fast roll-back of the Calabrian Slab and subsequent potential slab tear and polarity switch north of Sicily.

CRedit authorship contribution statement

Mariagiada Maiorana: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. **Andrea Artoni:** Conceptualization, Data curation. **Eline Le Breton:** Writing – review & editing. **Attilio Sulli:** Methodology, Software, Supervision, Validation, Visualization. **Nicolò Chizzini:** Conceptualization, Validation, Visualization. **Luigi Torelli:** Data curation, Software.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary materials to this article can be found online at <http://doi.org/10.1016/j.tecto.2023.230019>.

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2.4 REVIEW AND DETAILED ANALYSIS OF THE PLIO-QUATERNARY
TECTONO-STRATIGRAPHIC ARCHITECTURE IN THE SICILY CHANNEL
(CENTRAL MEDITERRANEAN)

Review and detailed analysis of the Plio-Quaternary tectono-stratigraphic architecture in the Sicily Channel (Central Mediterranean)

, Chizzini, N.², Maiorana, M.¹, adir, A.², Artoni, A.², Sulli, A.¹, Le Breton, E.⁴, Gasperini, L.³, Palano, M.¹, Polonia, A.³, Torelli, L.²

¹Department of Earth and Marine Sciences, University of Palermo, Via Archirafi 22, 90123 Palermo, Italy,

²Department of Chemistry, Life Sciences and Environmental Sustainability, University of Parma, Parco Area delle Scienze, 157/A Parma, Italy

³Institute of Marine Sciences, CNR, via Gobetti 101, Bologna 40129, Italy

⁴Géosciences Rennes, UMR 6118 Centre National de la Recherche Scientifique, Université de Rennes 1, Rennes, France

mariagiada.maiorana@unipa.it

Abstract

Even though it may be seen as a stable zone given its foreland nature, the Sicily Channel, located in the Central Mediterranean between Sicily and Tunisia thought to be a continental foreland of the Sicilian Maghrebian chain which exhibits a considerable tectonic complexity. With three main tectonic troughs - Pantelleria, Malta, and Linosa grabens - caused by the African plate continuous stretching, it hosts a foreland-foredeep-chain system that includes the Pelagian foreland, the Gela Foredeep Basin, and the offshore segment of the Neogene-Quaternary Sicilian-Maghrebian chain. This work illustrates in detail the stratigraphic architecture of the Sicily Channel and the main tectonic features that acted in this region during the Plio-Quaternary, based on an extensive review of the available literature, including already-published multichannel seismic reflection profiles and structural maps. In addition, we examine their timing to acquire an exhaustive understanding of this region's Plio-Quaternary tectonic evolution. Our findings indicate that the Sicily Channel cannot be considered a simple rifted foreland zone, but rather exhibits recurrent late Neogene/Plio-Quaternary extensional and compressional pulses. This additional evidence suggests that distinct tectonic regimes may coexist in a foreland area, further supporting the idea that foreland basins are reactive recorders of dynamic processes governing lithosphere deformation and are susceptible to tectonic reactivation.

1. Introduction

Foreland basins, commonly considered as the areas ahead the orogens not already affected by accretionary processes, are key tectonic elements in the periphery of orogenic belts, forming in direct response to oceanic subduction and continental underthrusting (*Allen et al., 1986; Allen and Allen, 1990; Cloetingh et al., 1994; Ziegler et al., 1994, 1995; DeCelles and Giles, 1996; DeCelles, 2012; Cloething et al., 2015; Royden and Faccenna, 2018*). In the past few years, a

number of marine campaigns and studies have been carried out in the Sicily Channel with the goal of determining the main tectonic structures affecting this region, arguing their timing, and ultimately suggesting a geological evolution for this area (*Finetti, 1984; Argnani et al., 1986; Antonelli et al., 1988; Lentini et al. 1990, 1994, 1996; Catalano et al., 1996, 2000; Finetti and Del Ben, 2005; Civile et al., 2008, 2010, 2014, 2016; Cavallaro et al., 2017; Meccariello et al., 2017; Civile et al., 2018; Fedorik et al., 2018; Ferranti et al., 2019; Civile et al., 2021; Volpi et al., 2022; Maiorana et al., 2023*).

All the recent studies recognized the existence of contractional and extensional structures in the Sicily Channel. The latter were believed to be positive inverted faults that enucleated from inherited Mesozoic extensional discontinuities. Such structures were explained as being caused by the compressive stress that the surrounding fold-and-thrust belts (Egadi Thrust Front-ETF; Adventure Thrust Front-ATF; Gela Thrust Front-GTS) transmitted to the Sicilian foreland and, more generally, as related to the ongoing convergence of the Africa-European plates (*Civile et al., 2021; Cavallaro et al., 2017; Maiorana et al., 2023*). Nevertheless, all the works focusing on the Sicily Channel limited their investigation strictly on single sectors of this complex area. Consequently, an overall overview is still lacking. The goal of this research is to fill this gap by offering these important but missing documentations. Based on an extensive review of the available literature, including already-published multichannel seismic reflection profiles and structural maps, we examine the major tectonic structures located in the Sicily Channel discussing also their timing, including the Capo-Granitola Sciacca (CGFSZ) offshore sector and the Adventure Plateau, as well as the frontal part of the GTS (Fig.1), in order to provide a more comprehensive and updated map of the Sicily Channel and the surrounding areas. We also focus on an overall Plio-Quaternary evolution of the Sicily Channel in relation with the Mesozoic paleogeography of this area also highlighting the main tectonic processes that shaped this complex area, thus providing some new general insights on foreland tectonics that could be extended for other study of foreland areas worldwide

2. Geological setting and post-Messinian evolution of the Sicily Channel

The Sicily Channel is a wide, shallow-water platform that stretches across an area of approximately 250,000 km², located between Tunisia and Sicily in the northern part of the African continental plate, or the so-called Pelagian Block or Northern portion of Africa Plate (Fig. 1) (*Burrollet et al., 1978; Argnani et al., 1986; Butler et al., 1992; Torelli et al., 1998; Lickorish et al., 1999; Holland et al., 2003; Corti et al., 2006; Civile et al., 2014; Cavallaro et al., 2017; Meccariello et al., 2017; Fedorik et al., 2018; Ferranti et al., 2019; Civile et al., 2021; Milia et al., 2021; Volpi et al., 2022; Maiorana et al., 2023, 2024; Micallef et al., 2024; Civile et al., 2024*). Reaching its southernmost point near Linosa Island, the Sicily Channel terminates at the West with Adventure Plateau, and at the East with the Malta Plateau (Fig. 1).

Since the Messinian, the variation in the Atlantic-Mediterranean connection led to the Messinian Salinity Crisis (MSC- *Butler et al., 1995; Roveri et al., 2014; Manzi et al., 2020, 2021; Pellen et al., 2022*), a significant event that impacted the paleogeographic and environmental evolution of the Mediterranean region, including the Sicily Channel (*Krijgsman et al., 1999; Butler, 2009; Lofi et al., 2011; Roveri et al., 2014; Aksu et al., 2018; Günes et al., 2018; Camerlenghi et al., 2020; Manzi et al., 2020, 2021*). This event led to a prominent sea-

level drop probably in the order of hundreds of meters (*de Alteriis, 1995*) and the consequent emersion and diffusive erosion of a large part of the banks/seamounts of the Sicily Channel (*Civile et al., 2015; Cavallaro et al., 2017; Meccariello et al., 2017*), as well as the sedimentation of very thick, locally up to 3 km, evaporites in the Ionian Sea to the East (*Lofi et al., 2011; Roveri et al., 2014; Haq et al., 2020; Manzi et al., 2020, 2021*).

In the Late Miocene a strike-slip regime affected this sector of the African plate, as well documented at Lampedusa Island (*Grasso and Pedley, 1985; Meccariello et al., 2017*). A continental rift-related process, started since the Lower Pliocene and controlled by sub-vertical normal faults, led to the formation of the Malta, Linosa, and Pantelleria WNW-ESE-oriented elongate grabens (*Finetti, 1984; Boccaletti et al., 1987; Cello, 1987; Grasso and Torelli, 1999; Carminati and Doglioni, 2005; Civile et al., 2010; Ghielmi et al., 2012; Cavallaro et al., 2017; Meccariello et al., 2017; Civile et al., 2021; Maiorana et al., 2023*), potentially with a dextral strike-slip component, especially in Malta and Linosa grabens (*Catalano et al., 2009*). Significant changes in asthenospheric flows, along with this Lower Pliocene extensional tectonic phase, prompted the Moho to rise under the major grabens of Malta, Pantelleria, and Linosa; this resulted in volcanic manifestations near the grabens' margins (*Maiorana et al., 2023*). The scattered anorogenic volcanism is mainly concentrated on the islands of Pantelleria and Linosa (*Rotolo et al., 2006; Civile et al., 2013; Micallef et al., 2024*), in the Adventure Plateau, and in the Sciacca offshore (*Peccerillo, 2005; Rotolo et al., 2006; Civile et al., 2013; Lodolo et al., 2019; Civile et al., 2024; Micallef et al., 2024*) (Fig. 2).

In the Lower-Upper Pliocene, the ongoing advancing of the GTS triggered a first compressional tectonic stage evidenced by the positive inversion of pre-existing extensional faults, especially in the Madrepore Graben (*Civile et al., 2021; Maiorana et al., 2023*). A strike-slip transfer zone developed at this time, named Capo Granitola-Sciacca Fault Zone (CGSFZ), which is interpreted by different authors as a wide active lithospheric structure that exhibits left-lateral kinematic movement, crossing the central part of the Sicily Channel (*Argnani et al., 1986; Antonelli et al., 1988; Fedorik et al., 2018; Civile et al., 2018; Ferranti et al., 2019; Palano et al., 2020; Civile et al., 2021*) (Fig. 1).

Throughout the Upper Pliocene to Lower Pleistocene, the region was affected by both extensional regimes relating to the Sicily Channel rifting and compressional regime marked by positive inverted faults (*Civile et al., 2021; Maiorana et al., 2023*). Nonetheless, because of the continuous stretching of the African upper plate, extensional tectonics is still present today, associated with a compressive regime, whose origin has been recently ascribed to a possible plate re-organization and change of subduction polarity (*Zitellini et al., 2020; Sulli et al., 2021*). An ongoing stretching of the African plate continued to occur, in particular south of the Gela Basin, marked by the development of WNW-ESE to NW-SE-oriented extensional faults (*Cogan et al., 1989; Cavallaro et al., 2017*). All these events could be related to the fast slab retreat of the Calabrian Arc (*Faccenna et al., 2001a, 2001b*), potential slab tearing (*Arab et al., 2020*), and the independent motion and rotation of the Adria Plate relative to Africa and Europe (*Le Breton et al., 2017*).



Fig. 1. Bathymetric map showing the main and structural elements - AP: Adventure Plateau; ATF: Adventure Thrust Front; CGSFZ: Capo-Granitola Sciacca Fault Zone; SRFS: Scicli-Ragusa Fault System; ETF: Egadi Thrust Front; GTF: Gela Thrust Front; GTS: Gela Thrust System; MG: Malta Graben; LG: Linosa Graben; PG: Pantelleria Graben (after Maiorana et al., 2024, in: Gasparo Morticelli et al., 2015; Civile et al., 2018; Sulli et al., 2021). The localization of the study area is marked by a yellow dotted box. Bathymetry data is from EMODnet (<https://emodnet.ec.europa.eu/en>) and the inset structural map is derived from Le Breton et al. (2021).

2.3 Seismicity and geodetic data

Historical seismicity in the Sicily Channel is poorly documented because of the geographic distribution of islands which hampered the development of a dense and well-designed seismic network geometry. In addition, the limited number of seismic stations operating in the area over the last five decades showed discontinuous functioning due to the lack of regular maintenance. Despite these limitations, data from instrumental seismicity catalogues highlights the main seismic features in the Sicily Channel region (Fig. 2). Regardless of the presence of active faults and its composite geodetic deformation, the region is characterized by a low-to-moderate seismic activity (Palano *et al.*, 2020). Along the southern margin of Sicily, seismicity is mainly clustered on the Hyblean Plateau and on Belice area, well remarking the lively tectonic activity of both areas (Fig. 2).

Historical catalogues document that large seismic events ($M \geq 6.5$) have taken place since 1125 (Palano *et al.*, 2020; <https://www.emidius.eu/SHEEC/>). Moreover, the SHEEC catalogue reports the occurrence of moderate earthquakes ($M > 4.5$) only since 1578, close to Pantelleria Island and along the south-western Sicily coast. The largest earthquake in offshore Sicily took place in 1740, with an estimated magnitude of 5.2 (Palano *et al.*, 2020; <https://www.emidius.eu/SHEEC/>). Different focal mechanisms available by the INGV database (ISIDE Working Group, 2007; https://emidius.mi.ingv.it/CPTI15-DBMI15/query_place/) highlight a widespread strike-slip type of movement (Palano *et al.*, 2012) (Fig. 2).

Seismological studies indicate that Sicily hosts two significant fault zones that extend offshore into the Sicily Channel, located to the east and west of the GTS, respectively. The first is to the west and runs from Sciacca to Linosa Island in an NNE-SSW direction, corresponding to the CGSFZ (Figs. 1) (Calò and Parisi, 2014; Civile *et al.*, 2018; Fedorick *et al.*, 2018; Ferranti *et al.*, 2019; Civile *et al.*, 2021). The second is the Scicli Ragusa Fault System (SRFS) (Figs. 1) extending from southeast Sicily, through Ragusa, to the offshore Sicily Channel. The entire fault zones has shown evidence of left-lateral strike-slip activity (Catalano *et al.*, 2008) (Fig. 2), which is associated with the formation of bend geometries that are both restraining and releasing between the various *en-echelon* segments (Grasso and Reuther, 1988).

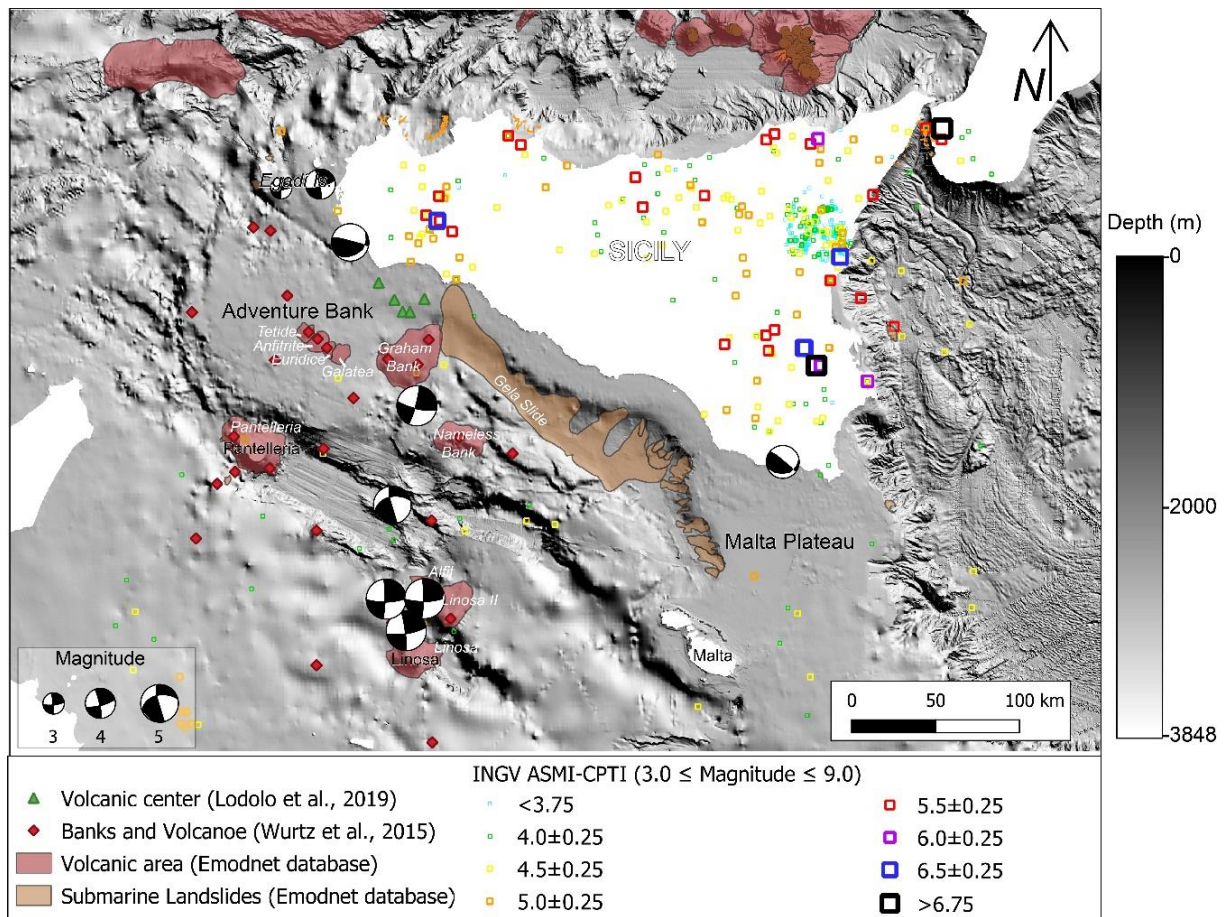


Fig. 2. Focal mechanisms of the earthquakes from the INGV database (https://emidius.mi.ingv.it/CPTI15-DBMI15/query_place/) and the instrumental seismicity from the SHARE European Earthquake Catalogue (<https://www.emidius.eu/SHEEC/>) in onland Sicily and offshore southern Sicily. Bathymetry data is from EMODnet (<https://emodnet.ec.europa.eu/en>).

2.4 Volcanic activity

The widest magmatic manifestations in the Sicily Channel are exposed on Pantelleria Island (Fig. 2), where rocks show an age of 0.324-0.003 Ma (Mahood and Hidreth, 1983; Civetta et al., 1998; Micallef et al., 2024). Linosa island, instead, formed between 1.06 and 0.53 Ma (Lanzafame et al., 1994), consists of a volcanic building that has developed partly above the sea level (Figs. 1, 2) (Calanchi et al., 1989; Corti et al., 2006; Lodolo et al., 2012). Recent bathymetric data show that only roughly 3.6% of the total volcanic complex (about 165 km²) is comprised of the emergent part of Linosa, indicating uncertainty regarding the area's volcanic product's submarine extension (Tonielli et al., 2019).

The Sicily Channel is also characterized by historical volcanic activity. The oldest magmatic activity has been discovered in a submerged volcanic seamount east of Nameless Bank, occurred in the late Miocene (Beccaluva et al., 1981). Later, in the pre-Last Glacial Maximum (ca. 20 ka B.P.) a tectonic event near the CGSFZ produced several volcanic structures (Lodolo et al., 2019). A few other noteworthy and recent eruptions occurred in 1831 in Ferdinanda Island's Graham Bank at a depth of about 200 m which gave rise to the temporary island known

as Foerstner volcano, which was about 65 m above sea level (Washington 1909., Colantoni et al. 1975; Corti et al., 2006; Conte et al., 2014)

The region's youngest eruptions occurred in 1891 approximately 5 km northwest of Pantelleria, where a submerged volcanic eruption was documented (Washington, 1909), in 1941 at the Pinne Marine Bank, located at the southeast wedge of Graham Bank (Imbò, 1965; Carapezza et al., 1979), as well as in 1981 near Pantelleria Island, approximately 5 km northwest of the island (Washington, 1909). Near the Graham Bank region, several geomorphic features associated with fluids emissions were recognized by Spatola et al. (2018). The diffused pockmarks, mounds, volcanic seamounts show a fault-controlled geometry in agreement with the Plio-Pleistocene extensional faults affecting the NW Sicily Channel as observed from the volcanic seamounts around the Pantelleria Graben (e.g. the Angelina seamount) which also show a volcano-tectonic origin (Civile et al., 2010; Lodolo et al., 2012).

3. Sicily Channel stratigraphy and pre-Plio-Quaternary paleogeography

The Sicily Channel consists of stratigraphic successions pertaining to the African continental margin, that after convergence and collision with the European plate, shortened and went on to form the tectonic units and domains of the Sicilian Maghrebian chain (Antonelli et al., 1988; Catalano et al., 1996). Since the Late Triassic, three main carbonate platform successions, represented by the Trapanese (in the Adventure Plateau), Saccense (in the Sciacca zone), and Iblean (in the Gela and Hyblean offshore) are found in the Sicily Channel (Fig. 3, 4a-f).

In detail, the Trapanese-Saccense expand from the Adventure Plateau to the GTS (Fig.1); the Saccense succession is similar to the Trapanese succession, except for Lower Oligocene-Miocene when the uplift of the Western sector of the Sicily Channel reorganized the distribution of emerged lands, wide regional highs (e.g. Mazara-Sciacca high) and shallow-water to outer shelf carbonate deposits in the Iblean sector to the East (Antonelli et al., 1988). The Late Triassic-Middle Liassic shallow platform dolomites and limestones (Sciacca and Inici Fms.) pass upward to Toarcian-Eocene pelagic seamount and deep marine limestones and marls (Buccheri, Chiaramonte, Hybla and Amerillo Fms.) (Figs. 3, 4a,b,c)(Antonelli et al., 1988; Catalano et al. 1996). In comparison, the clastic sequences are sedimentary rocks of the coastal and external platform (Fortuna, Ain Grab, Corleone, Terravecchia, and Ribera Fms.) mixed with open platforms and shallow water marl and limestone (San Cipirello, Mahmoud, and Nilde Fms.) and evaporitic deposits (Gessoso Solfifera Fm.) (Fig. 3).

The Sicily Channel as the whole African margin shows in the Lower Cretaceous, a typical deep-water sedimentation (Hybla and Amerillo Fms.) (Figs.3, 4b). These latter sedimentation conditions persist until the Oligocene, a period in which a variation occurs between sedimentation in the Iblean zone and the Madrepore Bank, where shallow-sea carbonate sedimentation (Ragusa Fm.) (Figs.3, 4c,d) persists, and the Adventure Plateau zone, where clastic sedimentation occurs (Antonelli et al., 1988).

The Hyblean domains, extending between the Ragusa-Malta Plateau and offshore of the Agrigento coast, presents a sequence mainly consisting of Late Triassic-Middle Liassic shallow platform and deep marine carbonates and shales (Gela, Noto, Streppenosa, Siracusa and Modica Fms.) followed by Toarcian-Eocene pelagic seamount and deep marine limestones and marls (Buccheri, Chiaramonte, Hybla and Amerillo Fms.) which are covered by external platform carbonates, marl, and evaporitic deposits (Ragusa, Tellaro and Gessoso-Solfifera Fms.) of the Oligocene-Miocene age (Figs. 3, 4d, e, f).

The sedimentation and evolution of the Sicilian Channel area records also the event that occurred in the Upper Miocene (5.96 and 5.33 million years ago) following the isolation of the Mediterranean basin from the Atlantic basin: the Messinian salinity crisis (MSC) (*Andretto et al., 2021; Haq et al., 2020; Roveri et al., 2014; Manzi et al., 2020, 2021*). This event, which occurred as a following the closure of the Strait of Gibraltar, resulted in the sedimentation of considerable amounts of evaporitic deposits (referred to as the Gessoso Solfifera Fm.) (Fig. 3, 4f).

After the Messinian event, clastic deposits of the Plio-Quaternary age (Trubi and Ribera Fms.) are prevailing (Fig. 3). They record a quick return to marine conditions, with megafloods (*Micallef et al., 2017*) and sea-bottom currents able to accumulate contouritic deposits (*Van Dijk et al., 2023*), followed by alternating clay and marls and sand deposited from shelfal area to deeper pelagic basins formed inside the grabens and foredeep that still shape the seafloor bathymetry (Fig. 1) associated to a complex tectonic and volcanic activity all over the Sicily Channel.

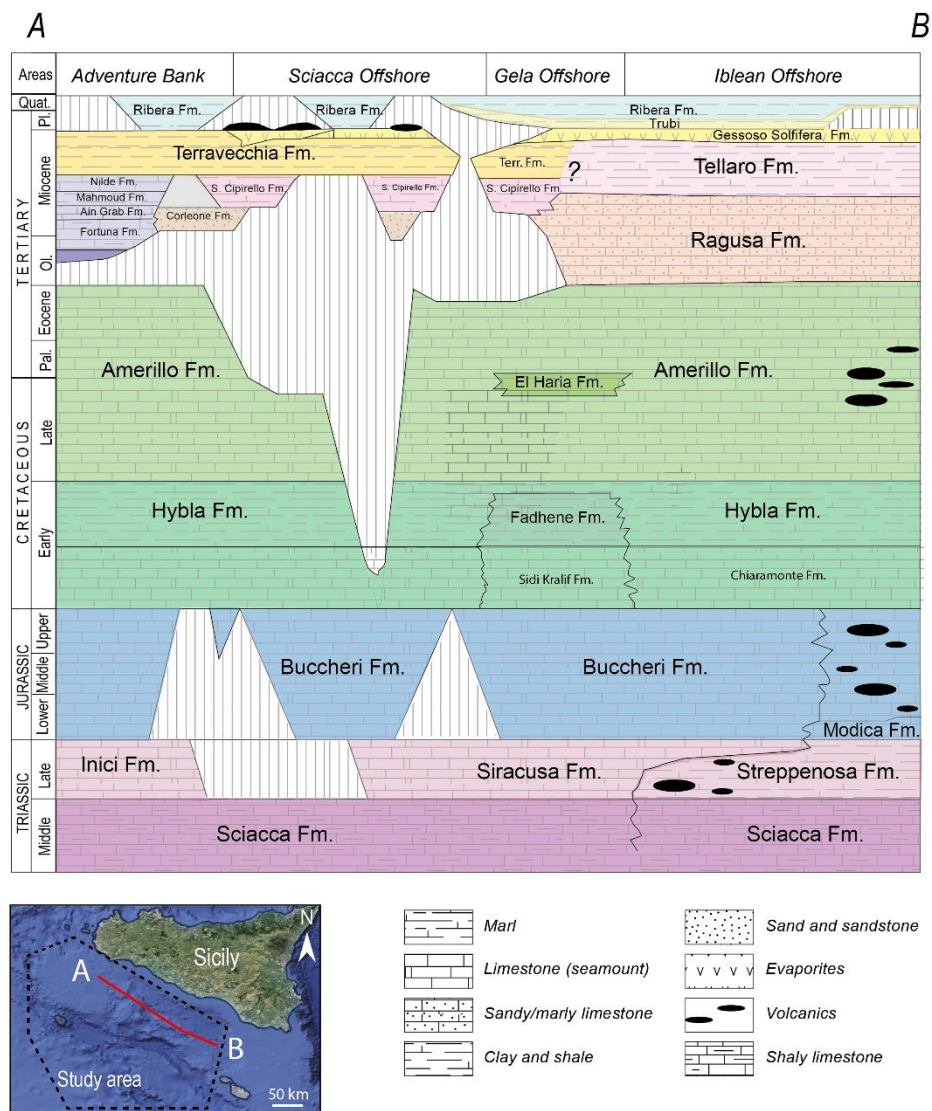


Fig. 3. Lithostratigraphic correlation chart along section A-B shown in the lower left corner; for details see section 3 in the manuscript (after Antonelli et al., 1988).

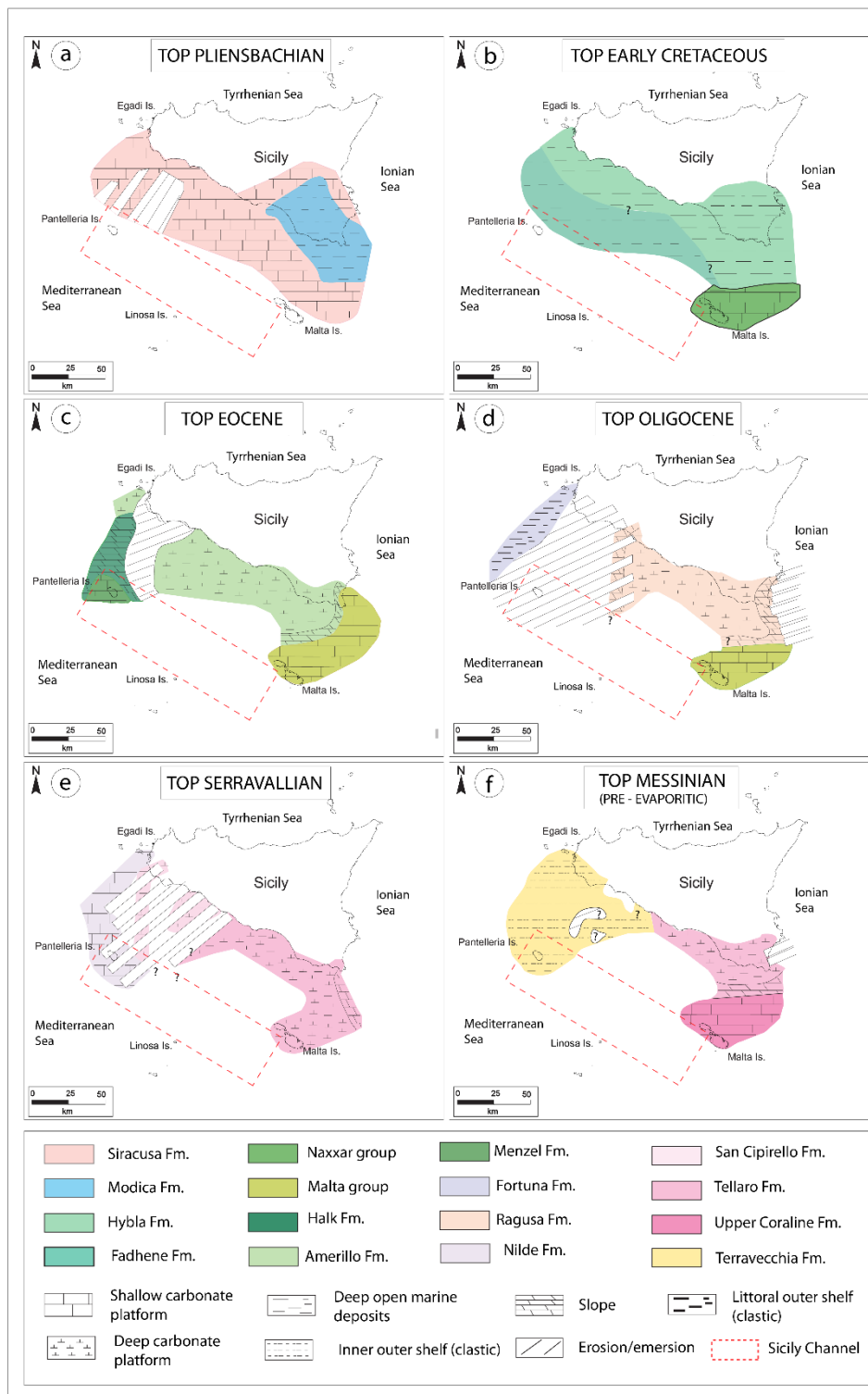


Fig. 4: Meso-Cenozoic paleogeographic evolution of the central and eastern sectors of the northern side of the Sicily Channel; a) top Pliensbachian, b) top Early Cretaceous, c) top Eocene, d) top Oligocene, e) top Serravallian, f) top Messinian; refer to the text for details (after Antonelli et al., 1988).

3. Data and methods

An extensive review of the Sicily Channel literature was conducted to extract the post-Messinian major tectonic and structural features along with the main regional unconformities to better constrain the stratigraphic architecture of this area and the timing of the main tectonic structures.

We report the line drawing of 9 seismic lines (Fig. 5), named Line 1 to Line 9 (Figs. 6, 7, 8, 9, 10, 11), realized using the Adobe Illustrator software coming from seismic profiles already published in the literature (see Tabs. 1,2 in Suppl. Mat. for seismic lines reference and details) covering the most representative Sicily Channel sectors (respectively Adventure Plateau, Sclacca offshore, Gela Basin, Malta, Linosa and Pantelleria Grabens) (Fig. 1).

Structural data (line extension, kinematic, age) were extracted from the available literature (see Fig. 12 for the literature considered) and public database, such as INQUA (<http://portalesgi.isprambiente.it/it/node/627>) and ITACHA (<https://sgi.isprambiente.it/ithaca/viewer/index.html>), in order to create a summary structural map of the Sicily Channel (Fig. 12). The map was georeferenced with World Geodetic System (WGS) 84 coordinate reference system on a bathymetric data derived from EMODnet (<http://www.emodnet-bathymetry.eu/>), and different colours were assigned to the structural features coming from different authors/databases to highlight the information source (Fig. 12).

The most representative horizons, significant for the current review study, were categorized for the different sectors of the Sicily Channel based on their attributed age and their significance with respect to the different tectonic phases that occurred in these areas (Tab. 3).

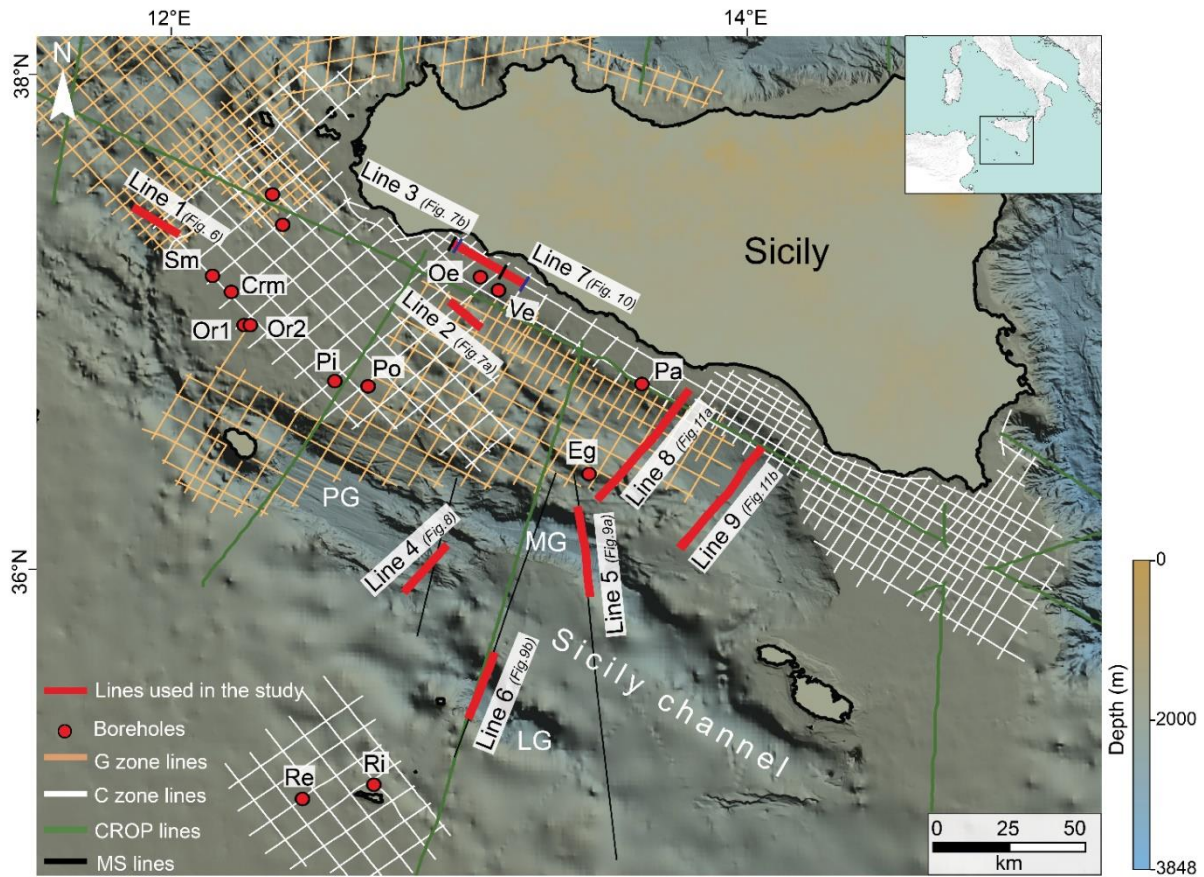


Fig. 5. Available seismic dataset and boreholes in the study area, derived from the literature and open access database (ViDEPI). Red lines correspond to the seismic reflection profiles reported in this work. Bathymetry data derived from EMODnet (<https://emodnet.ec.europa.eu/en>). Crm: Corvina Mare 1; Eg: Egeria 1; LG; Linosa Graben; MG: Malta Graben; Oe: Orione est-1; Or1: Orlando-1; Or2: Orlando-2; Pa: Palma-1; PG: Pantelleria Graben; Pi: Piera-01, Paola est-01; Re: Remo Nord-1; Ri: Riccio Sud-01; Samanta-1; Ve: Venere-1.

5 Review of Plio-Quaternary structural features in the Sicily Channel

5.1 Adventure Plateau

Situated in the northwest of the Sicily Channel, the 80,000 km² Adventure Plateau is the shallowest portion of the Sicily Channel, with average water depths of little more than 150 m (Figs. 1, 2, 6) (Corti *et al.*, 2006; Civile *et al.*, 2014).

In the Tortonian, a compressional deformation, coeval with the opening of the Tyrrhenian Sea, produced tectonic slices partially detached from the carbonate substratum, separated by ESE-verging thrusts and backthrusts (Catalano *et al.* 2000; Civile *et al.*, 2015).

During the Messinian, the northern part of the Adventure Plateau was affected by widespread compressive tectonics. ESE-verging thrusts and back-thrusts were generated, all belonging to the orogenic domain known as External Thrust System or Pelagian-Sicilian Thrust Belt, which represents the lowermost structural level of the Sicilian–Maghrebian Chain (*Lentini et al. 1990, 1994, 1996; Antonelli et al., 1988; Argnani et al., 1986; Civile et al., 2014*). This compressional tectonic is evidenced by the ETF, to the NW, and by the ATF to the SE (*Catalano et al., 1985, 1995; Lentini et al. 1990, 1994 Civile et al., 2014; Milia et al., 2021*) (Figs. 6, 12). Associated to the NE-trending Thrust System, the so-called Adventure Foredeep developed (*Argnani et al. 1986, 1987; Argnani 1993a, b; Civile et al., 2015*): a wide basin filled by clastic sedimentation, affected by compression and partially detaching from its substratum during the Late Messinian (*Argnani 1993a, b; Grasso 2001*).

Lentini et al. (1990) suggested that the Plio-Quaternary deposits sealed this compressional system. Instead, *Torelli et al. (1993)* proposed a recent reactivation of the ETF also supported by *Civile et al. (2014)* who interpreted the ETF as marked by several SE-verging thrusts (Figs. 6, 12) which affect the TCS and the TT; the latter clearly folded and disrupted by them, but they seem not affect the TMS and the shallowest Post-Messinian (Plio-Quaternary) sediments (Fig.6). Here, 0.1 s/TWT thick and typically unaltered and not influenced by compressive structures, except for a SW-verging thrust that clearly affects both the Pre-and-Post-Messinian successions reaching the seabed and, thus, testifies a recent tectonic activity of the ETF (Figs. 6, 12).

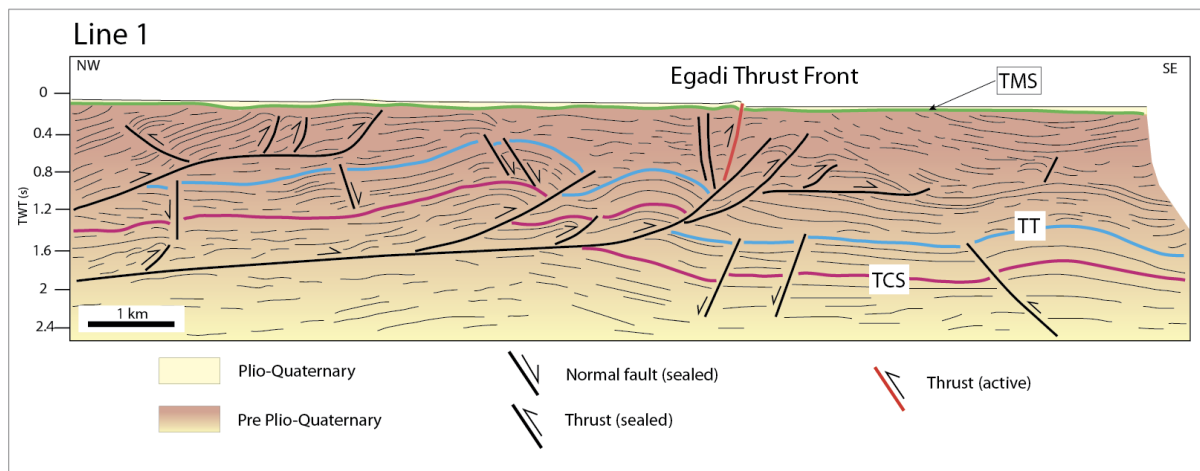


Fig. 6. Seismic Line 1 modified after Civile et al. (2014); see Fig. 5 for location and refer to Tab. 3 for the main horizons. Recent reactivation of the SE-verging Egadi Thrust Front (ETF) is visible, as it clearly affect the seafloor.

5.2 Sciacca

The north-western part of the Sicily Channel and the front of the Sicilian-Maghrebian Chain host a wide NS-trending, lithospheric-scale transfer zone (*Argnani et al., 1988; Argnani, 1990; Civile et al., 2008, 2010, 2014; Di Stefano et al., 2015*). This is associated to a wide fault zone, that is believed to affect the entire continental crust and the upper mantle to a depth of at least

70 km, as suggested by relocated seismicity and geochemical evidence (*Caracausi et al., 2005; Calò and Parisi, 2014*).

Monaco et al. (1996) interpreted as thrust with late Quaternary activity the faults recognized in the Sciacca offshore, which they interpret as the offshore extension of the 1968 Belice earthquake's area. Moreover, *Catalano et al. (2000)* recognized in the Sciacca zone a carbonate embriate fan (extending from the Tyrrhenian coast to the latitude of the Sciacca area) involving deposits composed of shallow to deep water carbonates and Tertiary terrigenous and clastic carbonate deposits belonging to the Trapanese and Saccense domains. Their interpretation suggest that the recent deformation is sealed by post-Messinian basinal strata.

Di Stefano et al. (2008, 2015) and *Lentini et al. (2014)* suggested instead that undeformed sequences of the Pelagian block are present in the Sciacca area, in continuity with those outcropping in the Hyblean plateau of southeastern Sicily. *Di Stefano et al. (2015)* recognized a shelf to deep water transition in the Sciacca area interpreted as a segment of the rifted southern passive margin of the Permo-Triassic Ionian Tethys that, at present, runs roughly N-S from San Vito Lo Capo to Sciacca (see location in Fig. 1). They suggest that this weakness zone may have been reactivated as a major right-lateral strike-slip fault on the basis of the variable direction of the stress field acting in the Central Mediterranean area since Late Miocene (*Mantovani et al., 2014*).

Recently, the Sciacca fault zone has been deeply investigated through the acquisition of seismic reflection profiles of variable depth and detailed morphobathymetric data. *Fedorik et al. (2018)* describes the N-S trending transfer zone as bounded by the Capo Granitola Fault to the west and by the Sciacca Fault to the east, those delimiting a 30-km-wide, mostly undeformed basin. The Sciacca Fault was formerly identified by several authors (*Argnani, 1990; Casero and Roure, 1994; Antonelli et al., 1988; Nigro and Renda, 2002; Finetti, 2003; Lentini et al., 2006; Ghisetti et al., 2009*).

The western fault (Capo Granitola) does not show clear evidence of present-day tectonic activity and, toward the south, it relates to the volcanic area of the Graham Bank (*Fedorik et al., 2018*). *Fedorik et al. (2018)* interpreted the Sciacca Fault as compatible with a right-lateral kinematics, that was reactivated in left-lateral during the Pliocene, as testified by the TMS unconformity disruption (Fig. 7a, b). They divided the Sciacca Fault into northern and southern parts. Along the northern segment, extended between the Sicilian coast and the northern margin of the Nerita Bank, the SF seems sealed by Late Pliocene-Quaternary deposits (Fig. 7b). The southern segment, extended between the Nerita and Terrible banks, shows clear evidence of active tectonics, particularly evident along the Nerita Bank (Fig. 7a).

Ghisetti et al. (2009) interpreted the Sciacca Fault as a structure composed of steep faults with positive flower-like geometry related to a N-S transpressive left system that bounds the "Sciacca High", an emergent salient of the Pelagian-African platform. *Civile et al. (2018)*, instead, interpreted it as part of the N-S transfer zone naming it CGSFZ, a fault system with evidence of Quaternary tectonics. They describe it as developed along a late Miocene foreland

structural high (Miocene peripheral bulge of the Sicilian-Maghrebian Chain). Part of the foredeep basin was later inverted along the CGFSZ and, since late Pliocene, a change from right- to left-lateral strike-slip tectonic regime with a compressional component of movement occurred (Fedorik *et al.*, 2018). This event was produced by a change in the direction of the African plate motion with respect to the fixed Eurasia, from NW to NE (Mantovani *et al.*, 2014).

Civile *et al.* (2021) describes instead the CGSFZ as mainly composed of positive flower structures in an active tectonic domain. On the other hand, Ferranti *et al.* (2019) suggest that the GGSFZ was active in left transpression since Late Miocene-Early Pliocene (previously than the Civile *et al.*, 2018 interpretation), when pre existing Late Tortonian-Early Messinian (Late Miocene) extensional or transtensional basins were inverted.

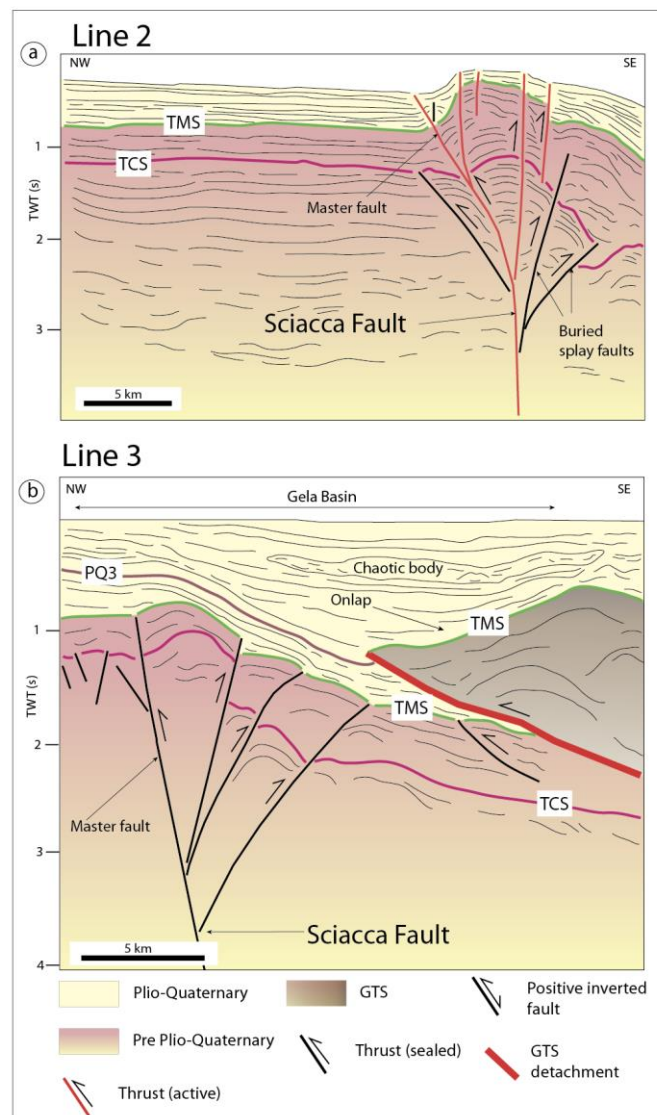


Fig. 7. (a) Seismic Line 2 and (b) Seismic Line 3, modified after Fedorick *et al.* (2018); see Fig. 5 for location and refer to Tab. 3 for the main horizons. The profiles show a positive flower structure associated with the Sciacca Fault, featuring the deformation of the Plio-Quaternary and Pre Plio-Quaternary strata.

5.3 Pantelleria Graben

Widely rectangular in shape, the Pantelleria Graben is a large depression of around 90 km in length and 30 km in width, broadening to about 40 km in correspondence of the Pantelleria Island (Figs. 1, 12) (Reuther and Eisbacher, 1985; Civile *et al.*, 2008, 2010). It is characterized by a linear NW-trending flanks controlled by NE-SW-dipping steep extensional faults with the same orientation (Figs. 1, 8, 12).

The southeastern border of the Pantelleria Graben is crossed by the NE-oriented seismic line reported in Fig. 8, the latter showing, in the SW part of the line, a structural high capped by a 0.78 s/TWT thick Post Messinian (Plio-Quaternary) succession. Here, the PQ1 divides the less deformed upper section of the Post-Messinian deposits, which is approximately 0.25 s/TWT thick, from the lower, 0.32 s/TWT thick, deformed part (Fig. 8). The substantial thickness of the Post Messinian (Plio-Quaternary) deposits visible in the Pantelleria Graben's southern edge (Fig. 8), according to Civile *et al.* (2021), suggests that the basin's original extent was wider than it is now, and that the succession that makes up the southern edge was later uplifted.

As previously mentioned, the main factor developing the Pantelleria Graben is an ongoing extensional faulting. However, according to a new interpretation proposed by Civile *et al.* (2021), the moderate folding that is evident in the graben's infill may be related to the existence of a supposed buried magmatic intrusion (Fig. 8). Here, several high-angle NE-SW-dipping and NW-SE-oriented normal faults disrupt the TMS and the PQ1 but are sealed by the shallower Plio-Quaternary sediments (Fig. 8).

As suggested by Civile *et al.* (2021), the TMS's location between the Graben infill and its southern edge indicates that a possible positive tectonic inversion, probably with a transpressive feature, likely occurred along the WNW-oriented, NNE-dipping fault that borders the Pantelleria Graben to the southwest, uplifting the basin (Figs. 8, 12). The juxtaposition of two zones with distinct tectonic deformations in this area (the Transpressive and Extensional regimes) raises the possibility of a potential NE-trending strike-slip structure between them (Civile *et al.*, 2021). On the other hand, the northern margin of the Pantelleria Graben is marked by a NW-trending structural high affected by an array of high-angle NW and SW-dipping extensional faults (Fig. 12).

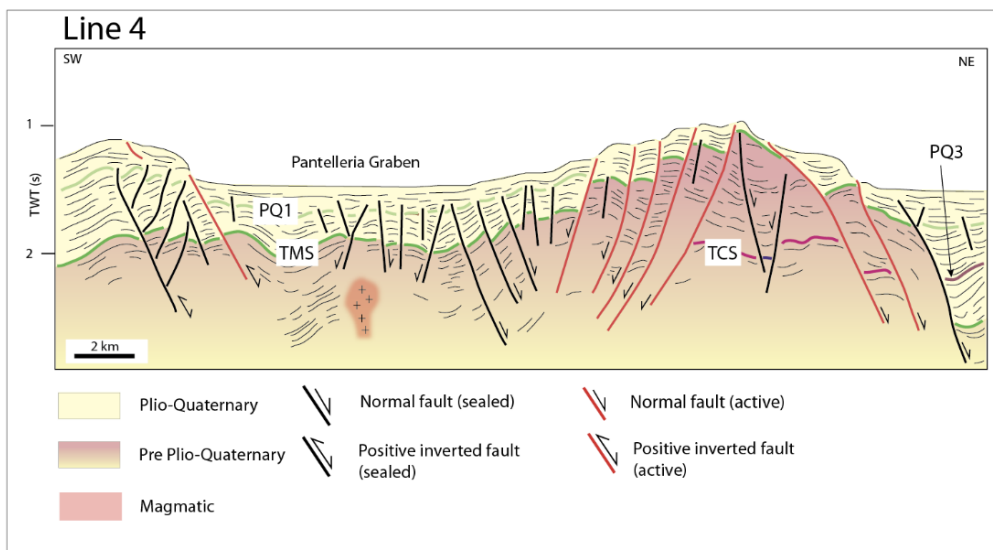


Fig. 8. Seismic Line 4, modified after Civile *et al.* (2021); see Fig. 5 for location and refer to Tab. 3 for the main horizons. The southern termination of the Pantelleria Graben is shown with highlighted a possible positive tectonic inversion; the folding in the sedimentary Plio-Quaternary infill of the graben is linked to the existence of a supposed buried magmatic intrusion by Civile *et al.* (2021).

5.4 Malta and Linosa Grabens

The Malta Graben is a NE-oriented tectonic depression that develops over 160 km in a sigmoidal form (Figs. 1, 12) (Civile *et al.*, 2021; Maiorana *et al.*, 2023). A maximum width of about 22 km is observed in the northwestern part of the graben, while in the southern portion it widens up to 30 km (Civile *et al.*, 2021). The maximum water depth of roughly 1700 m is reached in the northwestern part of the graben (Figs. 1, 12), where it is bounded by two prominent seafloor scarps associated with two prominent high-angle NW-trending and NE-SW-dipping extensional faults, as already evidenced in previous works (Figs. 8a, 11) (Dart *et al.*, 1993; Putz-Perrier and Sanderson, 2010; Civile *et al.*, 2021; Maiorana *et al.*, 2023).

Accordingly to Civile *et al.* (2021) and Maiorana *et al.* (2023), the graben's margins show evidence of wide magmatic intrusions (Fig. 9a). The Post-Messinian (Plio-Quaternary) infill is around 1.52 s/TWT (Fig. 9a), and within it there exist two major unconformities, i.e., U1 and U2, which record distinct deformational episodes (Fig. 9a). The Malta Graben records a younger extensional event, highlighted by the syn-rift geometry of the unit between U1 and U2, followed by a second event related to the positive inversion of pre-existing extensional structures. It follows a renewed extension, highlighted by the presence of normal faults affecting the seabed (Maiorana *et al.*, 2023).

Overall, the internal geometry of the Malta Graben is characterized by a roll-over anticline structure formed during an extensional phase, later inverted causing the folding of the deposits overlying the TMS and of the seafloor of the central Malta Graben (Fig. 8a) (Maiorana *et al.*, 2023). In fact, the seafloor highlights positive relief, at least 500 meters above the sea level, affected by a positive inverted fault NW-SE trending penetrating both the Pre and Post-Messinian sediments, and cutting the unconformities U2, U1 and TMS (Figs. 9a, 12). This indicates that compressive tectonics recently occurred inside the Malta Graben (Maiorana *et al.*, 2023).

Proceeding to the south, the Linosa Graben consists of a narrow depression with a width of about 20 km and a maximum water depth of over 1550 m (Figs. 1, 12) (Civile *et al.*, 2021; Maiorana *et al.*, 2023). The Post-Messinian (Plio-Quaternary) graben sedimentary fill has a maximum thickness of around 2 s/TWT (Fig. 9b). Two high-angle extensional faults that dip SW-NE and NW-SE, penetrate the Pre- and Post-Messinian sediment establishing a staircase pattern, and are associated to seabed scarps on both sides of the graben (Figs. 9b, 12) (Civile *et al.*, 2021; Maiorana *et al.*, 2023). The Plio-Quaternary infill between U1 and U2 exhibits a syn-rift geometry that indicates an extensional phase (Fig. 9b). The internal geometry of the Linosa Graben also shows the existence of a rollover anticline involving the TMS (Fig. 9b), extending for about 6-7 km with a NW direction (Civile *et al.*, 2021; Maiorana *et al.*, 2023). However, a

NW-SE striking and SW dipping fault that affects the TMS and the U1 is well imaged inside the Graben, but it is sealed by the shallowest Plio-Quaternary sediments (Fig. 9b). *Civile et al. (2021)* and *Maiorana et al. (2023)* recently interpreted this peculiar structure as a possible positive inverted fault that shortens the rollover anticline, which appears to be sealed by the U3 unconformity. According to *Maiorana et al. (2023)* and *Civile et al. (2021)*, the post-Messinian sediments lying above the U2 are interpreted as a post-rift succession that is up to 0.82 s/TWT thick. They are separated into an upper undeformed part (0.3 s/TWT) and a lower part that is up to 0.48 s/TWT thick. The upper part is marked by sub-parallel reflectors with onlap terminations against the U3, with the latter serving as the boundary between them.

Finally, according to recent findings by *Civile et al. (2021)* and *Maiorana et al. (2023)*, the Linosa Graben exhibits shallow magmatic intrusions concentrated along the margins of the graben (Fig. 8b), whose *Maiorana et al. (2023)* attributes to Linosa II volcanic activity (Fig. 2).

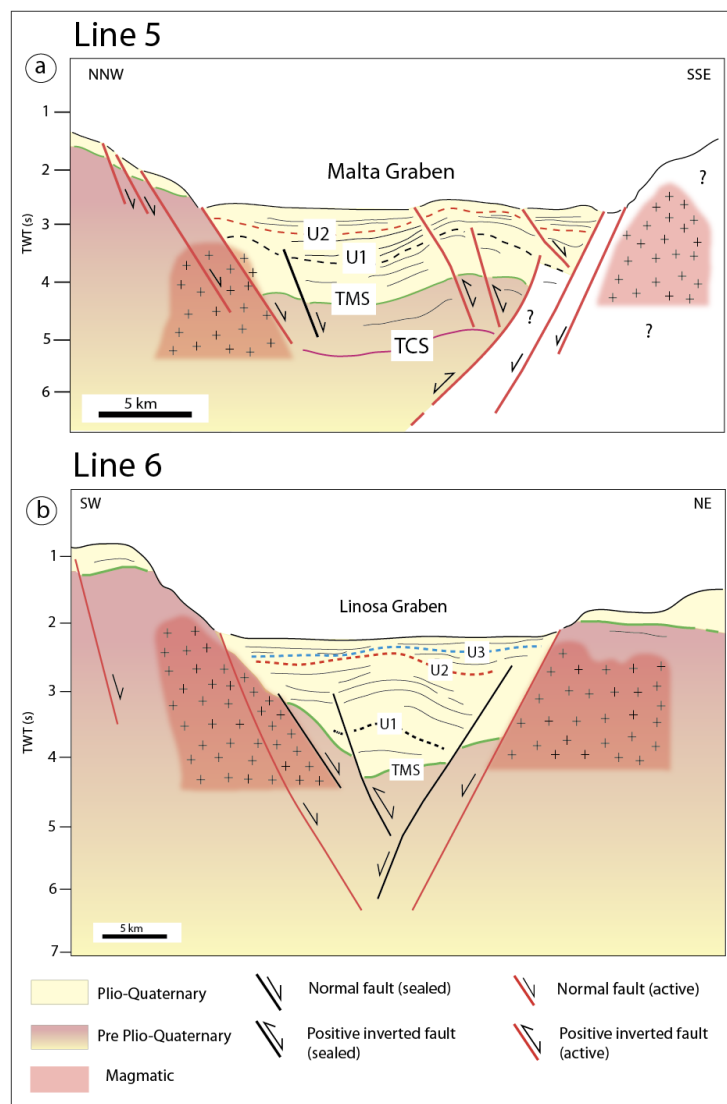


Fig. 9. (a) Seismic Line 5 modified after Maiorana et al. (2023); see Fig. 5 for location and refer to Tab. 3 for the main horizons. The line (a) shows the Malta Graben hosting a roll-over anticline affected by a positive inversion phase which folded the Plio-Quaternary deposits along with the seafloor; (b) illustrates the Linosa Graben, shows a

roll-over anticline geometry which has experienced an extensional phase, preserved in deposits between U1 and U2, and later a positive inversion event has possibly shortened the roll-over anticline which is buried under an unconformity U3.

5.5 The Gela Thrust System (GTS)

As the leading edge of the Sicilian–Maghrebian fold-and-thrust belt, the Gela Thrust Front (GTF) forms an accretionary wedge representing the youngest and outermost thrust sheet of the GTS (Figs. 1, 7b, 10, 11a, 12) (Ogniben 1969; Lentini, 1982; Catalano *et al.*, 1996; Ghisetti *et al.*, 2009; Cavallaro *et al.*, 2017). The GTF extends 20–25 km offshore the coast between Sciacca and Gela, facing the Sicily Channel, where it forms a large south-facing arc (Figs. 1, 12) (Ogniben, 1969; Catalano, 1987; Argnani, 1989; Grasso *et al.*, 1991; Butler *et al.*, 1992; Lickorish *et al.*, 1999; Catalano *et al.*, 1996; Corti *et al.*, 2006; Ghisetti *et al.*, 2009; Cavallaro *et al.*, 2017; Maiorana *et al.*, 2023). A foredeep basin, the so called ‘‘Gela Basin’’, stretches ahead of the GTF as a WNW-ESE-trending, narrow, and weakly deformed elongated depocenter (Figs. 1, 7b, 10, 11a, 12), mainly composed of 1–1.2 s/TWT thick post-Messinian sediments (Plio-Quaternary) (Figs. 7b, 10, 11a).

GTS’s structures resulted from the wedge’s internal deformation as well as the accretion of foredeep deposits into the thrust sheets (Lickorish *et al.*, 1999). Bianchi *et al.* (1989) show the GTS to be a composite structure with a higher unit consisting of Oligocene-Serravallian sandstones, Tortonian clays (Terravecchia Fm.) and younger Messinian-Pliocene units thrust onto a further sequence of Tortonian clays (Fig.3). The allochthonous nature of the GTS was reported by Butler *et al.* (1992) and Lickorish *et al.* (1999) who called it ‘‘Gela Nappe’’. They proposed that the latter is composed of a stratigraphic package that is repeated tectonically and internally shortened by a number of minor thrusts, the basal detachment of which is situated on top of the Lower Pliocene Trubi Fm. (PQ3; Figs. 7b, 10), on the basis of seismic reflection data and petroleum exploration wells.

Based on wells correlations, Catalano *et al.* (1996) and Cavallaro *et al.* (2017) indicated that the wedge is composed of imbricated clastic, evaporitic, and carbonate units from the Oligocene to Pleistocene in age, laying on the Pleistocene sediments of the Ribera Fm. of the Gela Basin. However, all prior study pointing that the GTS is a thin-skinned accretionary wedge characterized predominantly by compressive tectonics and a chaotic internal geometry marked by discontinuous, folded and faulted reflections, as a results of tectonic accretion processes (Figs. 7b, 10, 11a).

The GTS stacked units’ total thickness is ~1.5 s/TWT (Figs. 7b, 8, 11a). Close to the major deformation front, southwesterly vergent thrust sheets form a leading imbricate fan system, the latter overthrusts the northeastward dipping lower-Upper Pliocene foreland deposits and are sealed by the Plio-Quaternary sediments of the Gela Basin (Figs. 7b, 10, 11a). Its basal detachment thrust, which develops between 1.6 and 2.4 s/TWT, dips inland, exhibits an overall displacement of more than 5 km at an angle of ~8° (Figs. 7b, 10, 11a) and truncates the PQ3 and the sediments below (Figs. 7b, 10). Moreover, the undulation of the basal detachment

shown in Figs. 7b and 11a, suggest that some normal faults were reactivated with reverse mechanisms (Cavallaro *et al.*, 2017; Fedorick *et al.*, 2018), while Catalano *et al.* (1996) do not show evidence of such positive reactivation of previous extensional features (Fig. 10).

The TMS unconformity marks the top of the GTS, which is capped and draped by a thin (0.3-0.4 s/TWT) sediment cover (Figs. 7b, 10, 11a), ascribed to Pliocene age by Lickorish *et al.* (1999); the latter folded on the top of the nappe indicating that during the Pliocene the accretionary wedge was still moving and also subject to internal shortening. The GTF is clearly onlapped by Post-Messinian (Plio-Quaternary) sediments of the Gela Basin (Figs. 7b, 10, 11a). Internal thrusts involved the top of the GTS (TMS), the PQ3 and the PQ1 interpreted in the Gela Basin, as reported by Catalano *et al.* (1993, 1996) (Figs. 7b, 10, 11a).

On the top of the GTS, the Zanclean to Gelasian strata seem to be gradually folded, indicating that the accretionary wedge was still advancing southward and undergoing deformation due to internal shortening during this period. Furthermore, as has also been noted by prior authors (Trincardi and Argnani 1990; Lickorish *et al.* 1999; Cavallaro *et al.*, 2017), the GTS's surface slope plunges toward the Gela Basin, establishing to the gravitational instability of the sediments resting above the nappe and expressed by shallow and buried landslide bodies in the Gela Basin (Figs. 2, 7b, 11a).

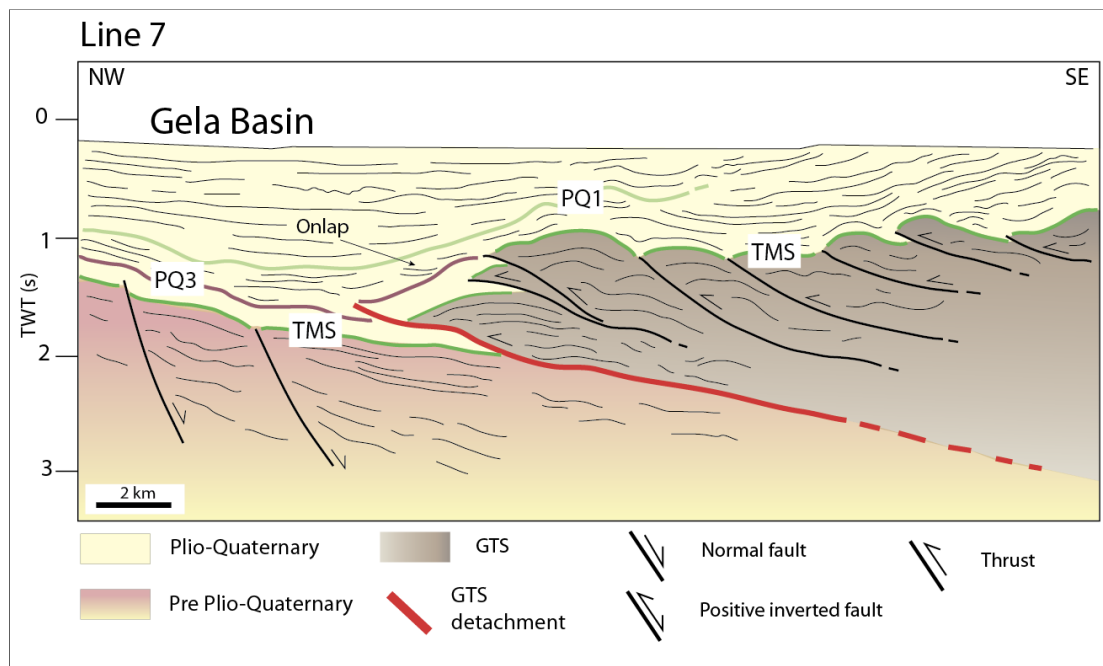


Fig. 10. Seismic Line 10 modified after Catalano *et al.* (1996); see Fig. 5 for location and refer to Tab. 3 for the main horizons; the relationship between the Gela Basin and the GTS are magnified: the Gela Basin extends south of the GTF as a narrow, and weakly deformed elongated depocenter, characterized by onlap termination against the GTS. The latter is marked by several SW-verging thrusts, clearly affecting the TMS and the PQ3.

5.6 The Madrepore Bank

The southern sector of the GTS is defined by the presence of the Madrepore Bank (Figs. 1, 11a, 12), a fault-bounded, 50 km long by 18 km wide, NW–SE trending monocline whose top has a depth range from 175 to 750 m bsl (Fig. 1) (Cavallaro *et al.*, 2017; Maiorana *et al.*, 2023). It is mainly composed by a Pre-Messinian succession, lacking the Post-Messinian (Plio-Quaternary) cover (Fig. 11a) (Cavallaro *et al.*, 2017).

Southward, the Pre-Messinian succession is covered by the middle-upper Miocene silty marls of the Tellaro Fm., in turn overlain by the Messinian evaporites and by a thin cover of Zanclean–Piacenzian sediments.

The Pre-Messinian succession is mainly composed of carbonates and marls (Ragusa Fm. - Oligocene–Early Miocene), limestones (Amerillo Fm. - Late Cretaceous–Eocene), marls (Hybla Fm. - Early Cretaceous), mudstones (Fadhene and Sidi Kralif Fms. - Early Cretaceous) and marls (Buccheri Fm. - Middle Jurassic) (Figs.3,4), according to correlations with Egeria 1 well log proposed by Cavallaro *et al.* (2017).

According to findings in this area (Antonelli *et al.*, 1988; Corti *et al.*, 2006; Cavallaro *et al.*, 2017), there have been localized reactivations of earlier normal faults that trend NW-SE (Figs. 11a, 12). A sharply SW-dipping and NW-SE-striking normal fault system over the Madrepore Bank is shown in Fig. 11a, affecting the whole post-Messinian succession and disrupting the TMS, the TCS, and TR, clearly reaching the seabed. Among them, one W-dipping and NW-SE-striking normal fault separate the Madrepore Bank from a depression, i.e, the Madrepore Graben (Maiorana *et al.*, 2023), filled of about 0,8 s/TWT of Post-Messinian (Plio-Quaternary) sediments; the latter seal a NW-SE-oriented normal fault system that also penetrates in the Pre-Messinian succession (Fig. 11a).

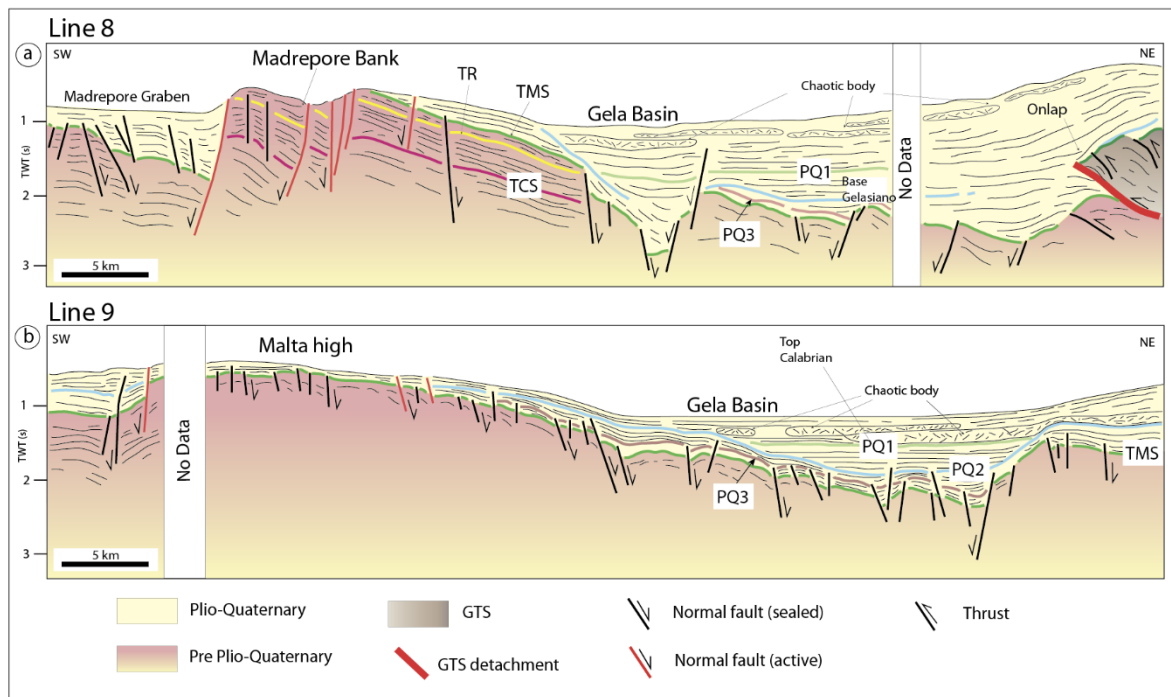


Fig. 11. (a) Seismic Line 8 and (b) Seismic Line (b) modified after Cavallaro et al. (2017); see Fig. 5 for location and refer to Tab. 3 for the main horizons. In (a) the Gela Basin, marked by onlap termination against the GTS and the Madrepore Bank; the latter is characterized by the absence of Plio-Quaternary sediments on its top and displays active extensional faults as they reach the seafloor; in (b) the Gela Basin and the Malta High, which is covered by a thin layer of Plio-Quaternary deposits and marked by a widespread extensional tectonics.

6. Discussion

6.1 Plio-Quaternary tectonic evolution of the Sicily Channel

The selected seismic lines reported in this work (Figs 5-11), integrated with a detailed review of the already published literature, allowed us to reconstruct the main tectonic evolutionary steps of this area from the post-Miocene up to Plio-Quaternary (Figs. 13, 14, 15).

The Mediterranean region underwent contractional deformation during the Upper Miocene due to the convergence between Africa and Europe (Dercourt *et al.*, 1986; Dewey *et al.*, 1989). This resulted in the formation of the Ionian-Tyrrhenian arc-trench complex and of the Sicilian-Maghrebian thrusts front, a fold-and-thrust belt situated in the northwest of Sicily (Fig. 13) (Antonelli *et al.*, 1988; Civile *et al.*, 2021; Sulli *et al.*, 2021). Within this framework, the Sicily Channel started to correspond as the foreland area of such chain.

In the Late Miocene-Lower Pliocene the subduction of the African plate was deactivated, resulting in the fast retreat of the Southern Apennines and Ionian Slabs (Civile *et al.*, 2021). Suddenly, a reorientation of the stress field and a change in the boundary conditions for the Central Mediterranean occurred, establishing a transitional area between the slow relative NW movement of the African plate and its eastward opening (Civile *et al.*, 2021). This differential motion was accommodated along the Sicily Channel by the onset of i) the Pantelleria, Linosa, and Malta Graben opening, resulted from a NW-SE-oriented extension of the African plate's foreland area (Corti *et al.*, 2006; Catalano *et al.*, 2009; Civile *et al.*, 2010; 2021; Maiorana *et al.*, 2023), possibly with a dextral strike-slip component (Catalano *et al.*, 2009; Civile *et al.*, 2021); and ii) the two roughly NS-trending regional-scale shear zones developing: the CGSFZ to NW, activated since the Upper Miocene (Ferranti *et al.*, 2019) or the Lower Pliocene (Fedorik *et al.*, 2018; Civile *et al.*, 2021), and the SRFS to NE, developed mainly onland and extending also offshore toward Malta Island for a minimum length of 40 km (Gardiner *et al.*, 1995; Pellegrino *et al.*, 2016) (Fig. 13). Both of them are the results of the reactivation in a strike-slip regime of previous N-S-oriented Mesozoic discontinuities, such as extensional faults controlling the platform-to-basin or shallow-to-deeper carbonate platform boundaries (slope) during Mesozoic in Sciacca and Malta areas (Antonelli *et al.*, 1988; Pellegrino *et al.*, 2016) (see, for instance, the paleogeographic map in Fig. 4d). In addition, NW-SE and NE-SW-oriented extensional faults developed nearby Malta Island and the SRFS (Antonelli *et al.*, 1988; Gardiner *et al.*, 1995) (Fig. 13).

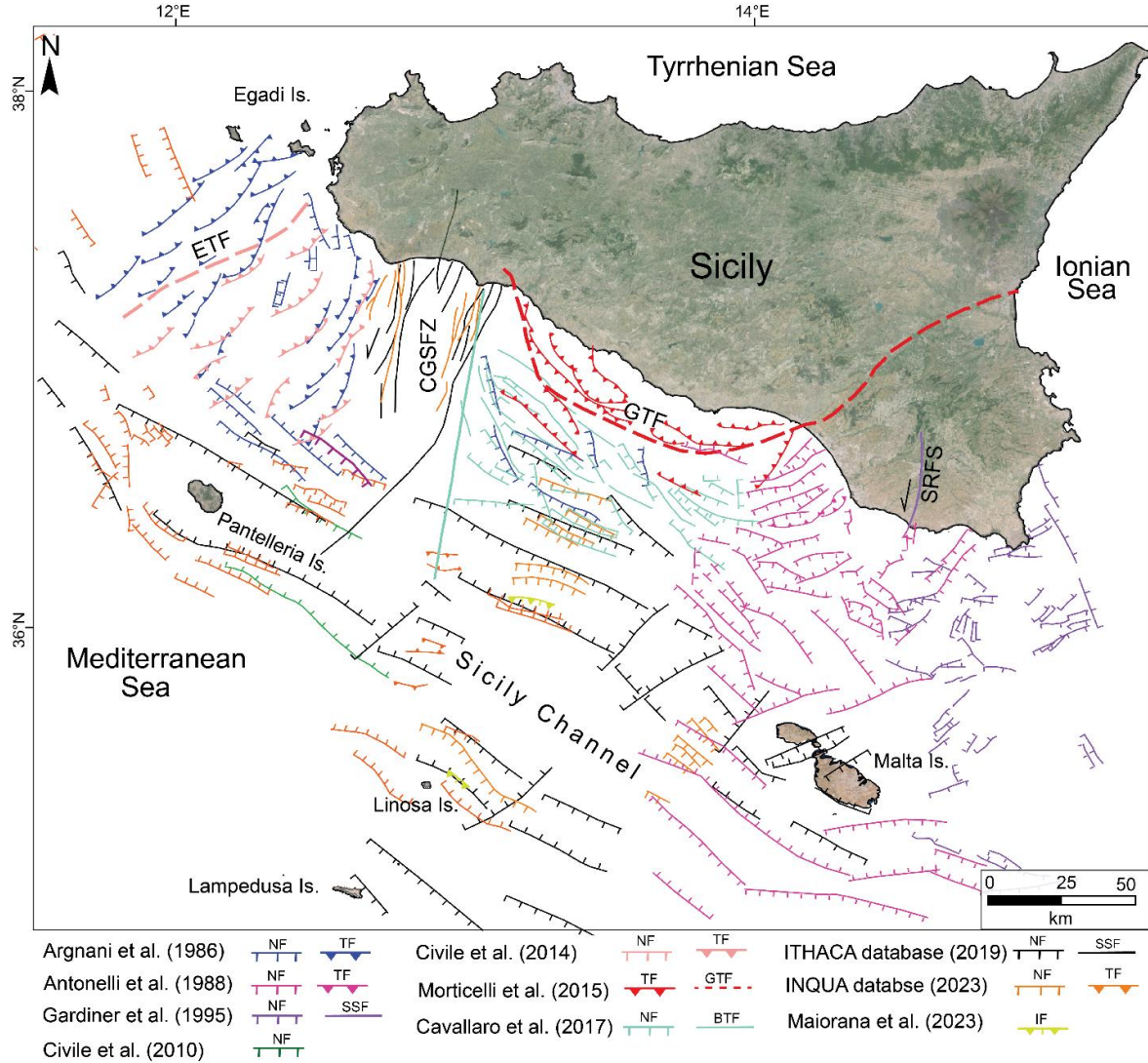


Fig. 12. Map of the Plio-Quaternary structural features of Sicily Channel. CGSFZ: Capo-Granitola Sciacca Fault Zone; ETF: Egadi Thrust Front; GTF: Gela Thrust Front; IF: Inverted Fault; SRFS: Scicli Ragusa Fault System; NF; Normal fault; TF; Thrust fault; SSF; Strike Slip Fault.

During the Lower Pliocene, the Sicilian-Maghrebian thrust front was segmented by the CGSFZ, resulting in two opposing and verging fold-and-thrust belts: the SE-verging ETF and the SW-verging GTS (Argnani *et al.*, 1986; Civile *et al.*, 2014; Morticelli *et al.*, 2015) (Fig. 13). These belts were both marked by strong compressive tectonics that was exemplified by thrusts and backthrusts (Civile *et al.*, 2021) (Fig. 13). Moreover, the GTS advance induced positive reactivation in the Madrepore Graben, in agreement with the first stage of advancement of the GTS dated to the Piacenzian (3.13 Ma) as reported by Cavallaro *et al.* (2017), Civile *et al.* (2021), and Maiorana *et al.* (2023).

In Early Pleistocene, the subduction in the Southern Apennines was inhibited by the entrance of the continental Apulian lithosphere at the trench, and the subduction process was active only

in the Ionian domain with the retreat of the oceanic slab that induced the rapid SE migration of the Calabrian Arc (Civile *et al.*, 2021). The ongoing GTS advancing to SSW transmitted compressive stress to the Sicilian foreland, inducing positive reactivation of previous SE-dipping and NW-SE-oriented extensional faults in the Linosa and Malta grabens (Cavallaro *et al.*, 2017; Civile *et al.*, 2021; Maiorana *et al.*, 2023) (Fig. 14), thus recording the last stage of the GTS advancement, in 0.8 Ma (upper Calabrian) (Di Stefano *et al.*, 1993; Cavallaro *et al.*, 2017; Maiorana *et al.*, 2023).

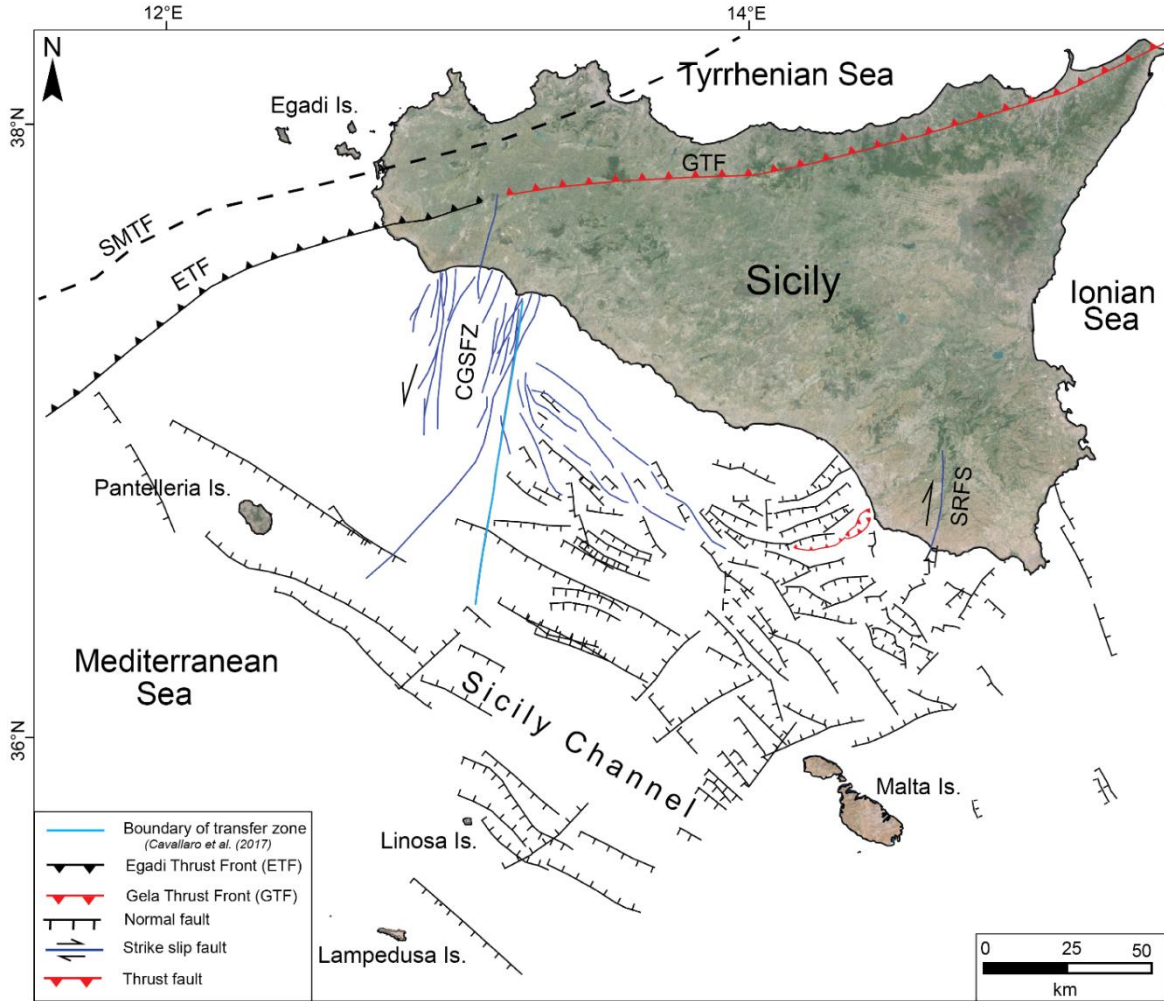


Fig. 13. Map of the Late Miocene-Early Pliocene structural features in the Sicily Channel. The eastward opening of the Central Mediterranean and the NW-SE oriented extension of the African plate's foreland area led to the formation of the Pantelleria, Linosa, and Malta grabens (Corti *et al.*, 2006; Catalano *et al.*, 2009; Civile *et al.*, 2010; 2021; Maiorana *et al.*, 2023). The two regional scale discontinuities developed: the Capo Granitola Sciacca Fault Zone (CGSFZ) to the NW and Scicli Ragusa Fault System (SRFS) to the NE (Gardiner *et al.*, 1995; Fedorik *et al.*, 2018; Civile *et al.*, 2021). The Sicilian-Maghrebian Thrust Front (SMTF) was emplaced in Late Miocene which was dissected by CGSFZ in Early Pliocene into opposing verging SE and SW verging ETF and GTS (Argnani *et al.*, 1986; Civile *et al.*, 2014; Morticelli *et al.*, 2015). Also, the GTS showed first stage of advancement which is dated Piacenzian (3.13 Ma) according to Cavallaro *et al.* (2017), Civile *et al.* (2021), and Maiorana *et al.* (2023).

Simultaneously, compression persisted in the NW sector of the Sicily Channel as well: the ETF kept moving to the SW and was characterized by a few minor NW-verging backthrusts as well as many SW-verging thrusts (Argnani *et al.*, 1986; Catalano *et al.*, 2000; Civile *et al.*, 2014) (Fig. 14). Extensional tectonics related to the Malta, Linosa, and Pantelleria Grabens remained active (Antonelli *et al.*, 1988; Civile *et al.*, 2010; Cavallaro *et al.*, 2017; Civile *et al.*, 2021; Maiorana *et al.*, 2023), as well as the system of NW-SE and NE-SW oriented extensional faults located in the easternmost part of the Sicily Channel, between Malta Island and the SRFS (Antonelli *et al.*, 1988; Gardiner *et al.*, 1995) (Fig. 14).

In the meantime, strike-slip activity continued in the lithospheric discontinuities CGSFZ and SRFS, which combined with the GTS compressive stress were probably partly responsible for the positive inversion observed in Malta, Linosa, and Pantelleria Grabens (Fig. 14). Throughout the entire CGSFZ, transpressional tectonic was active, and the SRFS may have shifted from a right-lateral to a left-lateral strike-slip motion sense (Fedorik *et al.*, 2017; Ferranti *et al.*, 2019; Civile *et al.*, 2021). However, shortening in the GTS ceased around the end of the Early Pleistocene when the GTS reached its present-day position (Catalano *et al.*, 1996, 2013; Civile *et al.*, 2021; Maiorana *et al.*, 2023); in contrast, shortening related to ETF persisted (Civile *et al.*, 2014) (Fig. 15).

At present day, Malta and Linosa Grabens show signs of positive inversion of former extensional faults (Fig. 15). These are primarily two NW-SW oriented and SW-dipping positive inverted faults that are thought to be a reaction to a potential plate reorganization and shift in subduction polarity (Sulli *et al.*, 2021; Maiorana *et al.*, 2023), as a results of the associated stress field (Sulli, 2000) that causes localized reactivations of such pre-existing extensional faults, which are prone to reactivation since they reflect zones of weakness (Maiorana *et al.*, 2023). This last stage is also accomodated by the ongoing activity of CGSF (Fig. 15) which today is seismically active, as testified by focal mechanisms in the area (Fig. 2). Also, ETF is active till date as suggested by the seafloor deformation described by Torelli *et al.*, (1993, 1995) and Civile *et al.* (2014) (Fig. 15). Towards the eastern part including the Malta plateau the normal faults seem to be more recently active as they have recently formed a series of seafloor horst blocks (Antonelli *et al.*, 1988; Gardiner *et al.*, 1995) (Fig. 15)

6.2 Plio-Quaternary structures in the Sicily Channel and implication on foreland (unstable) tectonics

The detailed review and analysis of the seismic reflection profiles reported in this study, along with the building of a general structural map, indicates widespread evidence of Plio-Quaternary tectonic activity affecting the Sicily Channel, despite the region's foreland nature suggests it should be part of a relatively stable continental area. According to the structural map in Fig. 14, the Sicily Channel is home of three major coexisting tectonic regimes.

The southernmost portion of the area features a pure and continuous extensional regime, exemplified by a NW-SE-striking normal fault system, at approximately 170 km from the surrounding orogens fronts (ETS and GTS). This extensional regime continues the predominant mode of deformation as it moves toward the northeast, here responsible for the development of

both surface and deep Plio-Quaternary tectonic structures. The evidence of this process are the extensional faults forging the grabens of Pantelleria, Linosa, and Malta (Fig. 12), as well as for the development of the roughly N-S trending volcanic belt that stretches from Lampedusa to Malta (Civile *et al.*, 2008) (Fig. 2).

Nonetheless, a new tectonic regime -a compressional regime- appears, localized and concentrated inside the grabens (at 129 km from the ETS-GTS). The greatest evidence can be found in NW-SE-oriented high-angle reverse faults, whose origin can be inferred to the positive inversion of previous Mesozoic normal faults (Cavallaro *et al.*, 2017; Civile *et al.*, 2021; Maiorana *et al.*, 2023). By contrast, a strike-slip/transpressional regime, typified by the CGSFZ, arises proceeding to NNW (added to the SRFS to NNE). It is noteworthy that the CGSFZ disrupts the NW-SE extensional faults connected to Malta, Linosa, and southern termination Pantelleria grabens in the NNW portion of the region, resulting in the overlap of two distinct tectonic regimes: strike slip/transpressive and extensional (Fig. 12).

All of the tectonic structures related the previously described regimes generally penetrate the deeper Pre-Pliocene layers, including the faults that are positively inverted, thus suggesting thick-skinned tectonics in the Sicily Channel (basement involved) (Cavallaro *et al.*, 2017; Civile *et al.*, 2021; Maiorana *et al.*, 2023). Given that the inverted faults enucleated from basement-affecting faults, which are linked to the rifting tectonic stage that preceded the compressive regime's development, this indicates a strong relationship between the two. In this sense, it is well known that positive inverted faults are generally largely influenced by the geometry and orientation of the structures developed during the previous phase of extension (Nalpas *et al.*, 1995; Ziegler *et al.*, 1995; Amilibia *et al.*, 2005; Del Ben *et al.*, 2010; Rodríguez-Salgado *et al.*, 2022). In particular, reactivation of extensional faults often occurs as reversal when the pre-existing extensional fabric is almost orthogonal to the direction of shortening (Ziegler *et al.*, 1995; Cooper and Warren, 2015; Rodríguez-Salgado *et al.*, 2022).

The GTS stress, that induced the Sicily Channel's inversion since the Middle Pleistocene (Cavallaro *et al.*, 2017; Civile *et al.*, 2021; Maiorana *et al.*, 2023), was almost orthogonal to the NW-SE-striking extensional faults, according to the recently published evolutionary model of Maiorana *et al.* (2023). As a result, these faults were reactivated in a compressive regime. There are several cases in the Mediterranean area where compressional stresses were transmitted several kilometers from the main deformation fronts, inducing the inversion of rifted and/or flexed foreland basins, thus sharing similar features with the Sicily Channel. Among them, the northern Tunisia, marked by a widespread compressional Eocene phase that led to reactivation as reverse of several extensional faults (Masrouhi *et al.*, 2008; Khomsi *et al.*, 2009; Rigane *et al.*, 2011); the Adriatic Sea, characterized by reverse reactivation of Mesozoic normal faults associated with the main phase of emplacement of the outer Apennine chain (Calamita *et al.*, 1991; Scisciani, 2009; Satolli and Calamita, 2012; Pace *et al.*, 2015); and the Ionian Sea, marked by several positive inverted faults generated due to the stress transmitted by the Calabrian Arc-Hellenic fold-and-thrust belt to the southern Adria Plate (Del Ben, 2009; Del Ben *et al.*, 2010; Basso *et al.*, 2021; Chizzini *et al.*, 2022, 2023).

It is important to point out that the presence of fluid-related features, well documented in the Sicily Channel in the form of pipes, bright spots, buried mud volcanoes, zones of acoustic blanking, and seafloor fluid seeps (Spatola *et al.*, 2018; Civile *et al.*, 2023; Maiorana *et al.*,

2024) may, in the presence of such compressive stress, facilitate the reactivation of extensional faults as reverse because they could reduce the friction along the fault plane (Sibson, 1995).

The intrusion of magmas and the consequently high heat flow are two further factors that can favor a significant intra-plate deformation in this area. It is generally known that, from a rheological point of view, the lithosphere of a rift that is destabilized by increased heat flow and/or magma intrusion is not as strong as that of thermally stable rift zones (Ziegler *et al.*, 1995; Rooney, 2017; Shillington, 2020; Pérez-Gussinyé *et al.*, 2023). The existence of several extensive volcanic zones (Fig. 2) and magmatic intrusion (Figs. 7, 8) most of them linked to a Moho rising at relatively shallow depths up to 17–18 km in the Malta and Linosa grabens (Maiorana *et al.*, 2023), may have contributed to weakening the Sicily Channel and making it prone to tectonic deformation with an high variability of tectonic regimes.

However, it is necessary to emphasize that regional plate tectonics is primarily responsible for controlling foreland tectonics and its architecture (Richardson, 1992; Zoback, 1992; Ziegler *et al.*, 1995; Doglioni *et al.*, 1999; Carminati *et al.*, 2010; Wang *et al.*, 2023; Zheng *et al.*, 2023). In the Sicily Channel, the interplay between slab-pull and roll-back, as plate driving forces, are considered as the main processes triggering the extensional tectonics affected this area during Plio-Quaternary and currently shaping it (Argnani, 1990; Govers and Wortel, 2005; Rosenbaum *et al.*, 2008; Argnani, 2009; Arab *et al.*, 2020; Maiorana *et al.*, 2023).. In this scenario the slow and oblique convergence and collision between Africa and Eurasia started since the Late Cretaceous (Bellon and Letouzey, 1977 ; Dercourt *et al.*, 1986; Dewey *et al.*, 1989; Stampfli and Borel, 2004; Mascle and Chaumillon, 1997; Polonia *et al.*, 2011; Jolivet *et al.*, 2021) associated with periods of plate-boundary reorganization, whose occurrence was already evidenced in this area by Sulli *et al.* (2021) in recent (Lower Pleistocene to present) times, are responsible for the nearly contemporaneous inception of compressive tectonic in this area.

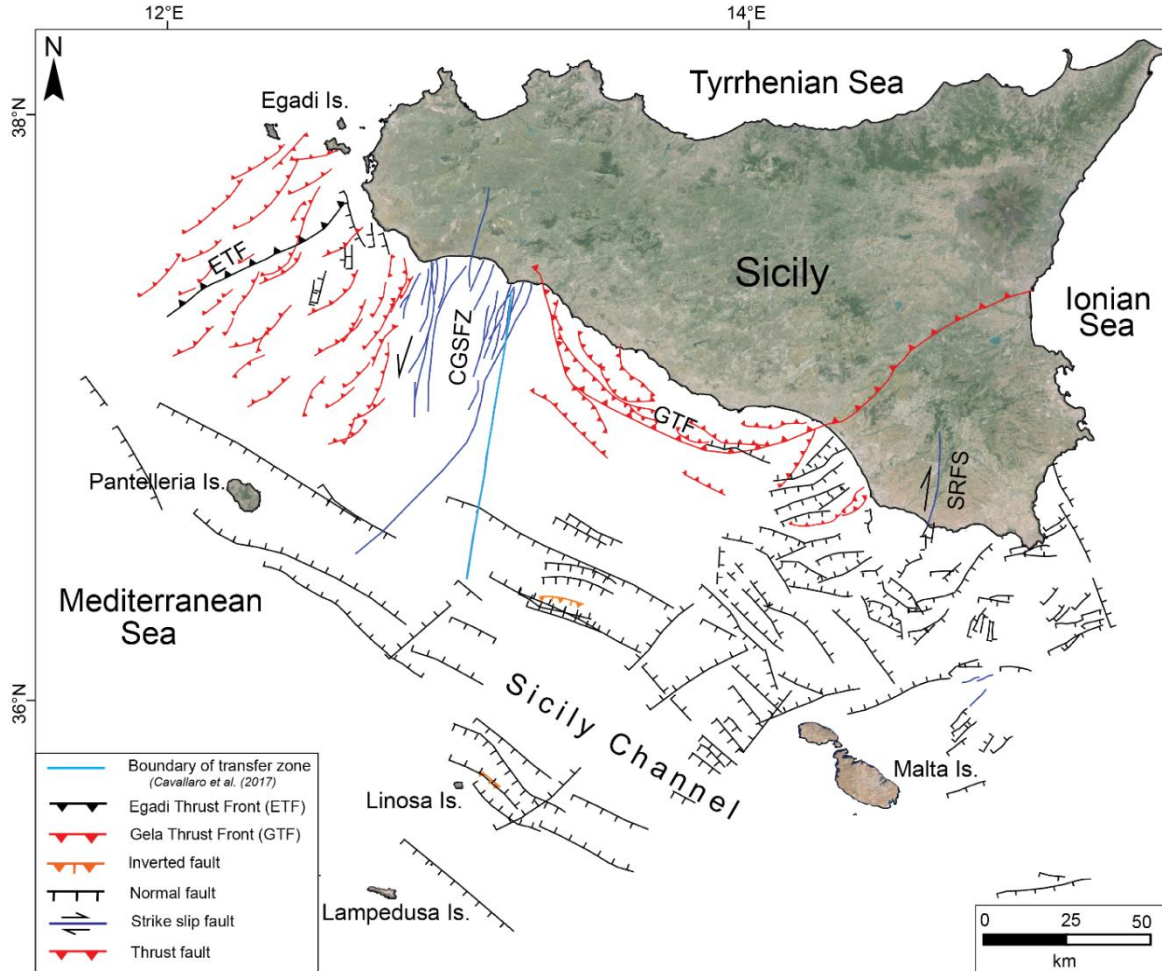


Fig. 14. Map of the Pleistocene structural features in the Sicily Channel. The Sicilian foreland witnessed compressive stress from the SSW advancing of GTS which gave birth to inversion (dated Piacenzian) in the sedimentary infill of Linosa and Malta grabens (Cavallaro et al., 2017; Civile et al., 2021; Maiorana et al., 2023). The GTS advancement came to an end in Upper Calabrian (0.8 Ma) (Di Stefano et al., 1993; Cavallaro et al., 2017; Maiorana et al., 2023). The compression persisted in the NW sector of Sicily Channel which led to the SW movement of ETF (Argnani et al., 1986; Catalano et al., 2000; Civile et al., 2014). The SRFS and CGSFZ remained active which according to Civile et al. (2021) and Maiorana et al. (2023) have caused the reactivation of the normal faults in in Malta, Linosa grabens and southern termination of Pantelleria Graben. The extensional tectonics linked to the grabens was also in force (Antonelli et al., 1988; Gardiner et al., 1995; Civile et al., 2010; Cavallaro et al., 2017; Civile et al., 2021; Maiorana et al., 2023). The movement of GTS came to an end while the shortening in ETF was still going on (Civile et al., 2014; Civile et al. 2021; Maiorana et al., 2023).

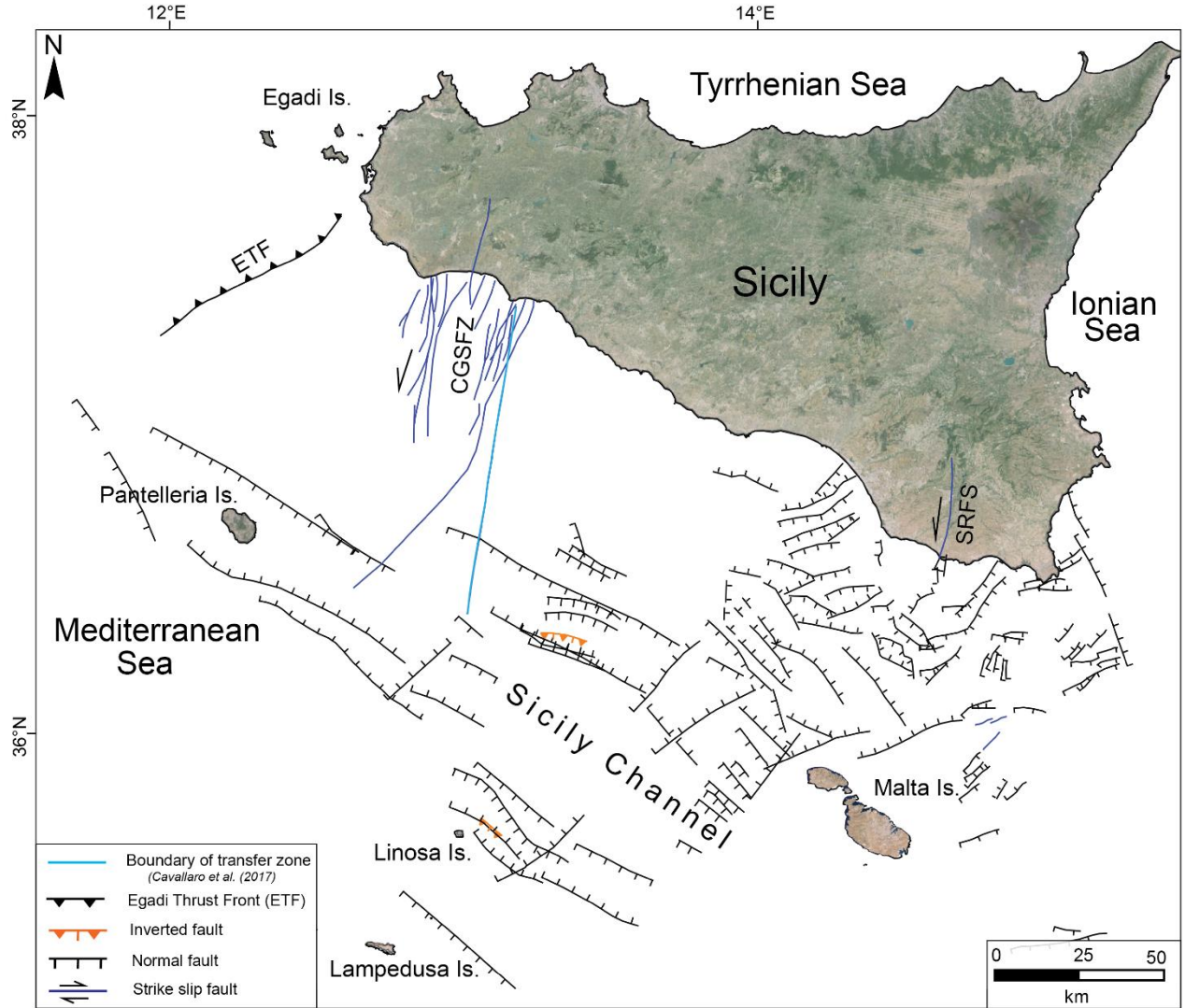


Fig. 15. Map of the active structural features in the Sicily Channel. The Malta and Linosa grabens show the evidence of positive inversion which is observed by Maiorana et al. (2023) by the persistent folding in the sedimentary strata which has even impacted the seafloor. The ETF is active till date which is justified by the seafloor deformation caused by it (Torelli et al., 1993, 1995; Civile et al., 2014). The extensional faults in the eastern part of the Sicily Channel including the Malta plateau seem to be recently active as these faults have recently formed a series of seafloor horst blocks (Antonelli et al., 1988; Gardiner et al., 1995).

Conclusions

Based on a detailed review of the already-published structural and stratigraphic data of the Sicily Channel, we have provided, for the first time, a general overview of the main tectonic features affecting this complex area, as well as a tectonic evolution since the Late Miocene to Present Day. Overall, all the previous considerations allowed us to establish the following broad findings:

- 1) Having its origin in a simple stage of passive rifting, the Sicily Channel developed from the interaction of multiple tectonic processes operating in a regional scale (slab pull and slab roll-back in particular) and linked to the complex geodynamic system of the Central Mediterranean, implying that regional plate tectonics represents the primarily responsible for controlling foreland architecture.
- 2) Structural discontinuities and preexisting weakness zones, such as previous extensional faults, are generally prone to reactivation in a compressional way, because they correspond to zones of preferential strain concentration that may favor the establishment of an intra-plate compressive regime, even if these zones are located far from the orogens. Moreover, the interplay between the early structural grain of a plate and the compressive stress orientation plays an important role in the localization of present-day tectonic structures as well as on the future basin architecture.

Considering the Sicily Channel as a natural laboratory, we can state that foreland regions can assume the role of sensitive recorders of the dynamic processes that control lithosphere deformation and are naturally susceptible to tectonic inversion. This is particularly true if they include a strongly faulted crust, as other regions in the Mediterranean area feature (Adriatic and Ionian Seas).

Our extensive analysis poses the basis for future studies on geohazards in this tectonically complicated region, as well as for interpreting and better constraining the kinematics of this area and other foreland locations worldwide.

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CHAPTER 3

Insights into the identification of fluid leakage pathways: a fluids pathway model

3.1 Introduction

The identification of fluid leakage pathways is a crucial element in the successful implementation of Carbon Capture and Storage (CCS) projects. CCS is a key technology for reducing atmospheric CO₂ levels, but its effectiveness depends on the secure containment of CO₂ in underground storage sites. One of the greatest challenges in CCS is ensuring that injected CO₂ remains trapped within the designated reservoir over the long term. Any potential leakage of CO₂ through subsurface pathways could lead to environmental harm, groundwater contamination, and failure to meet climate goals.

Fluid leakage pathways, such as faults, fractures, or abandoned wells, can compromise the integrity of a storage site. These pathways are often influenced by geological structures and geodynamic processes, including tectonic activity and pressure changes from fluid injection. Identifying and assessing these potential migration routes is therefore essential during the screening and selection of suitable CO₂ storage sites.

This chapter focuses on the methods used to detect and evaluate fluid leakage pathways in the Northwestern Sicily Channel (Adventure Plateau) gaining useful data for CCS screening. In a paper published in *Marine Geophysical Research* (Maiorana et al., 2024) a new fluids pathway model is presented, revealing the source of fluids emissions at depth in the Adventure Plateau. By applying geophysical surveys, seismic imaging, and geological modelling, it is possible to predict areas where leakage may occur.

3.2 SEISMO-STRATIGRAPHIC AND MORPHO-BATHYMETRIC EVIDENCE OF FLUID PATH ON THE ADVENTURE PLATEAU (NORTHWESTERN SICILY CHANNEL): A NEW FLUID-RISING MODEL



Seismo-stratigraphic and morpho-bathymetric analysis revealing recent fluid-rising phenomena on the Adventure Plateau (northwestern Sicily Channel)

Mariagiada Maiorana¹ · Daniele Spatola² · Simona Todaro¹ · Francesco Caldareri¹ · Fabrizio Parente¹ · Alessandro Severini³ · Attilio Sulli¹

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Abstract

The northwestern region of the Sicily Channel hosts a great number of morphological highs, the widest of which is the Adventure Plateau that is part of the Sicilian Maghrebic Fold and Thrust Belt system, formed since the Neogene. The Adventure Plateau was shaped in the Early Pliocene by an extensional phase that produced high-angle normal faults mostly WNW-ESE to N-S oriented. Through these faults, magmatic fluids ascended and produced widespread volcanic manifestations often associated to fluid flow processes. The interpretation of multibeam echosounder, seismic reflection (sparker, airgun) and well-log data allow us to identify several features related to the presence of fluids in the study area. The morpho-structural analysis showed a NW–SE oriented fault system and a string of pockmarks that follow the same trend. A detailed well-log analysis confirmed the presence of oil traces, at a depth of ~250 m, and gas (i.e., CO₂) at a depth of ~450 m. The seismo-stratigraphic analysis highlighted seismic signals located below the pockmarks, (e.g. seismic chimneys, bright spots) which suggest the presence of fluids that would rise to a few meters' depth. Based on the observations, two sources and two corresponding rising mechanisms have been identified. Morphometric analysis of pockmarks has been performed to delineate their possible interaction with the bottom currents. A fluids pathway model has been reconstructed, revealing the source of fluids emissions at depth in the Adventure Plateau, and providing new insights into the identification of fluid leakage pathways.

Keywords Pockmark · Seismic reflection profiles · Seismic chimney · Fluid seepage · Morpho-bathymetry

Introduction

Fluid flow and escape processes at the seafloor are widely and globally investigated phenomena affecting different geodynamic contexts (e.g., active and rifted continental margins, compression zones -subductions-, highly sedimented areas -deltas-), giving rise to diverse types of seabed morphologies, such as positive (e.g., mud volcanoes) or negative (e.g., pockmarks) features (Hovland 2011; Judd and Hovland

2007) as well as to a range of associated geological, geochemical and biological processes (Bünz et al. 2012; Hovland 2011; Judd and Hovland 2007; Sun et al. 2020).

Submarine fluid emissions occurring at the seafloor can be cold seeps, if refer to low-temperature emissions, lower than a few tens of degrees Celsius, and hot hydrothermal fluids, if reach 200 up to 400 °C. The main emitted gas is methane (CH₄) and secondarily carbon dioxide (CO₂) or nitrogen (N₂), either in the form of gas bubbles or dissolved gas (Claypool and Kaplan 1974; Judd and Hovland 2007). The methane generally originates from bacterial degradation of organic matter at low temperatures (biogenic gas) (Whiticar 1999, 2002), or thermogenic fluids produced from organic precursors at high temperature and pressure (Davis 1992; Etiope and Milkov 2004), CO₂ and N₂ are often related to hydrocarbon systems developed in proximity of subducting slabs or final phases of thermogenic gas generation (Motyka et al. 1989).

✉ Mariagiada Maiorana
mariagiada.maiorana@unipa.it

¹ Department of Earth and Marine Sciences, University of Palermo, Via Archirafi 22, 90123 Palermo, Italy

² Department of Earth Sciences, Sapienza University, Piazzale Aldo Moro 5, 00185 Rome, Italy

³ 7Seas Med Srl, Via Plinio 127, 74121 Taranto, Italy

The more recent geophysical tools in oceanic exploration such as multibeam echosounders, 2D and 3D high-resolution reflection seismics, imagine the water column, the seafloor (with information also on backscatter) and the sub-seafloor; these data allowed the mapping of fluid flow morphologies on continental margins and to reconstruct the migration patterns of the fluids to the seafloor. The seafloor depressions related to fluid flow detected from shallow to deep water via geophysical methods, direct observations (e.g., ROV images), and sediment and/or water samplings, are defined as pockmarks (Gentz et al. 2014; Judd and Hovland 2007; Spatola et al. 2017). They are strongly different in diameters and depths respectively from 150 m up to a few km (Sun et al. 2011), and have circular to elongate planform shapes, steep flanks, and flat to cone-shaped bottoms (Ceramicola et al. 2018; Ho et al. 2012; Micallef et al. 2022). The shape of pockmarks can be modified by the erosive action of the bottom currents (Miramontes et al. 2016; Picard et al. 2018). Pockmarks can be grouped in classes based on their size as follows (more detail in Hovland et al. 2002):

- (i) ‘Unit-Pockmarks’ to indicate very small depressions (1–10 m wide, and up to 0.6 m deep), usually isolated or organized in groups;
- (ii) ‘Normal pockmarks’ generally bigger (10–700 m wide, and up to 45 m deep).
- (iii) ‘Giant Pockmarks’ for depressions bigger than 250 m in diameter.

All the above-mentioned kinds of pockmarks can be found arranged in strings of pockmarks (up to a few km long). They often follow the weakness zones near-vertical faults, fractures or flexures (Hovland et al. 2002).

In the last years, evidence of fluid emissions has been recognized in the Sicily Channel around the Pantelleria Island, on the Graham Bank and on the Malta Plateau (Micallef et al. 2011; Savini et al. 2009; Conte et al. 2014; Spatola et al. 2018a, 2018b, 2023; Volpi et al. 2022; Ferrante et al. 2022; Civile et al. 2023), but the fluid flow process in the area is still poor known especially the mechanisms of migration of the fluids from deep sources to the seafloor and the role of the faults and/or fractures.

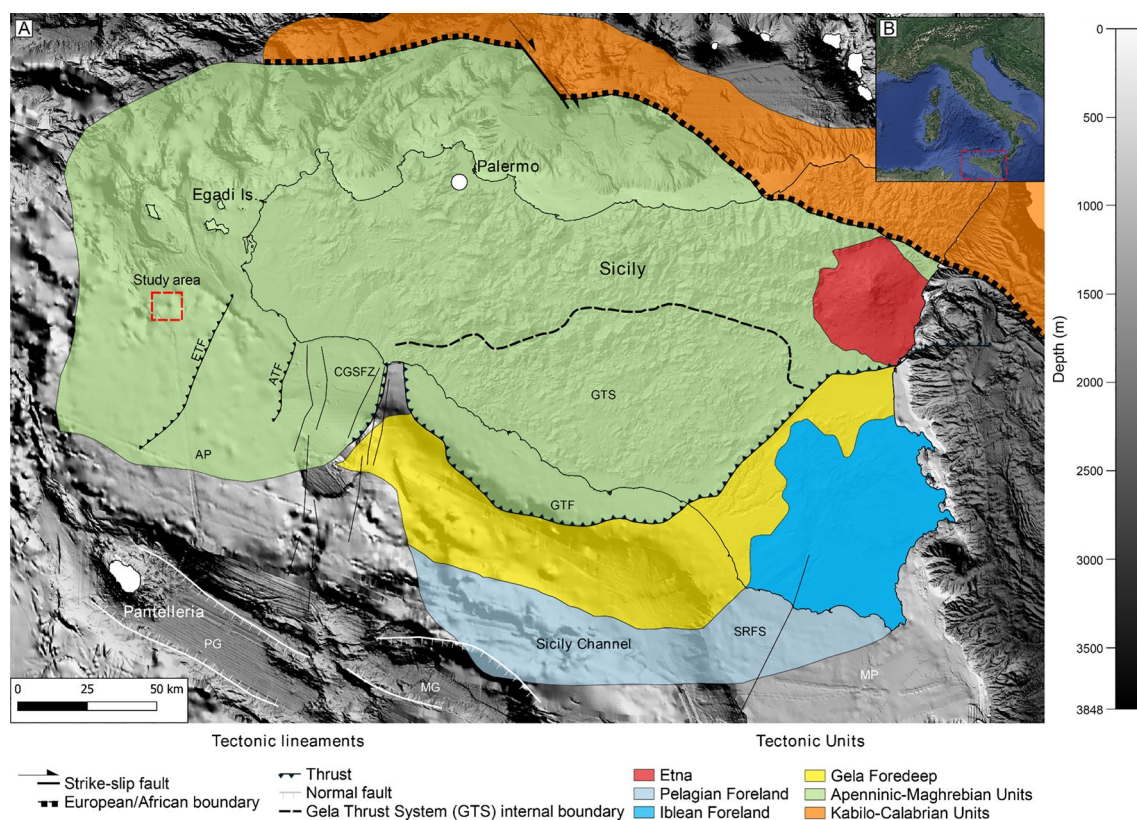


Fig. 1 Inset A shows the bathymetric map with the main and structural elements modified after Gasparo Morticelli et al. (2015), Civile et al. (2018), and Sulli et al. (2021). AP: Adventure Plateau; ATF: Adventure Thrust Front; ETF: Egadi Thrust Front; GTF: Gela Thrust Front; GTS: Gela Thrust System; MG: Malta Graben; MP:

Malta Plateau; PG: Pantelleria Graben; SC: Sicily Channel; CGSFZ: Capo-Granitola Sciacca Fault Zone; SRFS: Scicli-Ragusa Fault System. This map also shows the localization of the study area with a red dashed box. Inset B shows the geographical localization of Sicily Island. Source data: EMODnet (<https://emodnet.ec.europa.eu/en>)

In this paper, we document a large number of pockmarks located near different types of structures that may act as pathway for vertical fluid migration. The study, based on different geophysical datasets, aims (i) to delineate the fluid flow systems on the Adventure Plateau, (ii) to propose a potential origin, and (iii) to improve our general understanding of fluid flow focusing on terms of structural and stratigraphic controls.

Geological background

Geological setting

The Sicily Channel is a shallow marine region between Sicily and Africa with a large and gently sloping (generally less than $1\text{--}2^\circ$) continental shelf, where the shelf break is located at depths between ~ 100 m in the central part and ~ 150 m along the Adventure Plateau and Malta Plateau (Fig. 1) (Todaro et al. 2022, 2021). The Sicily Channel hosts several morphologies as ridges, volcanoes (e.g., Nerita and Graham banks, Pantelleria and Linosa islands) and deep basins (e.g., Pantelleria, Malta and Linosa grabens) (Figs. 1, 2).

The Adventure Plateau (Figs. 1, 2) has a maximum depth of ~ 150 m and is separated from Sicily by the NW–SE trending Mazara Channel that, towards the north, joints into the Marettimo Channel and the Egadi Valley (Fig. 2), two elongate incisions occurring respectively east and west of Marettimo Island (Fig. 2). The stratigraphic sequence is characterized by a thick Triassic–Eocene carbonate succession (Civile et al. 2014). In the Neogene, the post-collisional convergence between Africa and Europa plates caused the emplacement of the Sicilian Maghrebian Fold and Thrust Belt, which is composed of different tectonic units (Gasparo Morticelli et al. 2015; Sulli et al. 2021). These are characterized by (Fig. 1): – the Pelagian-Iblean foreland with its African crust; – a Late Pliocene–Quaternary narrow foredeep, called Gela Foredeep (GF); – a complex, south to southeast-vergent Fold and Thrust Belt. Along the south-western offshore the main structures of the Fold and Thrust Belt are the Egadi Thrust Front (ETF) and the Adventure Thrust Front (ATF) (Catalano et al. 1996; Fig. 1), while the frontal wedge is called Gela Thrust System (GTS, Fig. 1). The boundary between this accretionary wedge and the GF is represented by the Gela Thrust Front (GTF) (Fig. 1) (Gasparo Morticelli et al. 2015). The area has been characterized in the

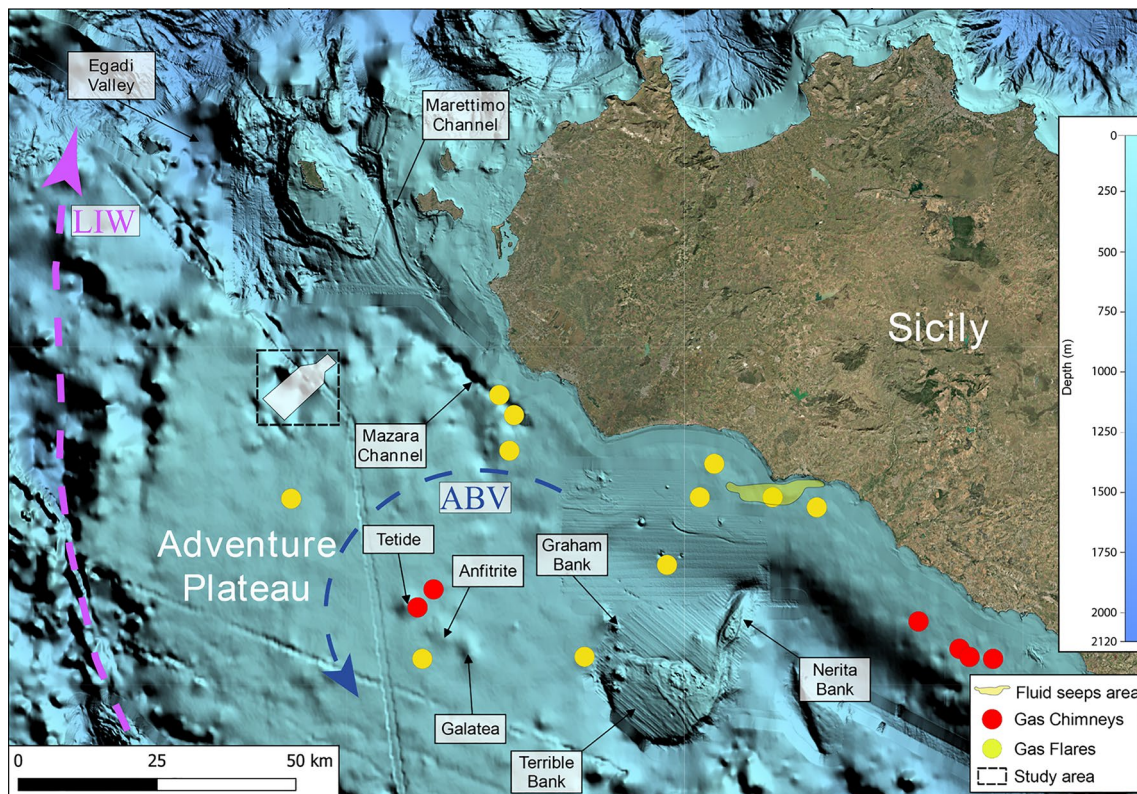


Fig. 2 Bathymetric map showing the main morphological elements from Aissi et al. (2014); the main fluids emission centres from Spatola et al. (2018a) and the fluid seeps area from Civile et al. (2023) the Adventure Bank Vortex (ABV, blue arrow) from Fortibuoni et al.

(2010); and the Levantine Intermediate Water (LIW, brown arrow) pattern from Santinelli et al. (2015). Source data: EMODnet (<https://emodnet.ec.europa.eu/en>)

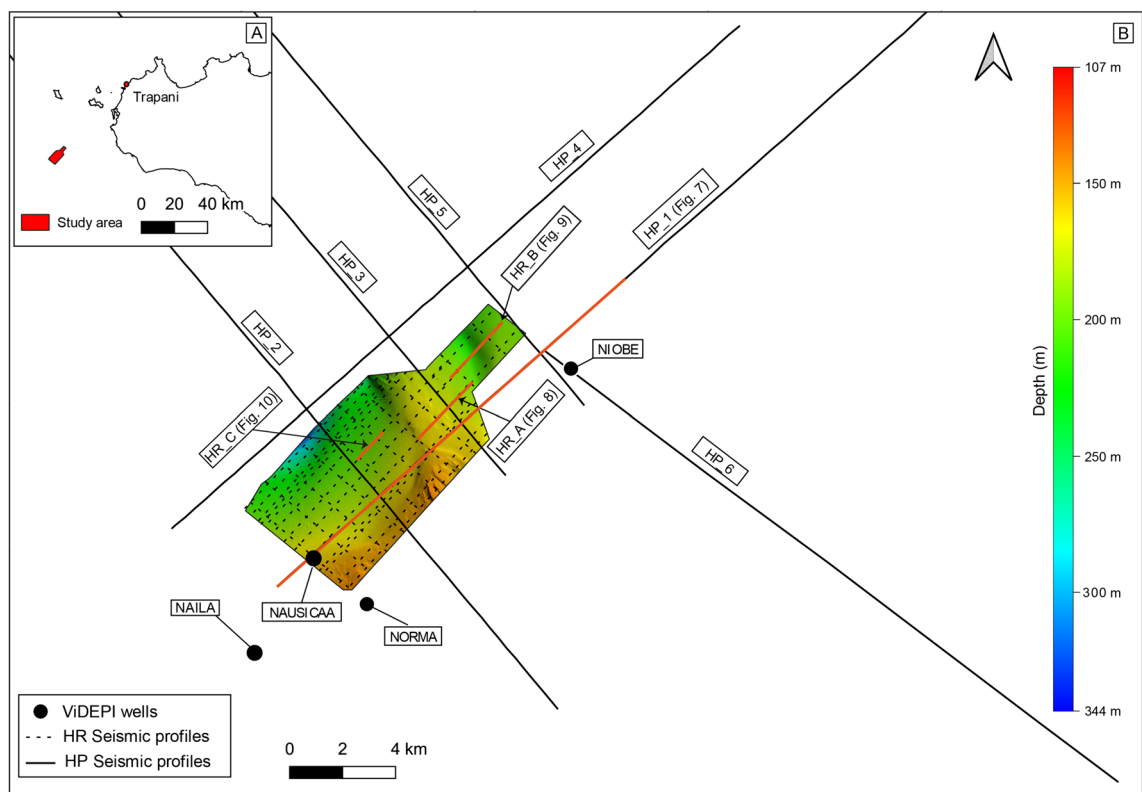


Fig. 3 Study area location (A); coverage map of the dataset used (B): HR (High Resolution) seismic reflection profile, HP (High Penetration) seismic reflection profile, which comprises ViDEPI G (HP_1-5) and LS-89-04 (HP_6) seismic lines, ViDEPI wells, and bathymetric data. Segments of the profiles in related figures are indicated in red

Table 1 Summary of processing sequence for HR seismic data

Application order	Processing steps
1	Band pass filter 20 Hz
2	Despike
3	Source and receiver deghost
4	Reflection coefficient inversion
5	Velocity analysis at 500 m interval
6	Stacking
7	Post stack time migration
8	Post-migration processing
9	Reference frequency 1000 Hz
10	Time Variant Filtering (200 Hz/36 dB – 1600 Hz/36 dB)

Early Pliocene by a regional extensional event that formed Malta, Linosa and Pantelleria grabens (Fig. 1) (Catalano et al. 1993; Gardiner et al. 1995; Corti et al. 2006; Civile et al., 2021). Today, a mild contractional phase is affecting

the Sicily Channel area, in particular the Malta and Linosa Graben (Maiorana et al. 2023), which, in further evidence of northern Sicily compressional phase, suggests a regional plate reorganization and potential subduction polarity switch north of Sicily (Zitellini et al. 2020; Sulli et al. 2021; Loreto et al. 2021). In the Plio-Pleistocene high-angle extensional faults, mainly NW–SE oriented, have modified the original structural setting of this area (Gasparo Morticelli et al. 2015; Parrino et al. 2023). The Adventure Plateau hosts some small and isolated positive reliefs formed of sedimentary or volcanic rocks with different age (e.g., Tetide, Anfitrite and Galatea in Fig. 2) (Civile et al. 2014, 2016).

Recent studies highlighted the occurrence of gas flares and gas chimneys (Fig. 2) by using high-resolution geophysical data testifying active fluid flow systems all over the Sicily Channel such as in the Adventure Plateau, Graham Bank (Coltelli et al. 2016; Spatola et al. 2018b; Ferrante et al. 2022; Volpi et al. 2022; Civile et al. 2023) and Malta Plateau (Micallef et al. 2011, 2019; Savini et al. 2009).

Oceanographic setting

In the Mediterranean region, the water exchange is represented by a two-layer model which comprises: (i) the

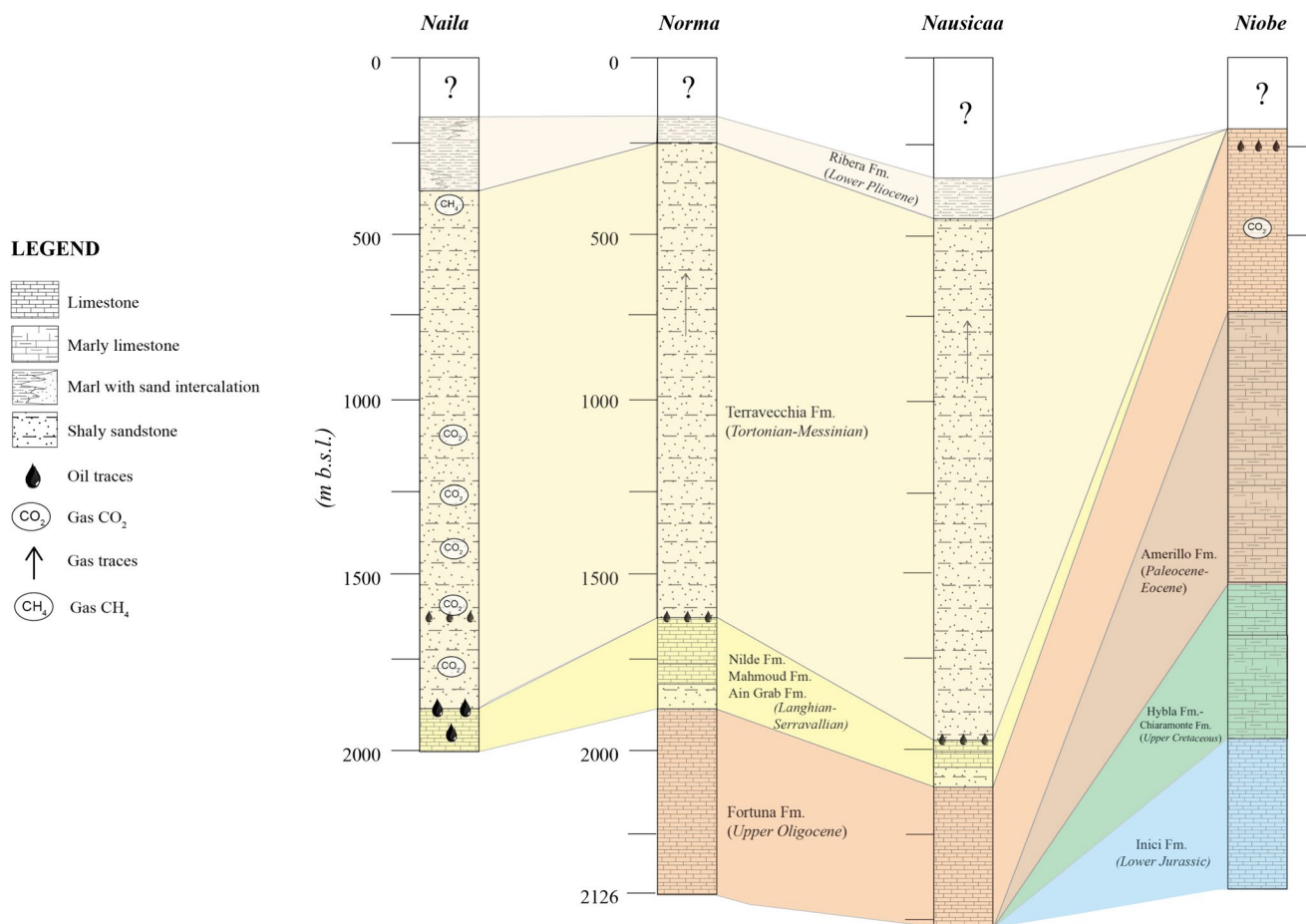


Fig. 4 Stratigraphic correlation table between wells Naila, Norma, Nausicaa and Niobe (location in Fig. 3) in the study area

MAW (Modified Atlantic Water), a relatively fresh water of Atlantic origin, that flows eastward into the eastern Mediterranean; (ii) the LIW (Levantine Intermediate Water), a salty water formed in the eastern Mediterranean during winter that flows out as an undercurrent into the western Mediterranean (García Lafuente et al. 2002). The MAW is a shallow current that is partly controlled by topographic features, coastal geometry, and thermohaline boundary forcing. In the Adventure Plateau is divided into two branches: one with a trend towards SE, and the second one that rises towards the NW following an anti-clockwise gyre that is established between Sicily and Sardinia (Istituto idrografico della Marina. Gênes, 1982). The path of MAW varies seasonally with the onset of a large cyclonic eddy (Béranger et al. 2004; Robinson et al. 2001) over Adventure Plateau, called Adventure Bank Vortex (ABV) (Fig. 2). The northern branch, called the Atlantic Ionian Stream (AIS), contributes to the MAW

transport into the eastern Mediterranean off the southern coast of Sicily. The Levantine Intermediate Water (LIW) constitutes the main source of water that outflows across the Gibraltar Strait as Mediterranean Outflow Water. It is a deep current (usually confined at a depth between 150 and 600 m) that comes from the Ionian Sea and flows westward crossing the channel south of Malta, occupying the lower part of the water column (around 250–400 m) (Lermusiaux and Robinson 2001; Gasparini et al. 2005; Incarbona et al. 2008; Gauchery et al. 2021). In the western edge of the Adventure Plateau, it flows following a NW-trend and, in the proximity of the Egadi islands, it turns towards the Tyrrhenian Sea (Fig. 2) (Incarbona et al. 2008; Santinelli et al., 2015).

Materials and methods

Seismic data

This study is based on the interpretation of seismic reflection profiles calibrated with well-log data and bathymetric data (Fig. 3). Seismic reflection data comprise variable resolution and penetration profiles. High-Penetration (HP) multi-channel seismic profiles made available through ViD-EPI project, were acquired using an airgun as seismic source with a sampling interval of 4 ms (250 Hz), a 6–7 s recording window. Well-log data used for well-tie derived from ViD-EPI database as well (Fig. 3). These data were integrated with a high-resolution (HR) seismic grid (Fig. 3) acquired with Dura-Spark sparker as seismic source equipped with 48-channels (150 m long) digital seismic streamer and a 3.125 m hydrophone group interval. The data has a dominant frequency of 1 kHz, resulting in ~0.4 m vertical resolution for thin beds. Tab. 1 presents the final processing sequence applied to the HR seismic data.

The seismic interpretation was carried out using the software IHS Markit Kingdom Suite 2021, while the seismo-stratigraphic and structural analysis was performed using MOVE 2022.1 software.

Stress analysis

To identify the leakage zones along faults, following the methodology proposed by Mattos et al. (2016), we evaluated the Leakage Factor (LF) through the tool “Stress Analysis” (MOVE 2022.1). The Stress Analysis Module allows the colour-scaled 3D visualization of the fault planes that are

more likely to reactivate and leak. This method was applied along the main structural element of the study area which was identified by the seismo-structural interpretation supported by HP data.

The leakage factor (LF) is (for each geometric portion of the fault plane) the ratio between the pore pressure (P_p) and the difference between the normal stress (σ_n) and the shear stress (τ):

$$LF : P_p / (\sigma_n - \tau)$$

Leakage factor (LF) allows the quantitative modelling of the fluid transmissivity of faults, identifying faults that either constitute migration conduits for sub-surface fluid or, instead, act as local seals (Mattos et al. 2016). It has been calculated based on the actual stress field of the study area considering: $\sigma_n = 203 \text{ N/m}^2$; $\tau = 123 \text{ N/m}^2$ (data from <https://www.world-stress-map.org/>), and the $P_p = 1.5 \text{ MPa}$ (data from Niobe well-log).

Morpho-bathymetric data

Bathymetric data have been acquired through MBES system by using a Teledyne SeaBat T50-P, with a differential Global Positioning Systems. These data were processed using the CARIS HIPS and SIPS v.10.4 software and entailed removal of erroneous beams, noise filtering, calibration and processing of navigation and correction for sound velocity. The derived Digital Terrain Model (DTM) has a bin size of 0.5 m. The interpretation of the Multibeam Echosounder (MBES) data (Fig. 3) was performed with Global Mapper (<https://www.blumarblegeo.com/global-mapper/>) software to identify and map key

Fig. 5 Stratigraphic succession of the Niobe well-log used to calibrate seismic facies units 1–4 in the HP_1 seismic profile. Next to the units are shown the seismic velocities values used for conversion from m to s (TWT) of the main stratigraphic levels

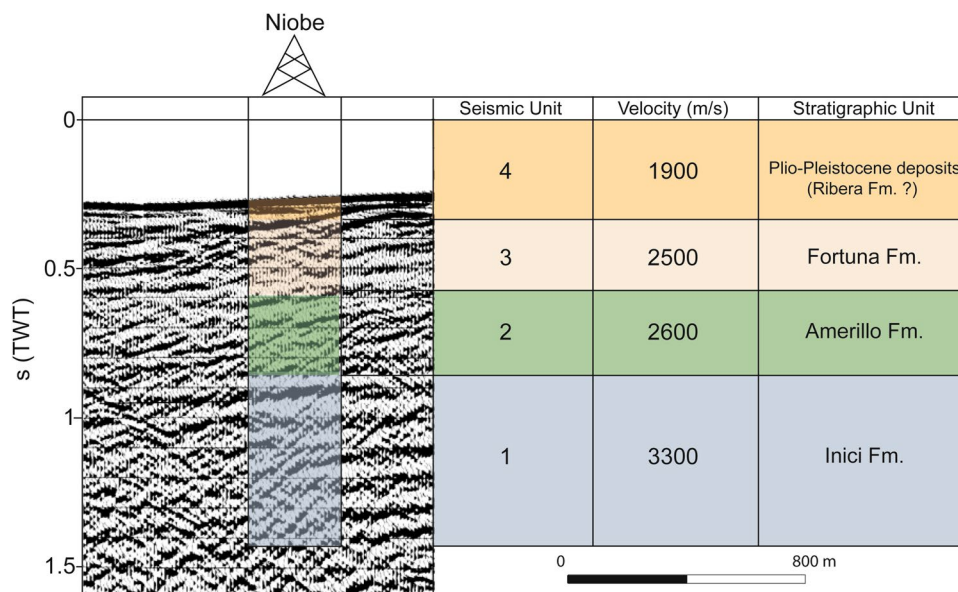
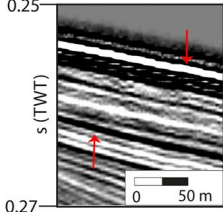
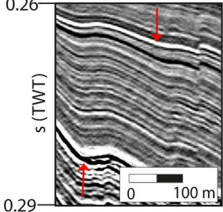
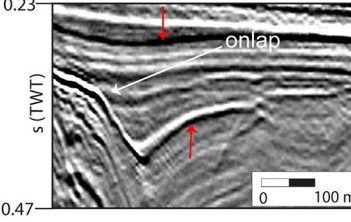
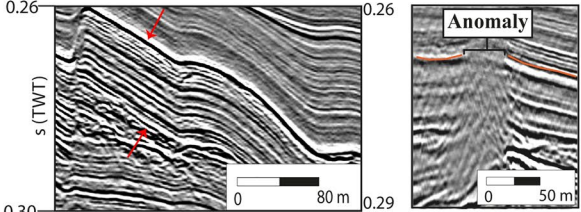
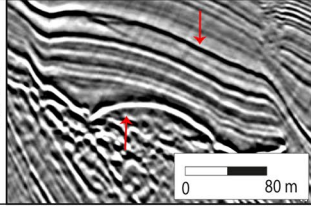
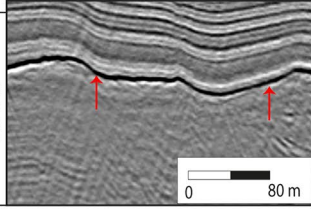


Fig. 6 Seismic units identified by the seismo-stratigraphic analysis of HR seismic reflection profiles

UNIT C3		Low amplitude sub-parallel reflectors with good lateral continuity and low frequency. Top and base of unit are indicated by red arrows.
UNIT C2		Medium to low amplitude sub-parallel reflectors with good lateral continuity and high frequency. Top and base of unit are indicated by red arrows.
UNIT C1		Medium to low amplitude sub-parallel reflectors with good lateral continuity. Locally onlap terminations on Unit B. Top and base of unit are indicated by red arrows.
UNIT B		Medium amplitude reflectors with good continuity. Top and base of unit are indicated by red arrows. Locally interruptions of reflectors in correspondence of transparent signals.
UNIT A2		Medium amplitude reflectors with good continuity characterizing a facies with parallel geometry. The top is marked by a high-amplitude reflector.
UNIT A1		Discontinuous reflectors characterizing a semi-transparent facies. The top is marked by a high-amplitude reflector representing the acoustic basement indicated by red arrows.

seabed morphological features associated with fluid flow phenomena, such as pockmarks.

Morphometric analysis

The morphometric characterization of the pockmarks was performed using the semi-automatic method for extracting the main parameters and applied for the first time to study pockmarks around the Ferdinanda Island (Sicily Channel)

by Spatola et al. (2023). In this study, authors modified methodologies applied for submarine volcanoes in the Tyrrhenian Sea (Sulli et al. 2020), in the Canary Islands (Ruiz et al. 2000), and in the Sicily Channel (Cavallaro and Coltelli 2019; Spatola et al. 2018b).

The pockmarks boundaries have been manually identified mapping the sharp breaks in slope, recognised in the cross-section profiles from the 0.5 m resolution DTM. This method was used to calculate both their basal surface and different

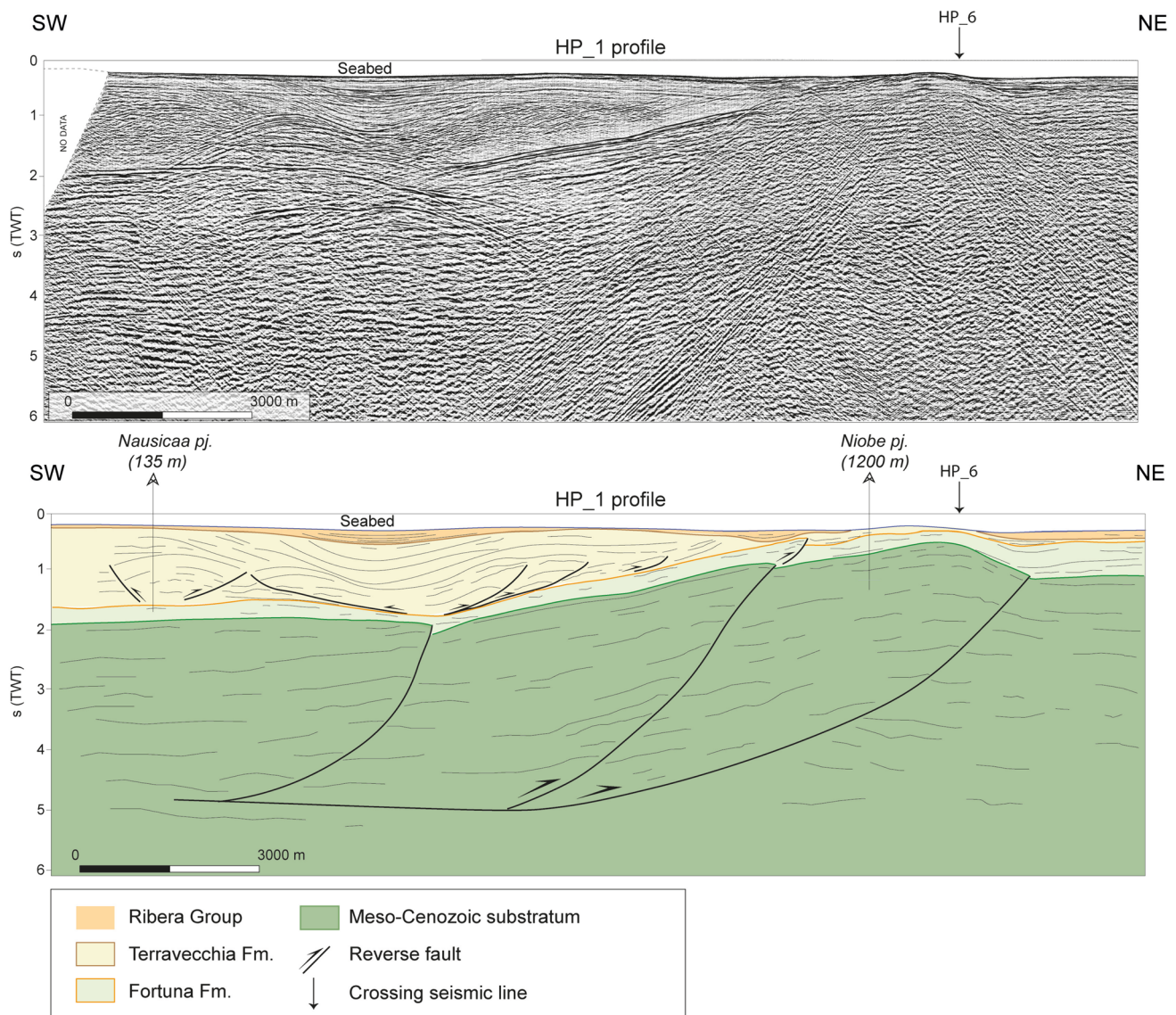


Fig. 7 Line drawing of the HP_1 seismic reflection profile (location in Fig. 3) showing the deep structural framework of the study area

geometrical parameters (e.g., major, minor, and mean axis). We also measured other parameters according to Grosse et al. (2009, 2012), such as:

- 1) “di” dissection index ($di = (\text{Perimeter}/2 \cdot \text{Surface}) \cdot (\sqrt{(\text{Surface}/\pi)})$). It quantifies the irregularity or complexity of the pockmark, relating the perimeter with the enclosed area.
- 2) “ei” ellipticity index ($ei = (\pi \cdot (\text{Major Axis}/2)^2) / \text{Surface}$). It quantifies the pockmark's elongation relating the length of the main axis with its area.
- 3) “e” eccentricity ($e = (\sqrt{(\text{Major Axis}/2)^2 - (\text{Minor Axis}/2)^2} / \text{Major Axis}/2)$). It defines if the pockmark shape tends to be circular ($e=0$), or elliptical relating to the pockmark's major and minor axes.

The last two indexes are two different options to define the same characters of the external shape of different kinds of morphologies. In this paper, we prefer to use both since they are used indifferently in the recent literature (Gafeira et al. 2012; Grosse et al. 2012).

Results

Well-log analysis

A well-log analysis has been carried out through a stratigraphic correlation (Fig. 4) among the well-logs of Naila, Norma, Nausicaa and Niobe wells (location in Fig. 3), available from ViDEPI database (source <https://www.videpi.com/videpi/videpi.asp>). This analysis highlighted the variability of the pre-Pleistocene substrate in the study area: in fact, it is possible to recognize the transition, from SW to NE, from the Lower Pliocene (Ribera Fm.) to the upper Oligocene (Fortuna Fm.) and so, the absence of the outcropping Pliocene units in the NE sector of the area.

Gas and oil traces have been detected in all the stratigraphic well-logs (Fig. 4), respectively in:

- Niobe well-log, showing the presence of oil traces at a depth of 250 m b.s.l., and gas (CO₂) at a depth of 500 m b.s.l., within the Fortuna Fm.;
- Norma well-log, showing oil traces from 1660 to 1676 m b.s.l. at the top of the Nilde Fm. and gas traces of undefined composition inside the Terravecchia Fm.;
- Nausicaa well-log, showing oil traces between 1948 and 1950 m b.s.l. at the top of the Nilde Fm. and gas traces of undefined composition inside the Terravecchia Fm.;
- Naila well-log, showing oil traces between 1885 and 1910 m b.s.l. at the top of the Nilde Fm. and gas (CO₂) between 1110 and 1875 m b.s.l..

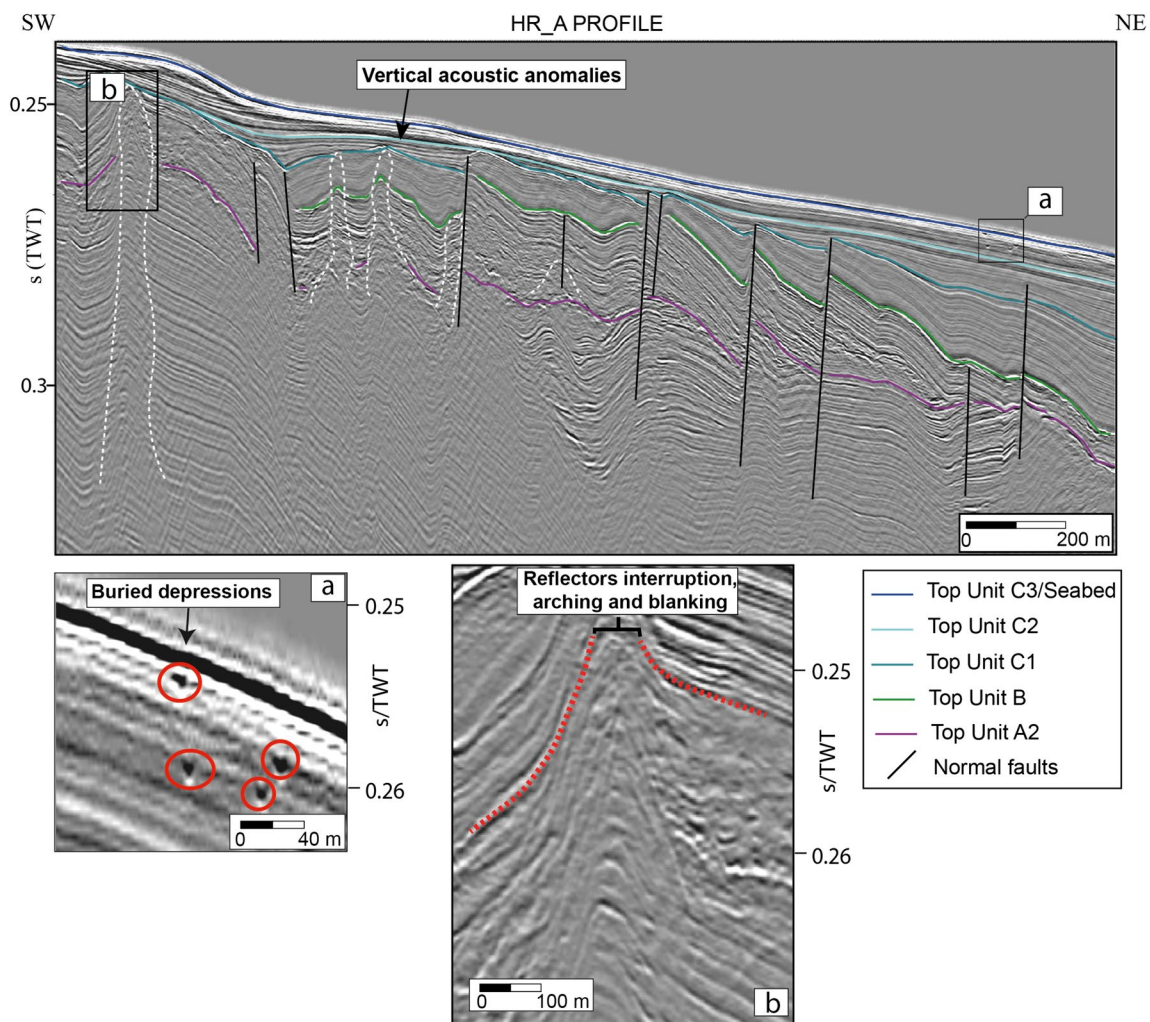


Fig. 8 HR_A profile (location in Fig. 3) showing the presence of vertical acoustic anomalies (white polygons) occurring with a vertical arching of the reflectors. Inset (a) shows the occurrence of buried depression; inset (b) shows a zoom of reflectors arching, interruption and blanking

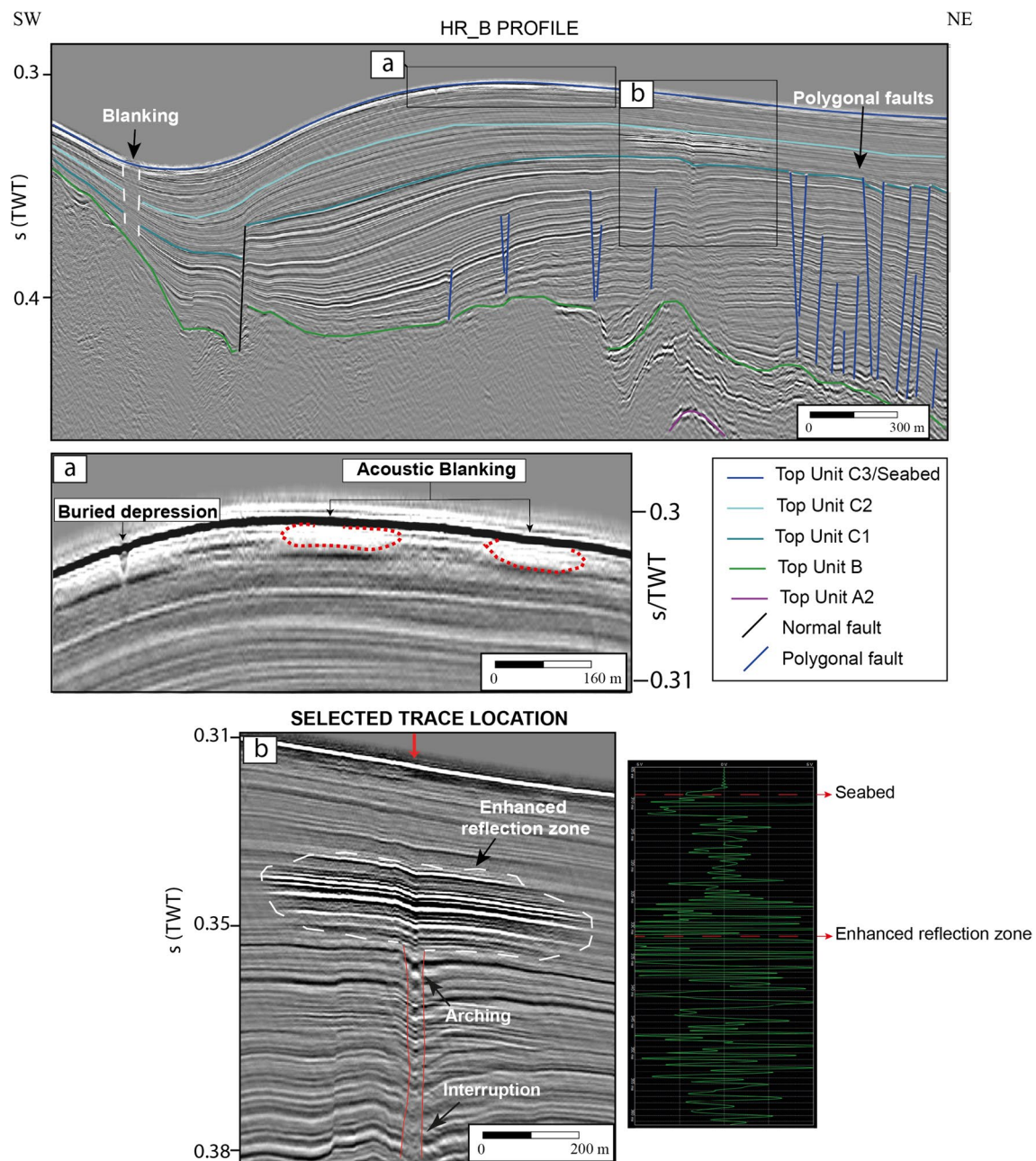


Fig. 9 HR_B profile (location in Fig. 3) showing the occurrence of wide vertical acoustic anomaly topped by an enhanced reflection zone. In the SW sector, an acoustic blanking is also observed. The inset (a) shows a detail of a shallow buried depression and two

acoustic blanking zones. In the inset (b), on the left, the zoom of the enhanced reflection zone and the vertical acoustic anomaly is visible; on the right, the upper part (from 0.31 to 0.38 s (TWT)) of the seismic trace is shown

Seismo-stratigraphic and structural analysis

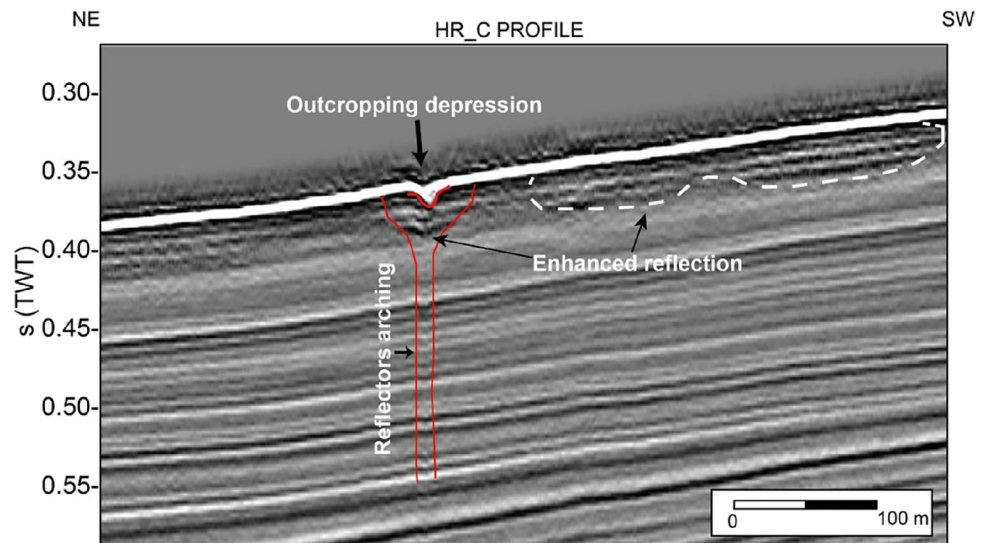
The joint analysis of seismic data of variable penetration allows us to identify the corresponding seismic units between the two different dataset and to characterize the presence of deep and shallow anomalies potentially related to a fluid occurrence.

High Penetration seismo-stratigraphy and well-tie

A seismo-stratigraphic analysis has been carried out to identify the seismic units of the HP seismic profiles (location in Fig. 3). The well-tie has been performed using sonic log data to obtain velocities for a depth-to-time conversion (Fig. 5).

We identified 4 different units named from 1 to 4, starting from the bottom (Fig. 5).

Fig. 10 HR_C profile (location in Fig. 3) shows the occurrence of an outcropping depression limited to the base by an enhanced reflection zone, also extending laterally in the SW sector of the profile. A vertical acoustic anomaly (downward arching of reflectors) develops from 0.55 s (TWT) to the base of the depression



- The seismic unit 1 shows low-frequency and high-amplitude reflectors. This has been attributed, through the well-tie process, to the Inici Fm. (Fig. 5).
- The seismic unit 2 shows, a medium frequency and amplitude of the reflectors, that has been attributed to the Amerillo Fm.
- The seismic unit 3 is characterized by discontinuous and semi-transparent facies and has been attributed to the Fortuna Fm.
- The overlying unit 4, shows high frequency and a plan-parallel geometry of reflectors, with low amplitude and good lateral continuity, The latter has been attributed to the Plio-Pleistocene deposits, not registered in Niobe well-log, but laterally correlated by Nausicaa well-tie (Fig. 5), and therefore attributed to the Ribera Fm.

High resolution seismo-stratigraphy

The seismic facies analysis of the HR seismic reflection profiles highlighted the occurrence of three main seismic units (A, B, C) and five sub-units (A1, A2, C1, C2 and C3) (Fig. 6), as follows:

Unit A: the lowest unit recognized in the HR seismic profiles was divided in two sub-units, respectively Unit A1 and A2. Unit A1 is characterized by a high amplitude reflector representing the acoustic basement, which is the bottom reflector of Unit A2. The latter is characterized by semi-transparent facies with parallel reflectors. Its top limit is marked by a high amplitude reflector.

Unit B: it is characterized by low amplitude reflectors with medium frequency. Locally anomalies characterized by interruptions of reflectors are observed in correspondence of transparent signals.

Unit C: it consists of medium to low amplitude sub-parallel reflectors with good lateral continuity, affected

by several faults. Unit C is composed by three sub-units (C1-3); Unit C1 shows onlap lateral terminations on the unit B, C2 (with high frequency of the reflectors) and C3 shows an upward progressive diminution of amplitude and frequency of reflectors.

High penetration seismic reflection profiles interpretation

The analysis of high-penetration seismic reflection profiles enables the comprehension of the deep structural geometry and the identification of pathways for deep-seated fluid migration within the study region.

The seismic profile HP_1, crossing the study area from NE-SW, for its proximity, has been calibrated by projecting of the closely located Niobe (1200 m far) and Nausicaa (135 m far) well-logs. A NE-vergent thrust dissects layers from 5 to 1 s (TWT) has been identified, involving the Inici, Amerillo and Fortuna Fms, in agreement with compressional tectonics mapped by Milia et al. (2021) in the same area and with the LS-89-04 seismic line (HP_6 in Fig. 3) interpreted and available in the ViDEPI database. This main thrust surface turns out to have a Leakage Factor (LF) of 1.5 which suggests a high permeability potential. In the southern sector, a significative filling, 1.8 s (TWT) of the thrust top basin is observed (Fig. 7); this, accordingly to the Nausicaa well-log, comprises respectively the Terravecchia Fm. and the Ribera Fm. (Fig. 7). Inside the basin (filled by Terravecchia Fm.) several thrusts have been observed (Fig. 7); those appear detached from the underlying level (Fortuna Fm.) and sealed by the parallel deposits of the Ribera Fm. Thus, a secondary compressive phase from post-Oligocene to Lower Pliocene is highlighted in the study area (Civile et al. 2014).

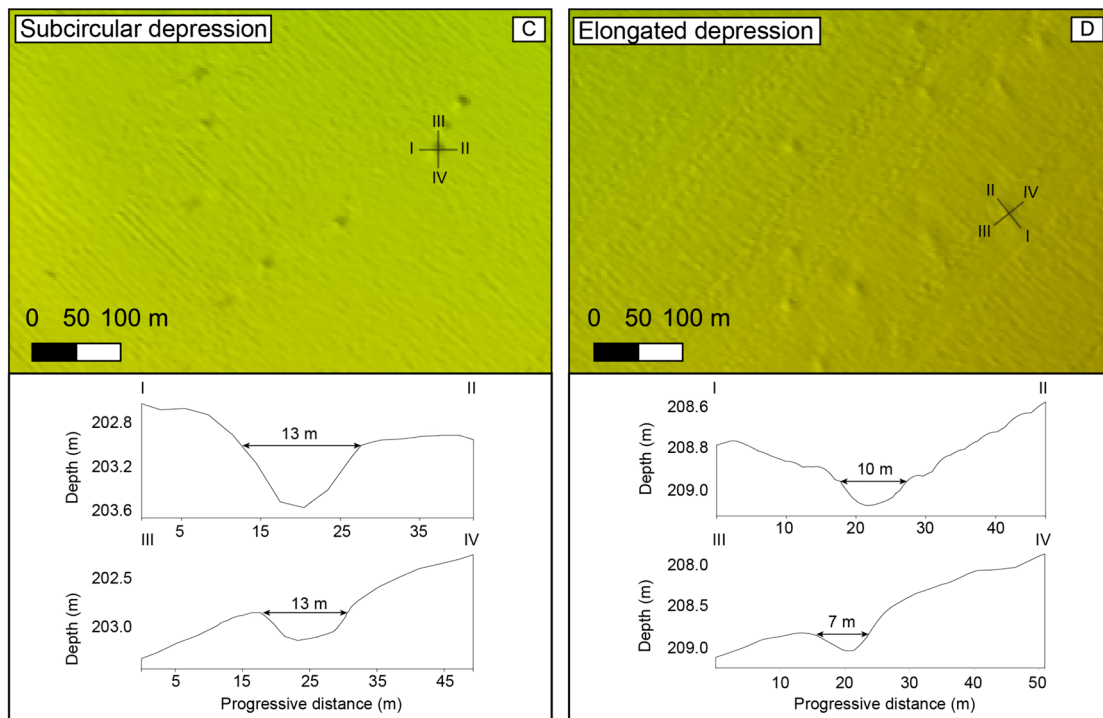
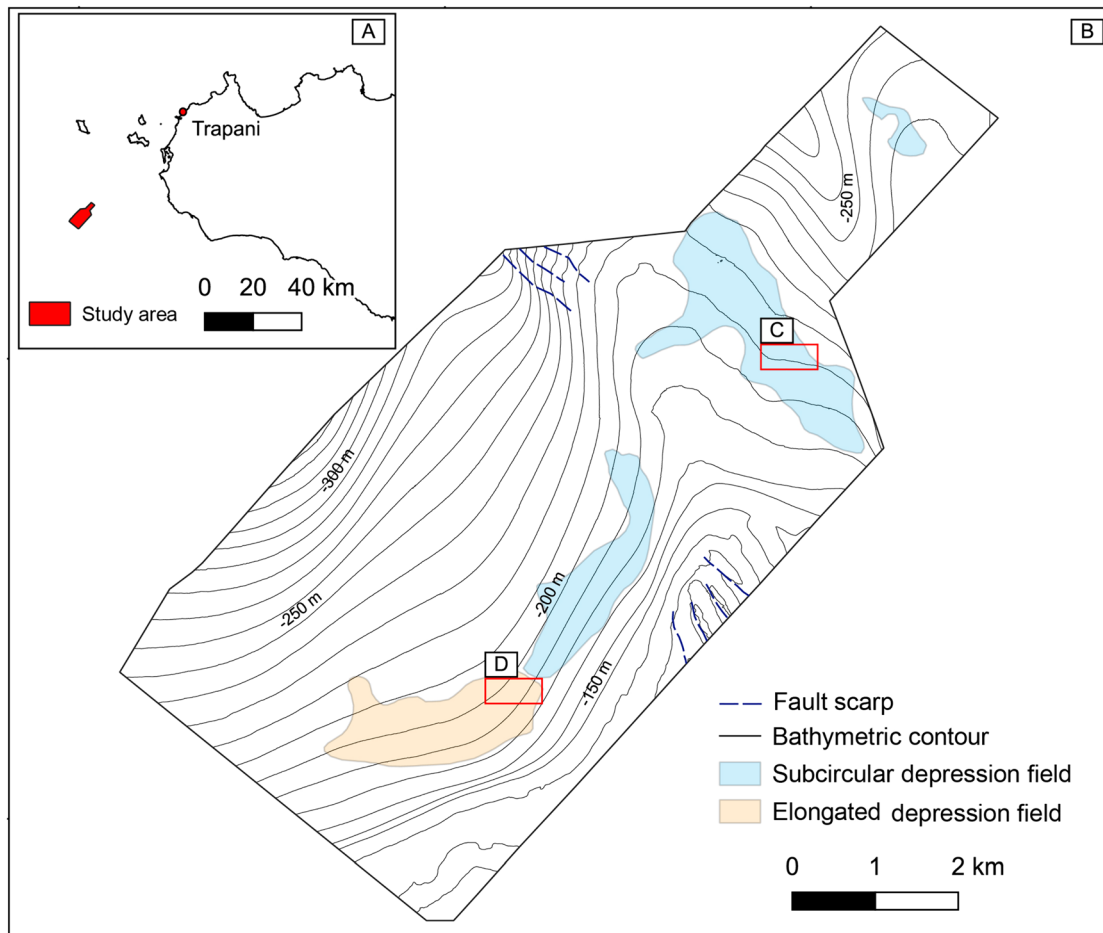


Fig. 11 Study area location (A); the inset (B) shows the geomorphological chart of the study area in which are represented the bathymetric contours (black lines), the fault scarp (blue dashed line), the subcircular pockmark field (light blue polygons) and the elongated pockmark field (light orange polygon). Inset C and D show the depressions on the high-resolution DTM with 2 perpendicular bathymetric profiles

High resolution seismic reflection profiles interpretation

New constraints on the stratigraphic setting of the shallower levels in the study area show an alternation of different layers located inside the Ribera Fm. Further, the evidence of vertical acoustic anomalies (e.g. gas chimneys sensu Hustoft et al. 2010), horizontal acoustic anomalies and buried and/or outcropping depressions, all generally associated with fluids indicators (Judd & Hovland 1992, 2007), prove the occurrence of fluids at shallow layers. The identified vertical acoustic anomalies in the area present three different seismic characters: the first one shows clear enhanced reflections, the second one is characterized by blanking areas and the last one shows clear reflectors arching; anomalies showing these all three seismic characters are indicated as gas chimneys similar to those mapped in the north-western Sicily Channel (Fig. 2; Spatola et al. (2018a)). The identified horizontal acoustic anomalies in the area present two seismic characteristics: acoustic blanking and enhanced reflections. The latter shows a strong increase in seismic amplitude, with reversed polarity compared to the seafloor reflection (Fig. 9b). This evidence has been linked to an abrupt change in the elastic properties of the sedimentary sequence, attributed to the presence of gas by many authors (Gay et al. 2007; Tinivella et al. 2009; Pennino et al. 2014).

Normal faults, cutting across units A2 to C1, are sealed by the subunits C2 and C3 (Figs. 8, 9) and are accompanied by the presence of vertical seismic anomalies; those appear as both concave or convex reflectors and are characterized by semi-transparent facies. These seismic characteristics, which have high similarity with those recognized in the nearby Graham Bank by Spatola et al. (2018b), have been interpreted as seismic chimneys. Thus, these faults represent a conduit for vertical fluid migration only within the A-C1 units, not exhibiting fluid escaping to the seafloor.

The HR_B profile shows also the presence of gas chimneys within Units B to C interrupted right below an enhanced reflection zone (Fig. 9). The seismic trace, which highlights the P wave recorded as amplitude peaks in the water column, was extracted along the enhanced reflection zone (horizontal acoustic anomaly), highlighting a signal inversion at the top of the anomaly (Fig. 9b).

HR_C profile shows the occurrence of an outcropping depression limited to the base by a horizontal acoustic

anomaly characterized by an enhanced reflection zone, extending laterally from the depression to the SW sector of the profile (Fig. 10). Another vertical acoustic anomaly, characterized by a downward arching of reflectors, has been detected from 0.55 s (TWT) to the base of the depression itself.

Analyzing the HR seismic dataset, a total of 15 vertical acoustic anomalies and 10 horizontal acoustic anomalies have been mapped. These are often associated with sub-vertical discontinuities mainly affecting Unit C2 that is characterized by complex kinematics, with throws between 5 to 20 m and small spacing of up to 500 m, therefore interpreted as polygonal faults (Berndt et al. 2012). In this unit, different enhanced reflections have been identified (Fig. 9). Right beneath the seafloor, in Unit C3, we observed the presence of acoustic blanking zones (Fig. 9a) and some buried depressions (Fig. 8a; Fig. 9a). In the whole area 20 acoustic blanking zones were identified. Assuming a sound velocity of 1500 m/s the width of this anomaly ranges from 50 to 180 m and the heights from 10 to 15 m. The identified 5 enhanced reflection zones appear extended laterally in a NW–SE direction for about 800 m.

Morpho-bathymetric analysis

The bathymetric data covers an area of ~80 km² with a water depth ranging between 107 and 344 m (Fig. 11). The study area is characterized by the presence of a structural high, evident from the bathymetric contours on the NE sector of the study area (Fig. 11B) oriented NNW–SSE with a height of about 40 m. Faults scarps of 20 m high, occupy respectively the southeasternmost and northwesternmost sectors of the study area. The bathymetric contours show an increasing depth towards NW, from ~140 m to ~340 m, due to the presence of a morphologically depressed sector in the western part of the study area. The seafloor is punctuated by 247 depressions of variable depth, that have been differentiated in “fields” based on their morphology. As visible in the Fig. 11, two different types of depressions have been

Table 2 Measured parameters of mapped depressions in the study area

Depressions	Minimum	Maximum	Mean	Standard deviation
Sumimt depth (m)	165	243	198	13
Basal depth (m)	166	244	198	13
Depth/Radius	0	2.36	0.07	0.15
Flank slope (°)	0	1.52	0.64	0.27
Ellipticity index	0.96	5.82	1.70	0.98
Dissection Index	1.03	7.42	1.34	1.01
Depth/Surface	0.0008	0.14	0.00	0.01
Eccentricity	0	0.98	0.61	0.23

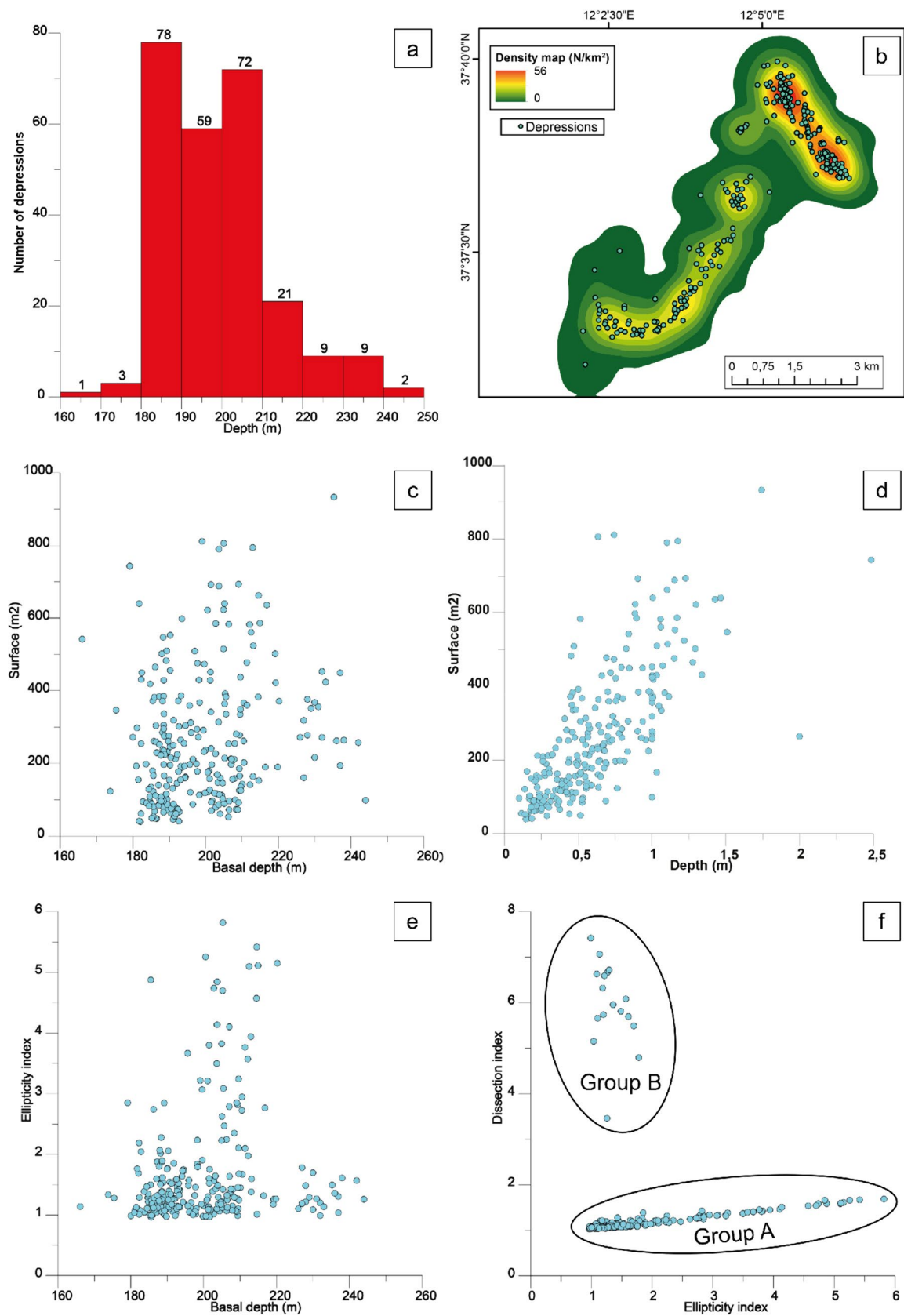


Fig. 12 Summary graphs of the morphometric analysis of the identified depressions

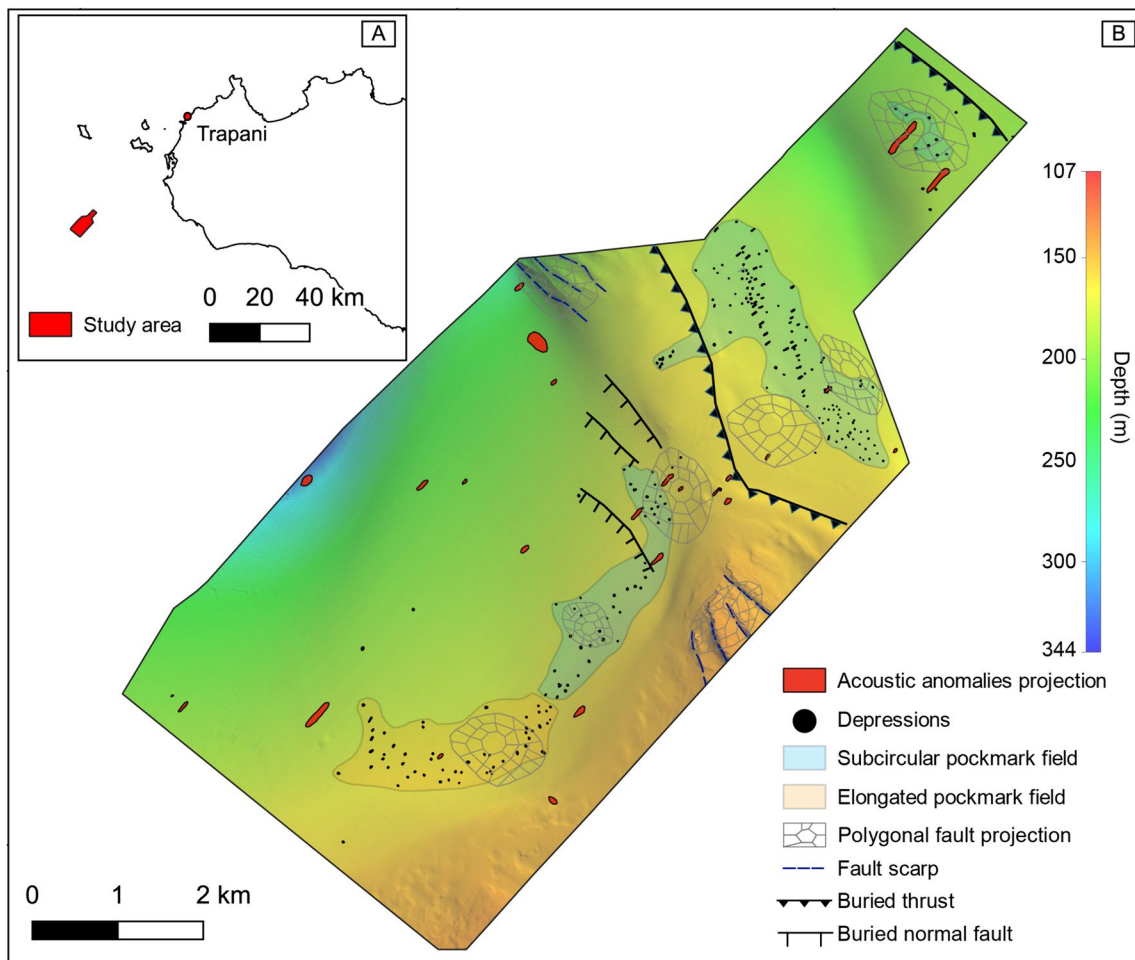


Fig. 13 Study area location (A) and high-resolution DTM (B) in which are represented the main morphostructural elements. Polygonal fault with a grayish pattern, fault scarp with a dashed blue line, buried thrust with black lines and triangles, buried normal fault with

black line, acoustic anomalies projection with a red polygon, pockmark depression with black dots, subcircular pockmark field with light blue polygon and elongated pockmark field with light orange polygon

distinguished, subcircular and elongated, that have been grouped into depression fields. Three subcircular depression fields occur in the northern sector of the study area, two showing a NW–SE orientation, and the southern one a NE–SW orientation. In the southern sector of the study area, a NE–SW oriented elongated depression field has been recognized.

Morphometric analysis of depressions

Based on the interpretation of morpho-bathymetric data, we measured and calculated some morphometric characteristics of the identified depressions such as (1) ellipticity index, (2) dissection index and (3) eccentricity (Table 2).

Figure 12 presents summary graphs, including a vertical histogram and scatter plots of the measured parameters. Figure 12a shows the depth distribution of the 247 depressions identified between 160 and 250 m: the most representative

depth range is 180 to 220 m. The depressions' density map (Fig. 12b) identifies two main trends: a NW–SE and a NE–SW array, which curves in an E–W direction in the southernmost part. The highest density of pockmarks (56/km²) is observed in the northern sector and shows a NW–SE orientation.

The graph in Fig. 12c shows that the average depth is mostly less than 1 m, with a surface extension ranging from ~50 to ~400 m².

The surface (m²) vs. depth (m) graph (Fig. 12d) shows that surface extension increases linearly with the depth of the depressions. Instead, the ellipticity index vs. basal depth (m) graph (Fig. 12e) shows that the ellipticity index remains confined mainly between 1 and 2, indicating that most of the depressions have a subcircular geometry. Finally, the dissection index vs. ellipticity index graph shows that as the ellipticity increases, the dissection index remains almost constant (Fig. 12f). In this graph, two groups of values have

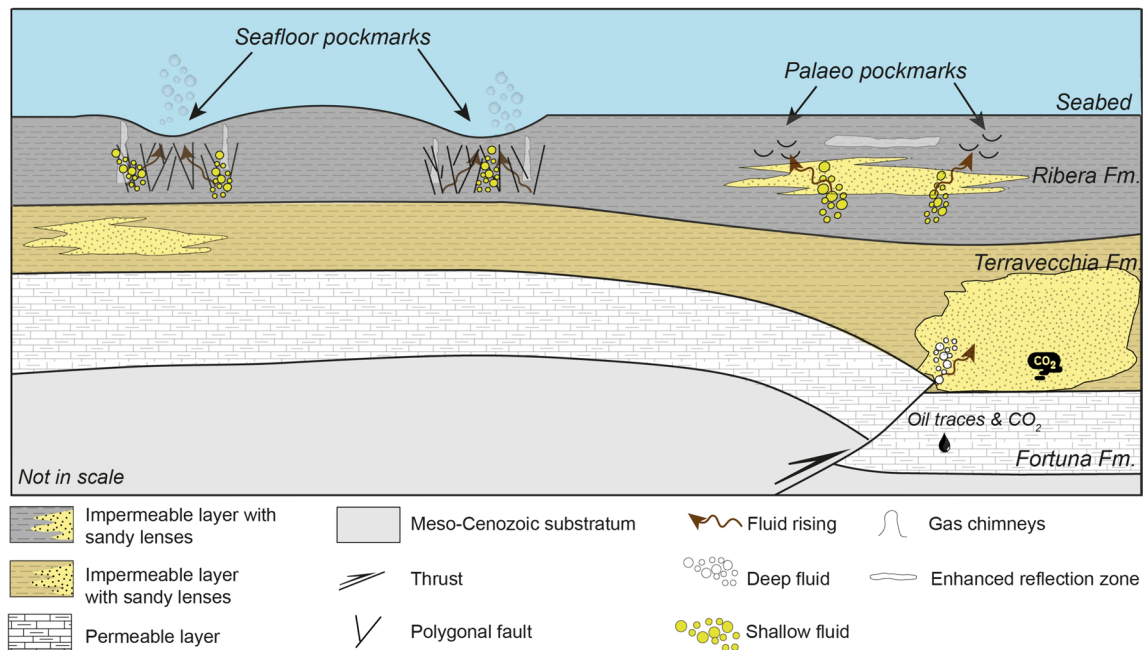


Fig. 14 Fluids rising model of deep and shallow fluids outlined by means of alternate permeable and impermeable layers

been identified. Group A shows an increasing ellipticity index and a constant dissection index, while Group B shows a reverse behavior (Fig. 12f).

Morpho-structural analysis

The main morpho-structural elements of the study area, deriving from both morpho-bathymetric and seismic reflection profile analysis, are summarized in Fig. 13. The seismo-structural interpretation of HP profiles shows the presence of a main buried thrust NW–SE oriented, crossing the study area (Figs. 7 and 13); close to the top of this high, buried normal faults with a NW–SE trend have been identified. Moreover, in the eastern boundary of the study area, several faults' escarpments occur, assuming values ranging from ~10 m to ~20 m (Fig. 13).

Fields of elongated and subcircular depressions are observed in correspondence with the 25 seismic anomalies identified in the HR profiles. Those are located directly above seismic offsets and fault zones (Figs. 9, 13) and below the outcropping depressions (e.g., Fig. 10). It is also visible how different polygonal faults lie inside the depression's fields, supporting the hypothesis of a correlation between the identified structures and the depressions (Micallef et al. 2019).

Discussions

Fluid flow could be responsible of a wide range of seabed morphological features (Hovland et al. 2010). Among these, pockmarks are often associated with subsurface anomalies e.g., gas chimneys or pipes that acts as pathways through the surface (Cartwright et al. 2007; Løseth et al. 2009).

The well-log data available, highlighted the presence of gas (CO_2 or probably also CH_4), in the Terravecchia Fm., Amerillo Fm. and Fortuna Fm., and the presence of oil traces at high-to-shallow depth within the Fortuna Fm. Through the analysis of different resolution seismic data, we highlighted the occurrence of several acoustic anomalies on the Adventure Plateau at high to shallow depth. Those are characterized by both acoustic blanking areas, enhanced reflections and reflectors arching and their projection corresponds to buried and outcropping depression fields where also polygonal faults projection lies (Fig. 13). The presence of polygonal faults suggests the occurrence of a dewatering and compaction process (Berndt et al. 2012) developing from the host sediment composed of the clays of the Ribera Fm. Such faults, which do not have a tectonic origin (Cartwright et al., 1994), are tightly linked to the basin fluid flow system, as they are generated by pore water expulsion.

Evidence of the occurrence of (i) fluids in the boreholes recorded at different depths, (ii) acoustic anomalies branching to the seafloor, sometimes below outcropping

depressions, and (iii) polygonal faults, allowed us to link the detected depressions to fluid escape structures and to interpret them as pockmark. Considering the absence of gas flares from seismic evidence, we assume that they were active in recent times, but are no longer active today.

The identified subcircular and elongated depression fields have therefore been attributed respectively to subcircular and elongated pockmark fields. The highest density of pockmarks occurs in the northern sector, where they follow a NW–SE trend, inside a subcircular pockmark field.

The morphometric analysis highlighted the presence of two main groups of pockmarks in the dissection index versus the ellipticity index graph. Group A shows a linear correlation between dissection and ellipticity index (Fig. 12f): considering the low value of dissection index, indicating regular/smooth edges, and growing values of ellipticity index, we suggest a potential role of the bottom current in the shaping of these fluid flow morphologies. Group A corresponds to the elongated depression field in Fig. 13, reinterpreted as an elongated pockmark field. The elongated pockmark field shows a major axis orientation, orthogonal (NE–SW) to the tectonic trend, so their elongation cannot be attributed to tectonic control. Instead, the NE–SW direction of the elongated pockmark in Group A is in agreement with a potential influence of the ABV; although it is a surface current, given the shallow depth of the seafloor in the study area, we suggest that ABV could have effects on shaping the pockmarks morphology.

Conversely, Group B shows very high values of dissection (irregular edges), and very low values of ellipticity (Fig. 12f) indicating a subcircular morphology that is therefore not affected by the bottom current.

Fluid rising model

The fluid rising model we propose reconstructs the source and the paths of the rising fluids, taking into account the geometry of sedimentary layers and the occurrence of permeable and impermeable layers derived from well-log analysis (Fig. 14).

Based on these observations, two fluid sources were identified in the study area:

The deepest (i), which does not create outcropping fluids emission morphologies, is documented by oil traces and CO₂ contained in the Fortuna Fm. limestone (Fig. 4). The buoyancy generated in the ramp anticline at the hanging wall of the Miocene thrust, induces the migration of the fluids, which rise by advection to the Terravecchia Fm., thanks to the positive LF of the thrust. These fluids are locally confined in small sandy and more permeable lenses of the Terravecchia Fm. (Fig. 14).

The shallowest (ii) is related to biogenic gases formed in the impermeable clay layer (Ribera Fm.) as observed in the Zagara well (ViDEPI), some tens of kilometers to the ENE from this area.

Based on the observed features, we suggest that these shallow fluids migrate by two different mechanisms: (a) dewatering and compaction of sediments confirmed by the polygonal faults presence (Berndt et al. 2012) and focused emissions (e.g., gas chimneys); (b) diffusion through sandy lenses (Fig. 14) that induces the generation of dispersed emissions on the seafloor, as suggested by the presence of broad horizontal anomalies (e.g., enhanced reflections) and paleo pockmarks, similar to those described on the Malta Plateau by Micallef et al. (2011) (Fig. 14).

Conclusions

This study highlights the presence of two different types of fluids: (i) one containing mainly gas, identified at 700–820 m b.s.l., at the boundary between Amerillo Fm. and Fortuna Fm.; (ii) the second one, mainly composed of oil, identified at shallower depth, between 242 and 282 m b.s.l., inside the Fortuna Fm.

Two sources have been identified: one, deeper, unrelated to the surface, the other, shallower, responsible for pockmark formation.

The deeper source derives from the Fortuna Fm., rises through advection in the Terravecchia Fm., and confines in the sandy layers.

The shallower source, generating the highlighted pockmarks, is the impermeable clay layer constituting the Ribera Fm. The shallow fluids produced migrate to the seafloor with two different mechanisms: in the first one by dewatering and compaction of sediments, polygonal faults and focused emissions (e.g. gas chimneys) are generated; in the second they rise by diffusion through sandy lenses.

The distribution of the pockmark fields is not affected by structural control. Our morphometric analysis suggests instead a potential role of ABV current in shaping the elongated pockmarks field morphology.

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Author contributions All authors wrote the main manuscript text and reviewed the manuscript.

Data availability The High Penetration multi-channel seismic reflection dataset and well-log data are available at ViDEPI public database. The High Resolution seismic reflection profiles are available upon reasonable request at the University of Palermo (DiSTeM).

Declarations

Competing interests The authors declare no competing interests.

Conflict of interest The authors declare that they have no known conflict of interest.

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CHAPTER 4

Classification of suitable ccs sites at the regional scale

4.1 Introduction

This multidisciplinary research aims to carry out a structural geological analysis of part of the Sicily Channel to identify and characterize potential CO₂ storage sites.

The project develops within the framework of European policies that require countries to reduce CO₂ emissions by 55% by 2050, considering the possibility of achieving this through direct capture and storage of CO₂ from industrial plants via the Carbon Capture and Storage (CCS) process.

The northern sector of the Sicily Channel, between the Adventure Bank and the Malta Escarpment, is an area of interest for its geological features and the richness of hydrocarbon deposits. The presence of these exploited deposits has provided and continues to provide essential information about the stratigraphic and structural context of the southern Sicilian offshore.

Additionally, depleted hydrocarbon reservoirs close to high CO₂ emission sites (industrial plants) offer a strong foundation for thinking about the implementation of CCS in the Sicilian offshore.

This study seeks to understand how the geological context could accommodate the construction of CCS sites. From the literature, it's known that southwestern Sicily has rich petroleum traps mainly tied to two systems:

- (1) The Ragusa, Gela, Irminio, Mila, and Perla fields consist of locally fractured carbonate rocks formed in the intra-platform basin of Streppenosa during subsidence;
- (2) Fields like Nilde and Narciso in the western offshore of Sicily, where Oligocene-Miocene calcarenite deposits are hypothesized as source rocks.

Using available seismic and well data from the ViDEPI database, deep and shallow tectonic structures, as well as the stratigraphic context in the southern Sicilian offshore, were examined to identify potential CO₂ reservoir and seal formations. A preliminary georeferenced database of potential CO₂ storage sites was created by assigning classification parameters derived from literature analysis and public data.

The project aims to create an atlas of suitable sites present in the offshore area of the Sicily Channel. Future activities will be conducted in collaboration between the University of Palermo and ENI,

focusing on identifying promising exploration areas for CO₂ storage based on geological characteristics.

4.2 Paleogeography and Lithostratigraphic Units

The analysis of facies and stratigraphy, together with biostratigraphy, has been used since the 1970s to study rock bodies outcropping in Sicily, both onshore and offshore. The African margin, which hosts the study area, began its complex evolution in the Upper Triassic. During this period, sedimentation was typical of a carbonate platform (represented by the Taormina, Gela, and Noto/Sciacca Formations) (Catalano & D'Argenio, 1982; Catalano et al., 1996) (Fig. 1, 2). In the Rhaetian, there was a change in sedimentation due to the beginning of an extensional phase, which initiated deep-water sedimentation (Streppenosa Formation, widespread in the Iblean area) (Fig. 3, 4). In the Lower Jurassic, a period of stasis led to the covering of the previously formed basins and the establishment of platform conditions (Inici, Siracusa formations) (Fig. 1, 2). Subsequently, in the Toarcian, there was a reactivation of extension that caused the break-up of the platform and the formation of several deep basins (Buccheri Formation), accompanied by intense magmatic activity (Fig. 1, 2). In the Lower Cretaceous, deep-marine sedimentation (Hybla and Amerillo formations) continued (Fig. 1, 2). These sedimentation conditions persisted until the Oligocene, a period during which a variation occurred between sedimentation in the Iblean zone and the Madrepore Bank, where shallow-marine carbonate sedimentation (Ragusa Formation) (Fig. 1, 2) continued, and the Adventure Bank, where clastic sedimentation took place. This latter sedimentation reflects the advancement of the Sicilian-Maghrebide chain and the more recent Gela Nappe, with the subsequent formation of various foredeep basins, filled with clastic deposits (Numidian Flysch) derived from the erosion of the advancing chain (Argnani et al., 2001). Other paleogeographic units of African origin consist of sedimentary successions containing deep-marine silico-carbonate rocks from the Mesozoic-Lower Miocene, locally named the Imerese and Sicana units, while Meso-Cenozoic carbonate platform rocks characterize the Pre-Panormide, Panormide, Trapanese, Saccense, and Ibleo-Pelagiana units (Fig. 1, 2). The Panormide and Trapanese-Saccense successions represent the Meso-Cenozoic carbonate platform domains, as does the Iblean carbonate platform, which today constitutes the foreland zone (Fig. 1, 2). The Sicilian successions were deposited in both deep-marine and shallower-marine environments. They all formed along the African passive continental margin and, with the convergence and collision with the European continent, these rocks were shortened and became part of the tectonic units and domains of the Sicilian Maghrebide chain.



Figure 2. Stratigraphy and facies domains in Sicily (Catalano et al., 2002).

4.3 Oil Exploration in the Sicily Channel

Oil exploration began in the Pelagian Platform in the 1950s, expanding mining concessions to the eastern offshore of Tunisia around the mid-1960s and to the Sicily Channel in 1968 (Klett, 2001). Notable campaigns include Agip's 1959 'Gela Mare 21' and the 1976 campaign with the first remotely operated platform in Italy at Perla 1 (Fig. 3). In the Sicily Channel, the most important petroleum systems are located in the Iblean sector, including the Vega, Prezioso, and Perla fields (Fig. 3), while the Nilde field (Fig. 3), located about 57 km southwest of Marsala, represents the largest exploration area in the northwestern Sicilian-Tunisian sector. Its main target is the karstified bioclastic limestones of the Nilde Formation. From 1973 to 1988, the field was active, but production was economically viable only from the Nilde_2 well. Currently, there are no open mining concessions for the Adventure Bank area due to a lack of sufficient data to identify possible new reservoirs, and exploration is only active in the Iblean platform sector. Here, the Siracusa Formation (equivalent to the Inici Formation) produces heavy oil enriched with sulfur, and it is believed that the source rock consists of limestones and shales from the Streppenosa Formation. Caldarelli and Smith (2012), based on recent geochemical analyses, theorize that the liquid hydrocarbons from the western fold and thrust belt (Nilde field) were generated from source rocks in a restricted marine environment characterized by carbonate sedimentation and a lack of clastic input, suggesting a possible correlation with the oils extracted from the Ragusa Formation reservoir in the Iblean area (Fig. 4). Hydrocarbon exploration in the Sicily Channel has not only focused on oil fields (the first being Gela_21 in 1959), but recent attention has also been directed towards biogenic and thermogenic gas basins, respectively accumulated in the Plio-Pleistocene foredeep deposits and Miocene sands. In 2000, the Panda, Argo, and Cassiopea gas fields were discovered as part of the 'Offshore Ibleo' project (which aims at the integrated development of the three fields), with the main target being the biogenic gas contained in the Plio-Pleistocene clastic series (from <https://www.mise.gov.it/it/per-i-media/pubblicazioni/il-mare-numero-speciale-del-bollettino-ufficiale-degli-idrocarburi-e-delle-georisorse-seconda-edizione-revisionata-e-ampliata-marzo-2015>).

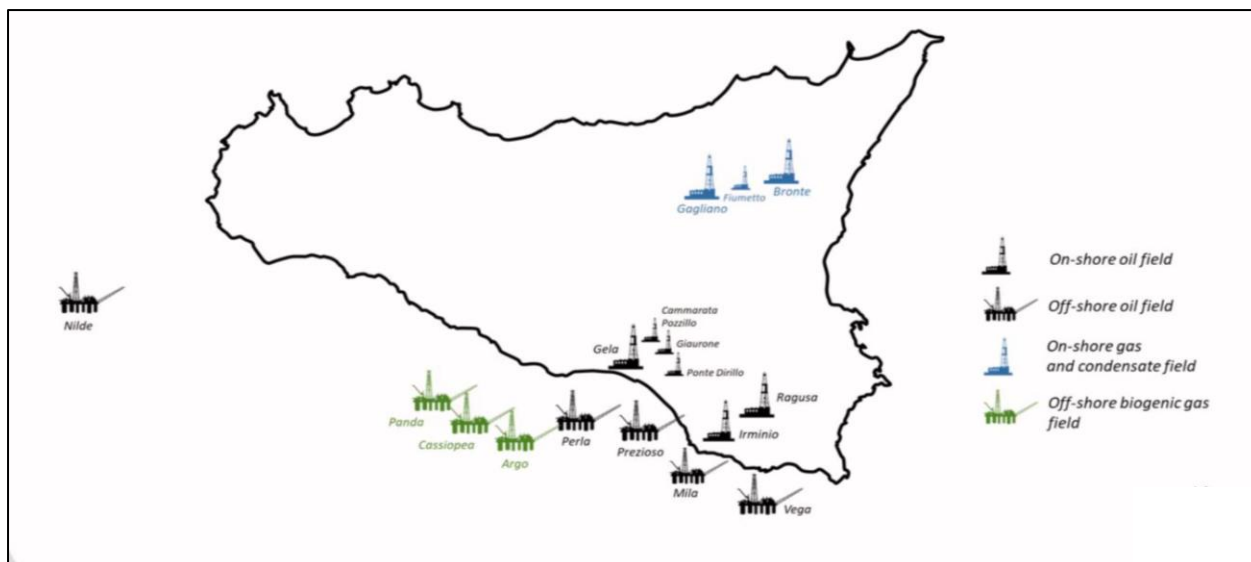


Figure 3. Scheme of oil and gas field in onshore and offshore Sicily (Miuccio & Frixia, 2000).

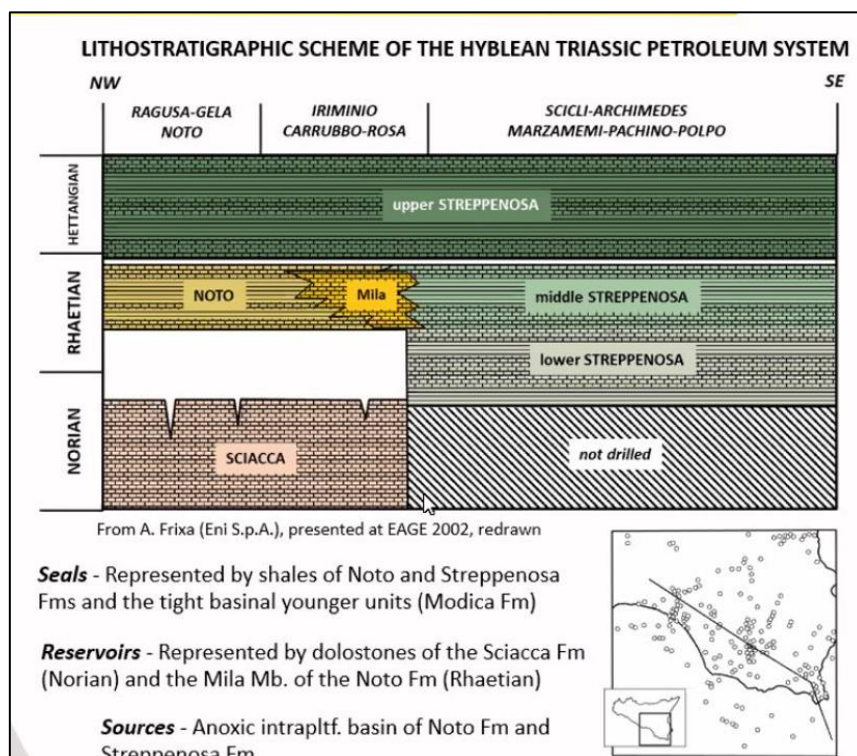


Figure 4. Lithostratigraphic scheme representative of the Iblean petroleum system (Miuccio & Frixia, 2000).

4.4 Materials and Methods for Selecting Suitable Sites

The geophysical exploration dataset, available on the unmig.sviluppoeconomico.gov.it website (VIDEPI project), includes both lines acquired during exploratory seismic surveys (at the opening of the area for oil exploration) and seismic lines acquired from expired mining leases (during the phase of reservoir identification to define its depth and geometry). The former provides extensive coverage of the entire plateau, defining the northwest block of the C marine zone, where the Adventure Bank almost entirely falls, while the latter is available in this area only for the Agrigento offshore. The northwestern, southern, and southeastern sectors of the bank are instead covered by the overlapping grids of the C and G zones (Fig. 5). The profiles from the C grid were acquired using an Aquapulse source (detonation of an oxygen and propane mixture without release into the sea), with a 2 ms sampling interval (500 Hz), a 5-second recording window, 1200% coverage, and a 1:50,000 scale. The profiles from the G grid, on the other hand, were acquired using an Airgun system (a battery of compressed air devices equipped with a double piston, where the trigger first generates an expanding bubble in the water, followed by successive cycles of expansion/contraction until it reaches the water/air interface), with a 4 ms sampling interval (250 Hz), a 6-7 second acquisition window, 4800% coverage, and a 1:25,000 scale. However, the main differences between the profiles of the two grids, for which unit correlations were made, relate to the slightly higher resolution of the C profiles and the different horizontal scale, which required appropriate adjustments while maintaining the dimensions of the bodies based on their velocity. Overall, these are multichannel profiles with relatively low resolution, a fact considered during the interpretation and seismic stratigraphic analysis phase, along with the fact that all sections were subjected to only basic pre-stack processing with the application, generally for both grids, of muting, deconvolution, velocity analysis, NMO correction, and stacking.

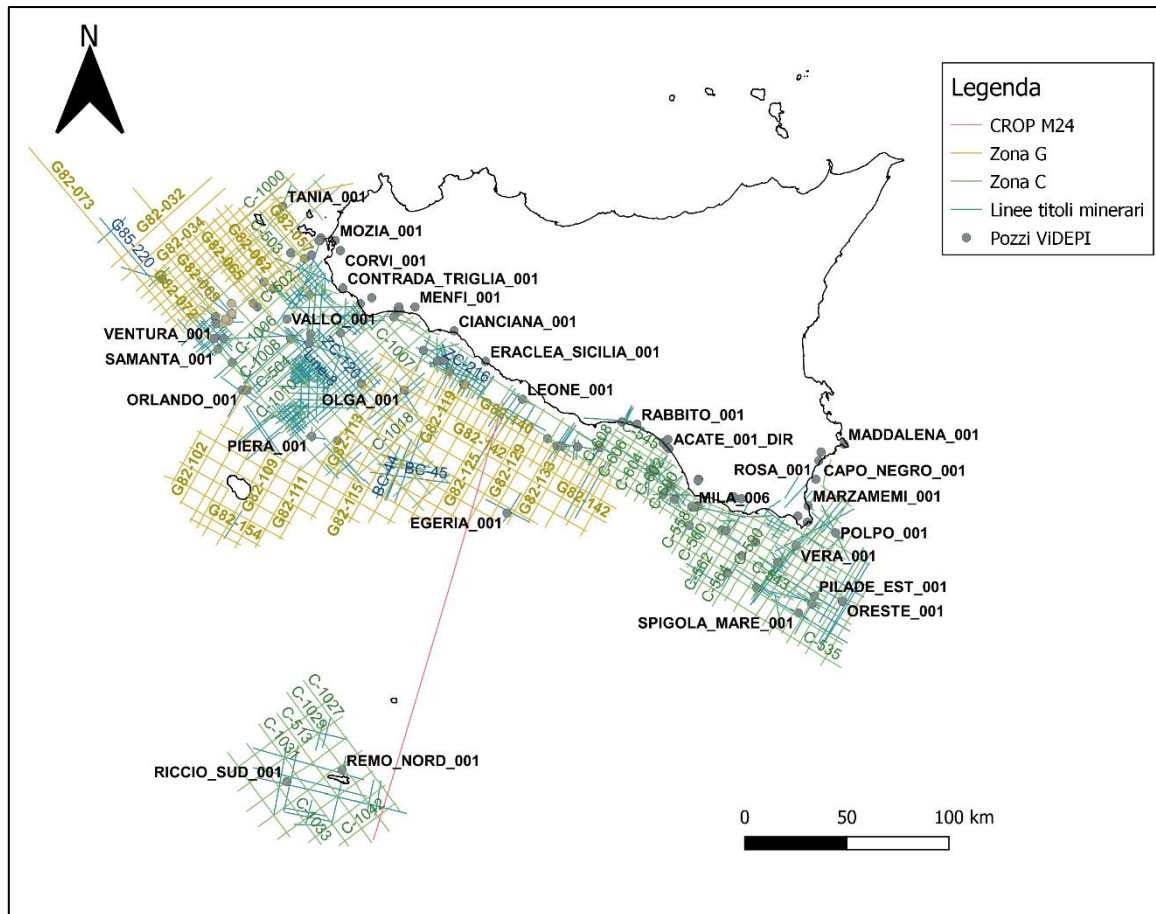


Figure 5. Dataset used for this study (Fonte: database ViDEPI).

4.5 Parameters for Identifying Suitable CO₂ Storage Sites

The identification of reservoir and seal formations was based on well data analysis, while their areal extent was evaluated through the analysis of seismic reflection profiles. Following the guidelines of European projects (Fig. 6) (e.g., the Geocapacity project of the 6th EU Framework Programme), areas suitable for CO₂ storage in carbonate rocks must be selected based on specific criteria, which include:

- A preliminary assessment of data availability and coverage in the study area;
- The identification of a carbonate reservoir with adequate permeability and porosity characteristics, sealed by an impermeable formation, located at a suitable depth (800-2500 m);
- Cover formations with a thickness greater than 50 m are considered suitable to ensure a sealing action;

- Low heat flow values. In sedimentary basins with an average thermal gradient of 25-30°C/km, the supercritical condition is generally reached at a depth of 800-1000 m (Holloway, 2005; Suekane et al., 2005);
- An evaluation of the area's seismicity, particularly the distance from seismogenic sources.

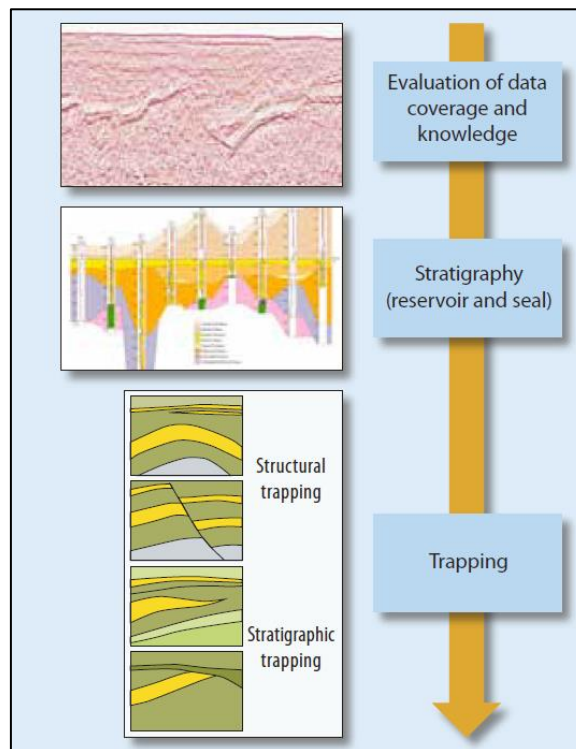


Figura 6. Example of a workflow to carry out a preliminary study to identify suitable sites for geological storage of CO₂ (Geocapacity Project).

Literature data, together with VIDEPI data, were analysed to identify suitable parameters for the study area as follows:

- 1) Formations with possible reservoir and seal character are first determined from the stratigraphic data (literature data and well data analysis) of the study area and the analysis of existing hydrocarbon reservoirs. Therefore, the formations related to the Triassic carbonate platform (F.ne Siracusa and F.ne Gela for the Ibleo offshore and F.ne Sciacca for the Saccense offshore and in the Adventure Bank) were identified as suitable reservoir formations. Sealed formations include F.ne Streppenosa and F.ne Buccheri for the Hyblean offshore and F.ne Terravecchia for the Adventure Bank.
- 2) Heat flow is a very important parameter to allow the injected CO₂ to remain in a supercritical state (31.1°C and 73.9 bar) (Bachu, 2003) and to have a density similar to that of a liquid

(approximately 500-800 kg m⁻³), which provides the potential for efficient utilisation of the underground storage space. Heat flow maps (Cataldi et al., 1995; Della Vedova et al., 2001) (Fig. 7) were used to identify areas of low heat flow. The highest values are generally found in volcanic areas where the values are between 100 and 250 mW/m². Analysing the data collected both at sea (Della Vedova et al., 1987) and in onshore and offshore exploratory boreholes in western Sicily (concerning the intensity of the heat flow in the Strait of Sicily), the presence of a series of thermal anomalies arranged along the axis of the sector affected by extensional tectonics was noted. The heat flow recorded in this sector has values of 100-150 mW/m² (Fig. 7). In particular, the most intense thermal anomalies are recorded on the island of Pantelleria, where the heat flow measured in the central part of the island's caldera has a value of 460 mW/m² (Fig. 7). High values are also recorded in the Hyblean area, both onshore and offshore (Fig. 7).

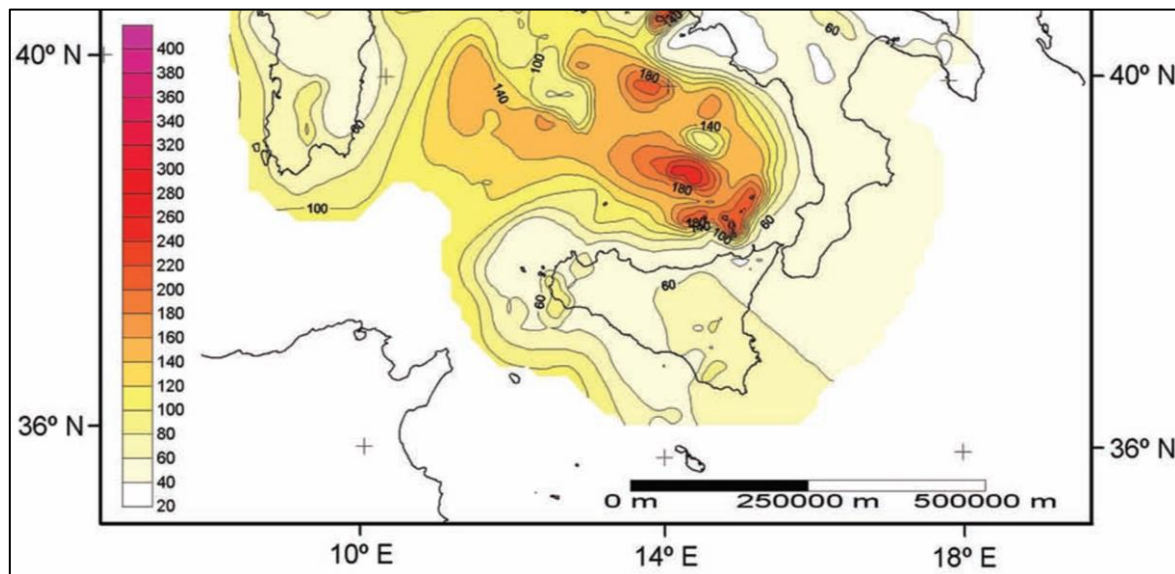


Figure 7. Heat Flow Map of the Central Mediterranean (Della Vedova et al., 2001).

3) The sources of the strong earthquakes that struck Sicily have not yet been unequivocally identified, however, the catalogue of seismogenic sources in Italy (Database of Individual Seismogenic Sources, DISS Working Group, 2018), based on geological, seismological and

geophysical evidence, has identified numerous structures capable of producing earthquakes of magnitude greater than 5.5. Only sources deemed capable of generating earthquakes of magnitude greater than 5.5 are characterised in the DISS (Fig. 8).

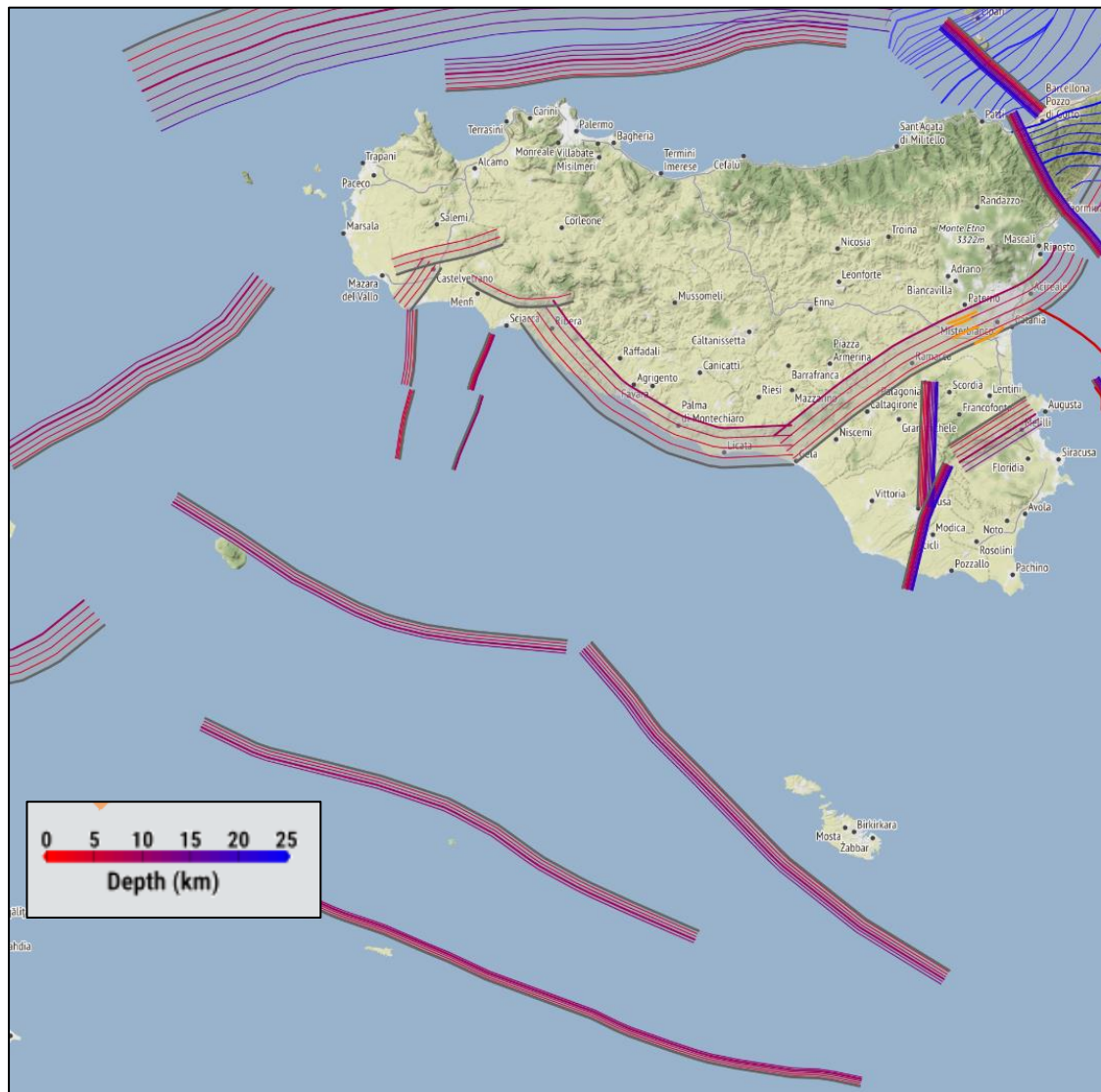


Figure 8. Representation of the Composite Sources for Sicily, which represent a homogeneous set of possible seismogenic sources, designed to describe extensive fault systems (source: DISS database).

4.6 Classification of suitable sites

By means of a stratigraphic and structural analysis, sites with structural highs in the reservoir formations were then identified with a polygon. A classification was then carried out by means of assigning a quality index to each identified site. In particular, values from 1 to 3 were attributed to

each index, with the higher value identifying the one considered most suitable for the purpose of this research.

The five basic parameters used are as follows (Fig. 9):

1. The depth of the reservoir formation (P);
2. The thickness of the seal (S);
3. The available data coverage (C);
4. The heat flow (F);
5. The distance from seismogenic sources (D).

The P parameter was classified considering the parameters used in the literature (Chadwick et al., 2003; Geocapacity Project) which agree that the depth for suitable storage should be between 800 and 2500 m. Therefore, a value between 0.8 and 2.5 s/TWT (using an average v of 2700 m/s) was considered adequate. Similarly, parameter (S) was classified considering the parameters used in the literature (Chadwick et al., 2003; Geocapacity Project), which indicate a seal thickness greater than 50 m and preferably not crossed by discontinuity elements (fractures and/or faults) as necessary.

Parameter C was instead assigned on the basis of the public ViDEPI data, since, in the absence of sufficient well data or good seismic profile coverage, it is complex to define the areal extent of suitable geological structures.

The D parameter, on the other hand, was assigned experimentally using the DISS database described in Section 5.3, the metadata of which were projected into the study area. In order to define a safe distance from these seismogenic sources, it was decided to use literature data from the Messina earthquake (Mulargia and Boschi, 1983), which defined a damage area extending 4300 km² from the epicentre. The radius of the area (37 km) was applied to the seismogenic sources, and a value of at least 37 km away from the sources was therefore considered safe and suitable. The F parameter was attributed on the basis of the work of Holloway, 2005; Suekane et al., 2005 and Civile et al., 2013, who define suitable sites as those close to a heat flux less than or equal to 60 mW/m². The heat flux values were derived from literature data as described in Section 5.3.

Checklist		
Profondità reservoir (P)	3	800-2500 m/ 0,8-2,5 s TWT
	2	<700 (0,5-0,8 s TWT) o >3000 m (2,5-3 s TWT)
	1	<0,5 o >3 s TWT
Seal (S)	3	>50 m e non attraversato da faglie
	2	>50 m ma attraversato da faglie/fratturato
	1	<50 m
Copertura dati (C)	3	Più profili sismici e pozzi
	2	Almeno un pozzo e profili sismici adiacenti
	1	Solo un pozzo o solo profili
Distanza da sorgenti sismogenetiche (D)	3	>37 km
	2	>35 o <37 km
	1	<35 km
	0	In corrispondenza di una sorgente sismogenetica
Flusso di calore (F)	3	< 60 mW/m2
	2	<60<80 mW/m2
	1	> o uguale a 80 mW/m2

Figure 9. Checklist of values attributed to each identified parametric class.

To finally integrate the contributions of each parameter obtained at each analysed site, a sixth parameter, called PCDFS, was added. In fact, less weight was given to the heat flux parameter (F) as the reference data is not high resolution, and to the data coverage (C) as it might be possible to supplement the database with non-public data.

The PCDFS parameter was obtained by applying the formula to each selected site:

$$(P*0.25) *(C*0.15) *(D*0.15) *(F*0.1) *(S*0.25)$$

4.7 Results

The public data analysed, together with literature data, made it possible to obtain a mapping of the areas potentially suitable for geological storage of CO₂ throughout the Strait of Sicily.

Georeferenced maps of the classification applied (from 1 to 3) to each parameter (P, C, D, F, S and PCDFS) were obtained.

Each map is represented below and subdivided by sector of the Strait of Sicily (for the P, C, D, F, S parameters only), respectively for the NW sector of the Strait of Sicily (Fig. 10, 11), south of Sciacca (Fig. 12, 13), offshore Gela (Fig. 14, 15) and offshore Ibleo (Fig. 16, 17).

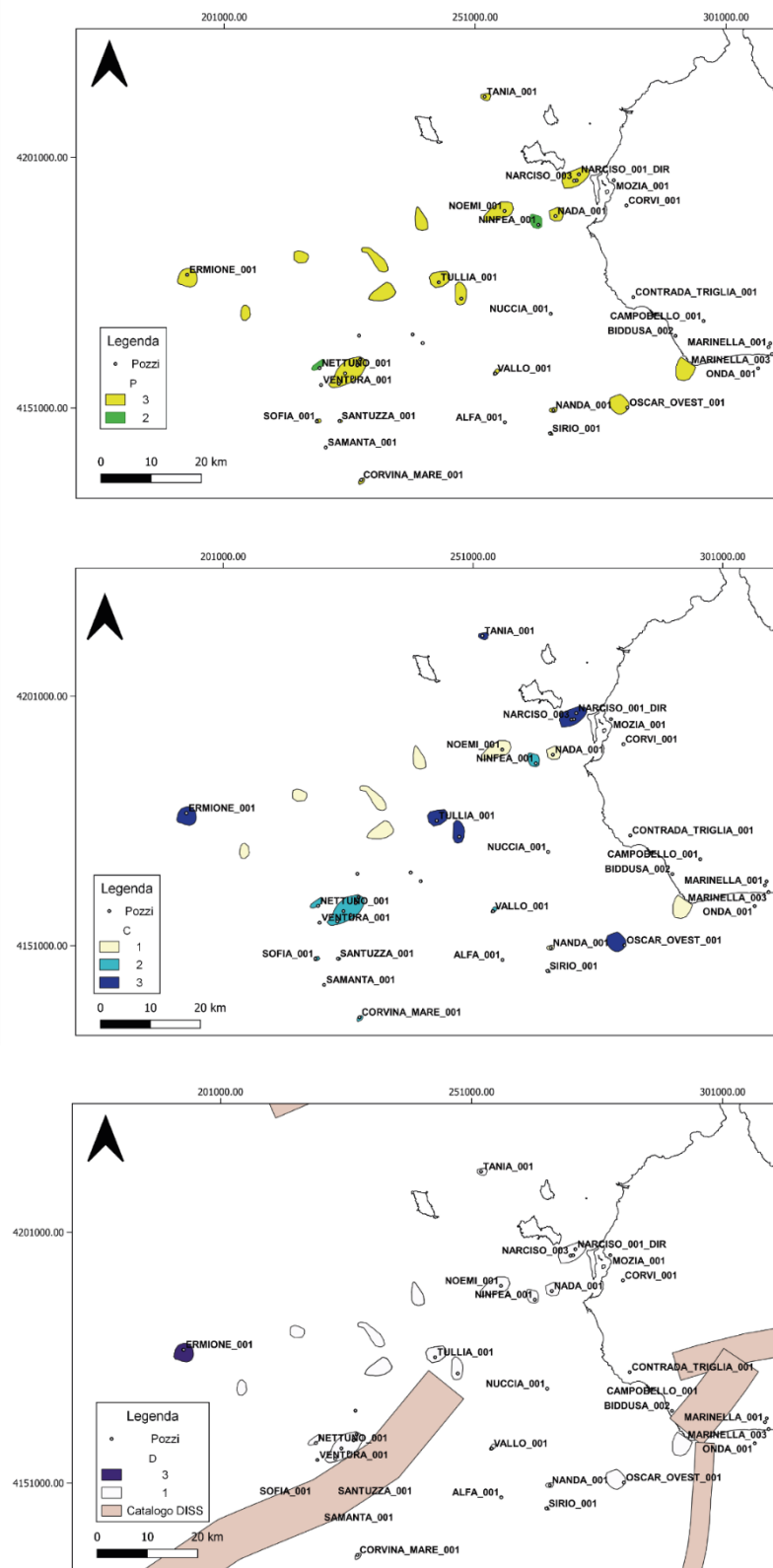


Figura 10. Maps representing the values obtained from the P, C and D classes for the NW sector of the Sicily Channel.

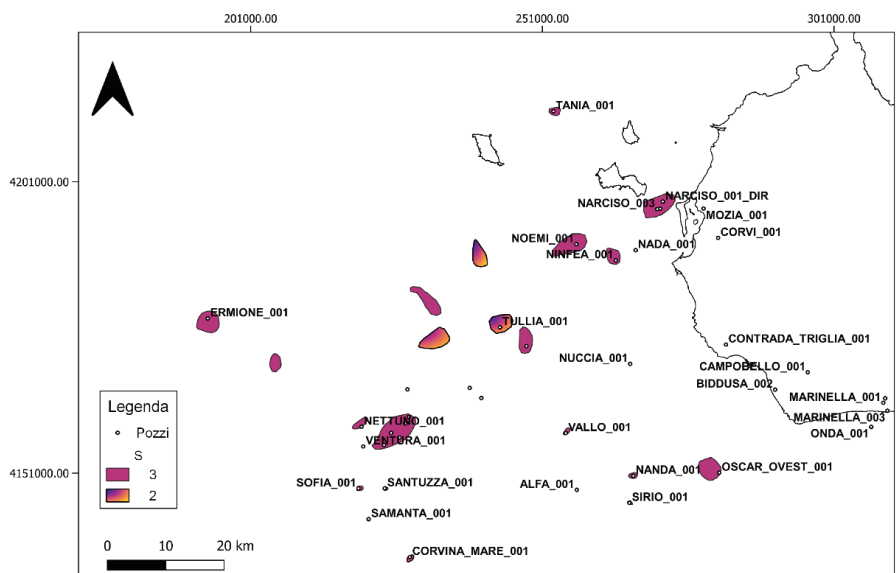
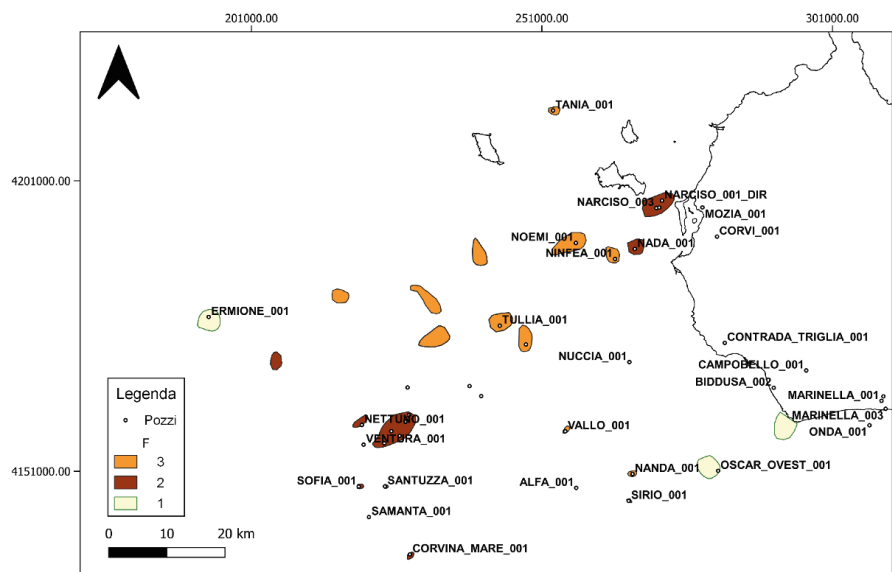


Figure 11. Maps representing the values obtained from the F and S classes for the NW sector of the Sicily Channel.

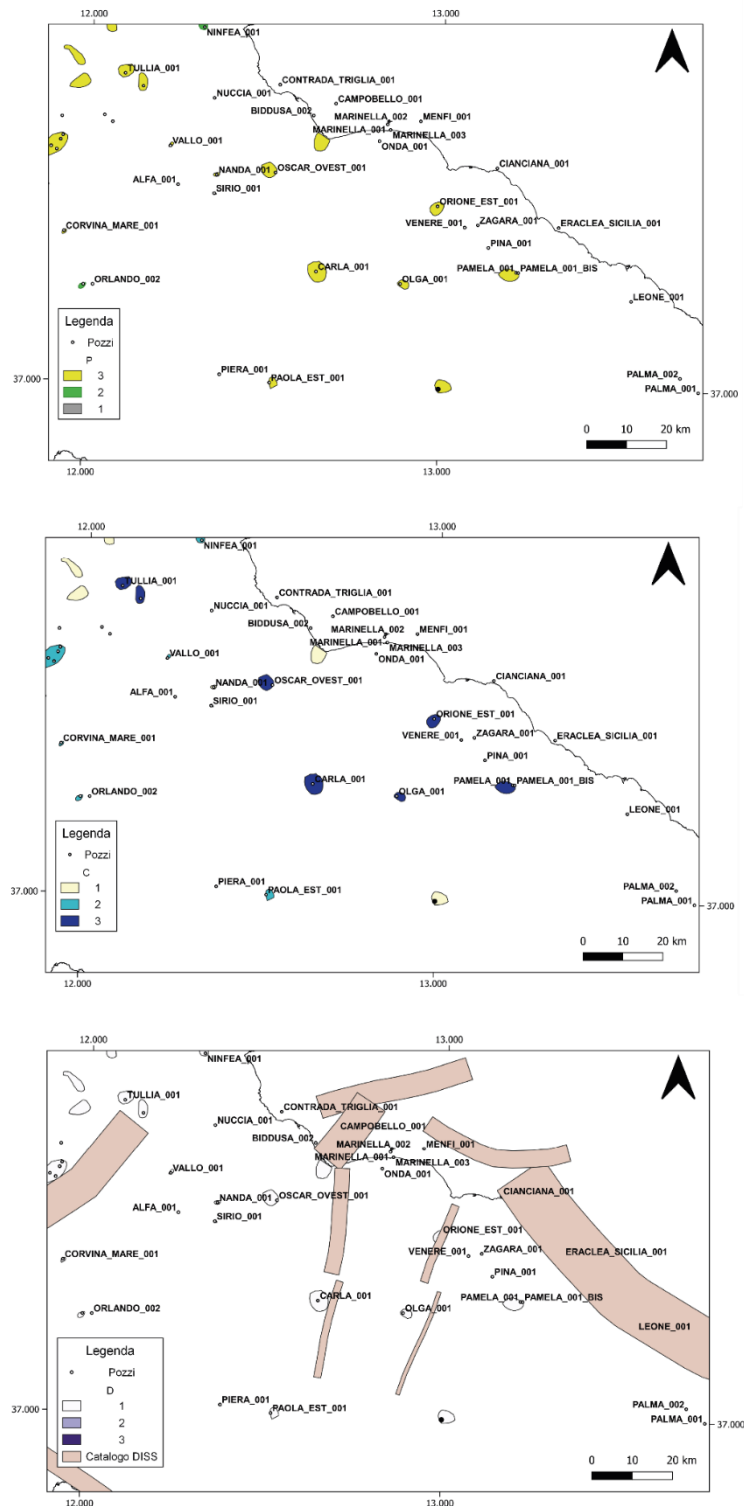


Figure 12. Maps representing the values obtained from the F and S classes for the NW sector of Sicily Channel.

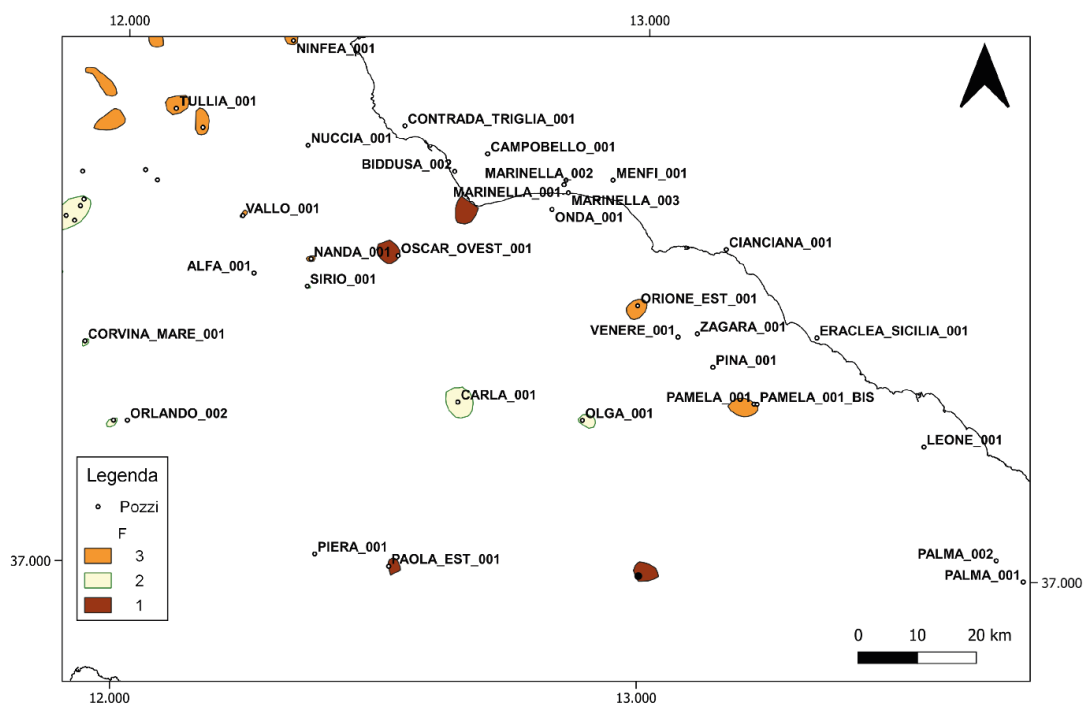
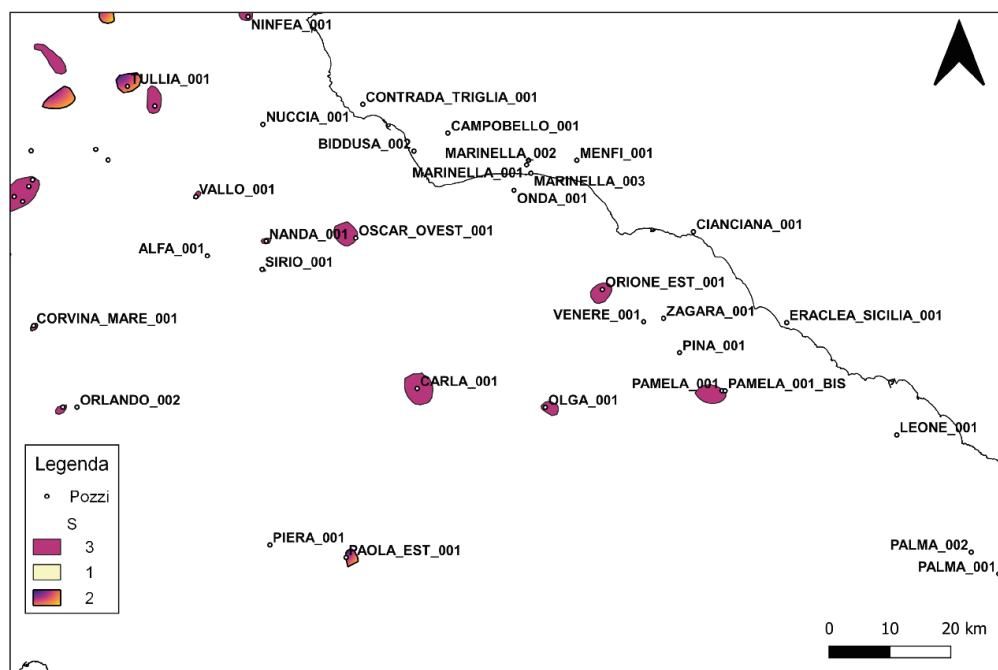


Figure 13. Maps representing the values obtained from the *F* and *S* classes for the NW sector of Sicily Channel

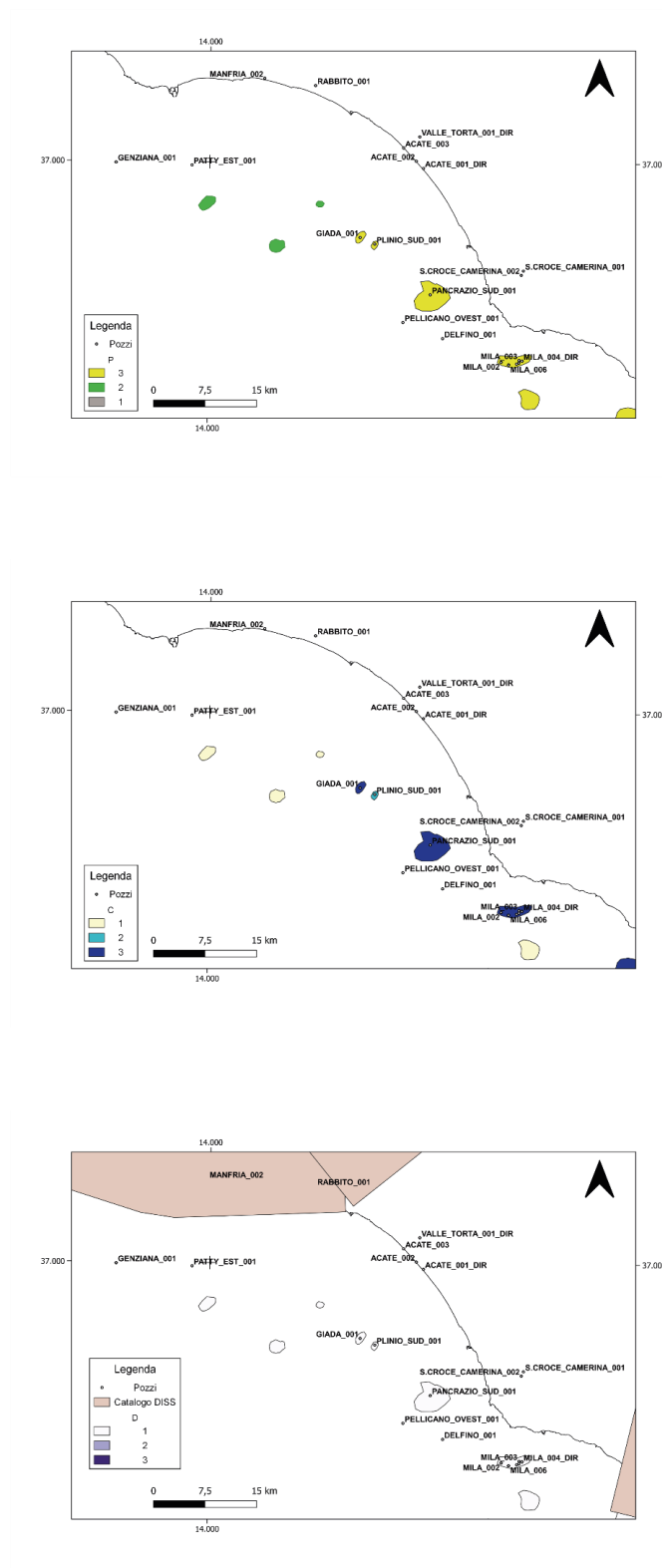


Figure 14. Maps representing the values obtained by classes P, C and D for the sector south of Gela.

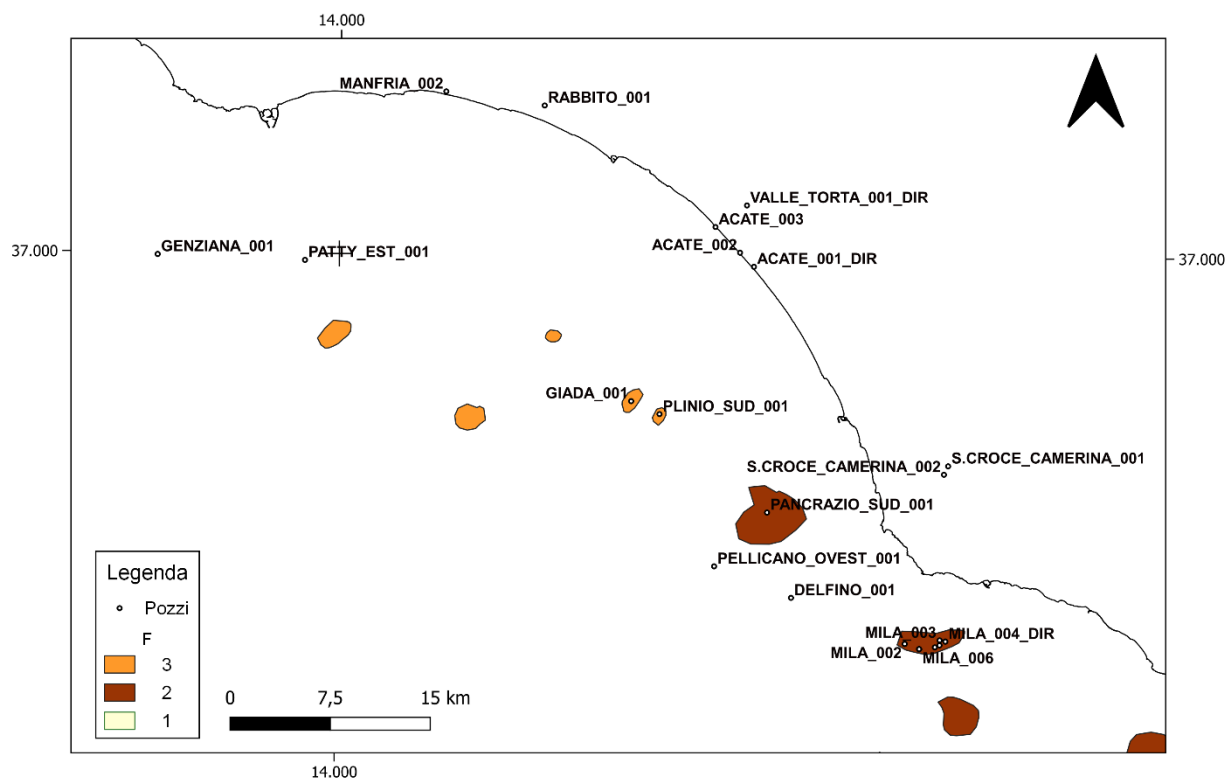
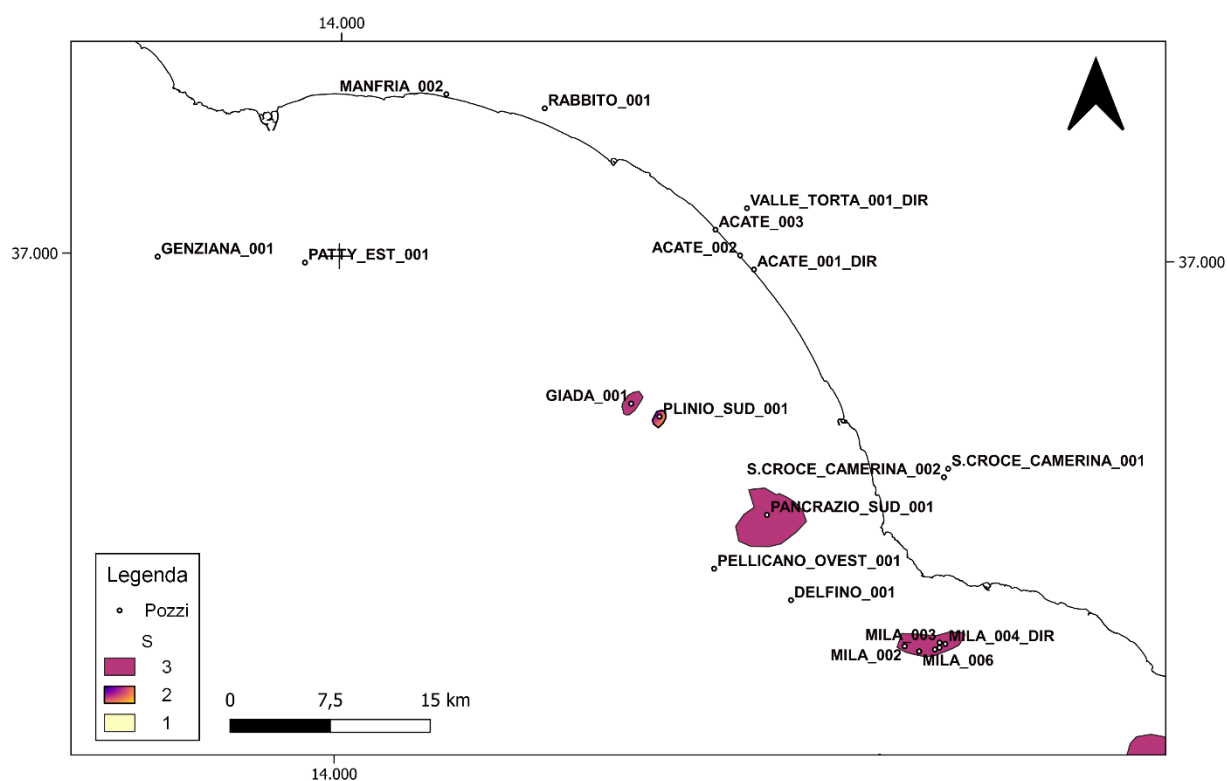


Figure 15. Maps representing the values obtained by classes F and S for the sector south of Gela.

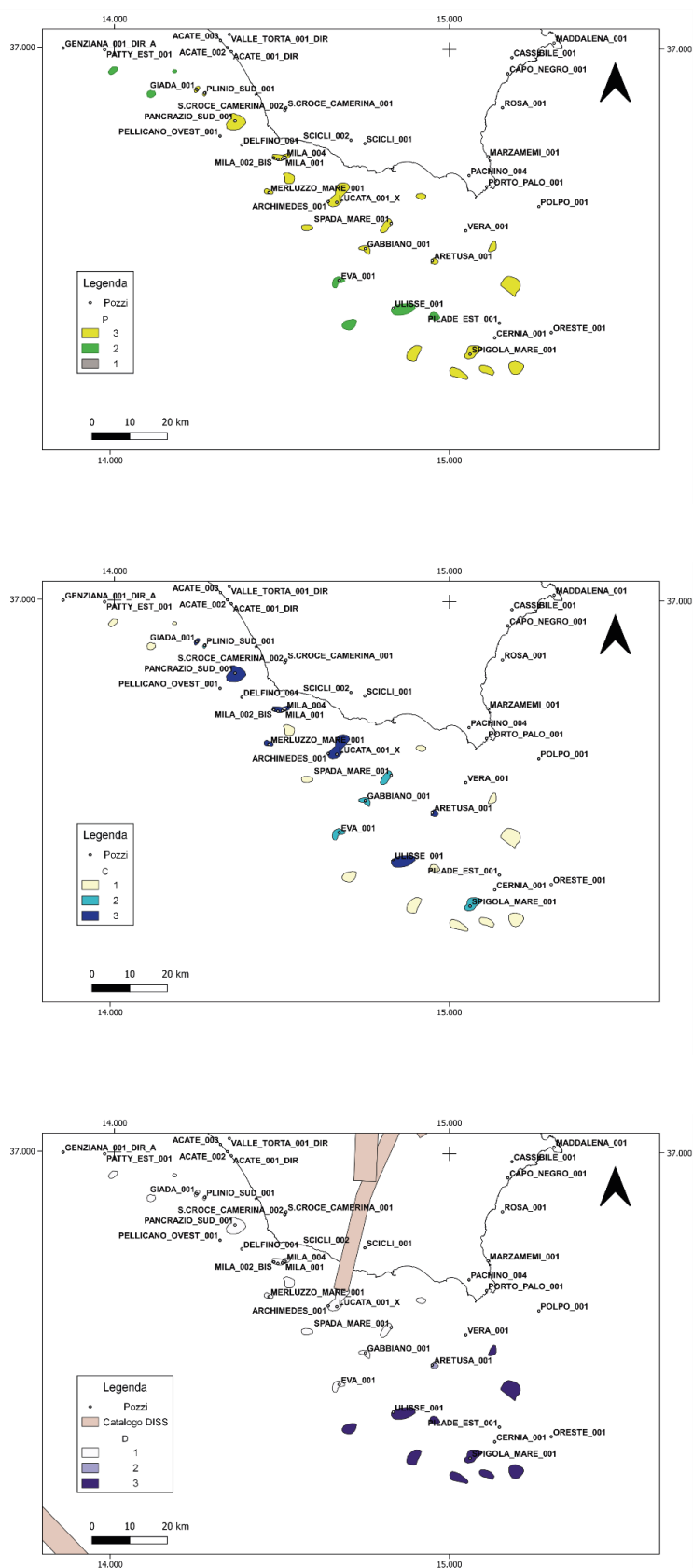


Figure 16. Maps representing the values obtained from classes P, C and D for the Iblean sector.

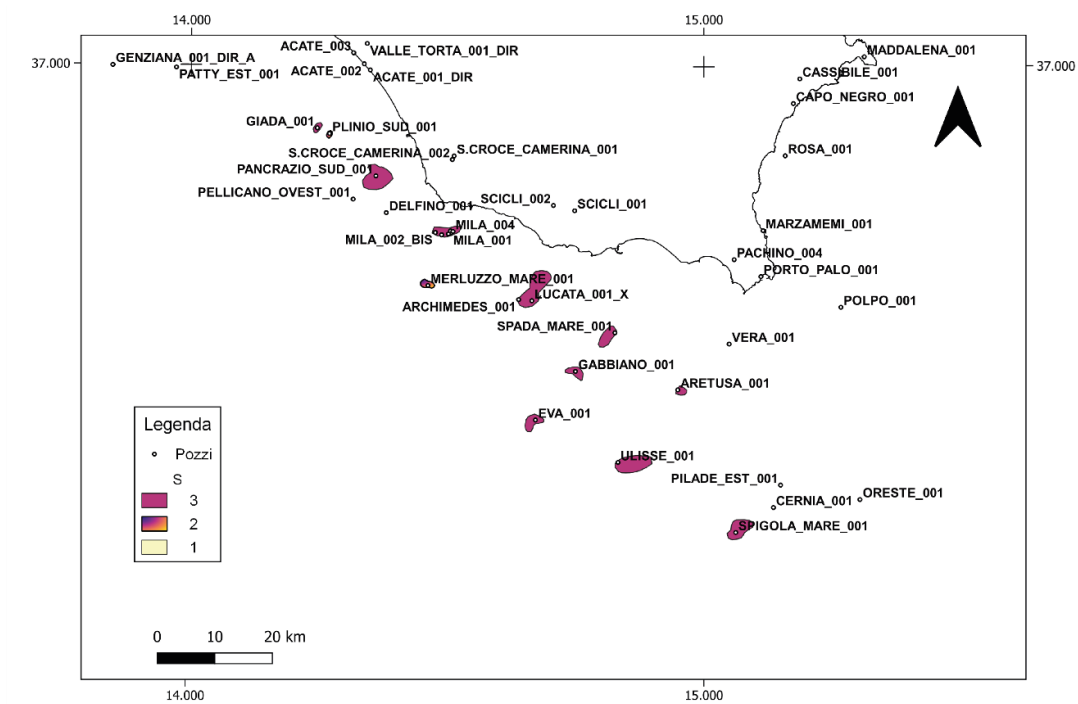
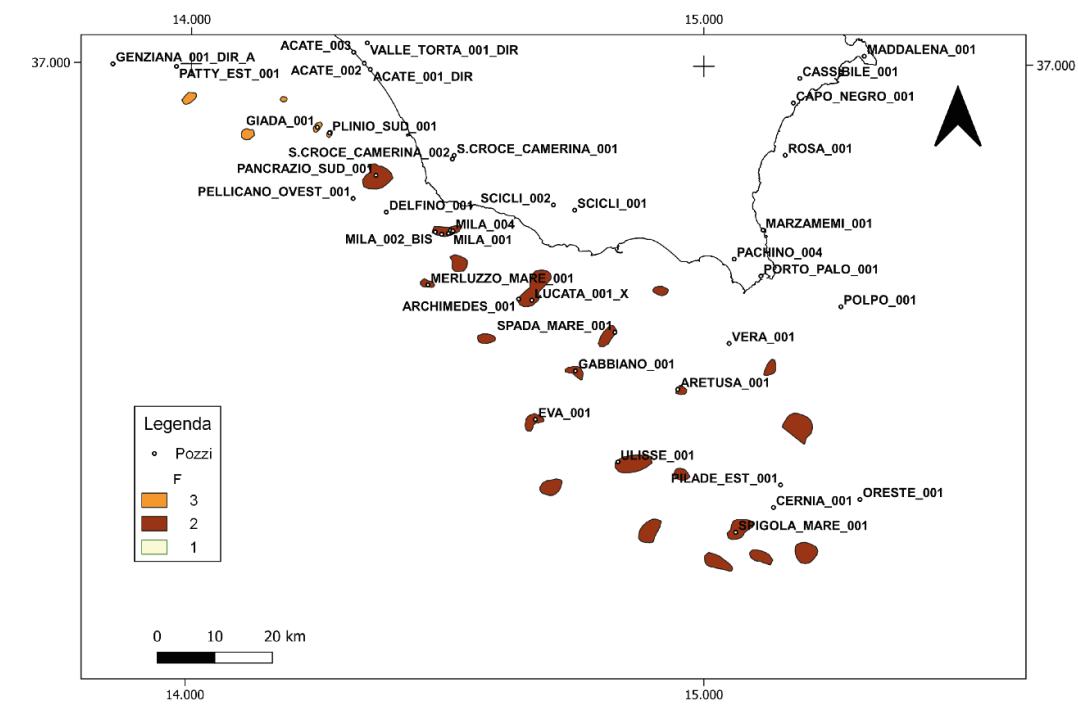


Figure 17. Maps representing the values obtained by classes F and S for the Iblean sector.

Finally, a map of the entire sector showing the classification of the PCDFS parameter is depicted in Figure 20. This shows values ranging from 0 to 0.03, where values of 0 are found at sites located in correspondence with seismogenic sources, while the highest values are found in the north-western sector of the Adventure Bank (e.g. in correspondence with the Ermione well) and in the Hyblean offshore (e.g. in correspondence with the Arethusa well).

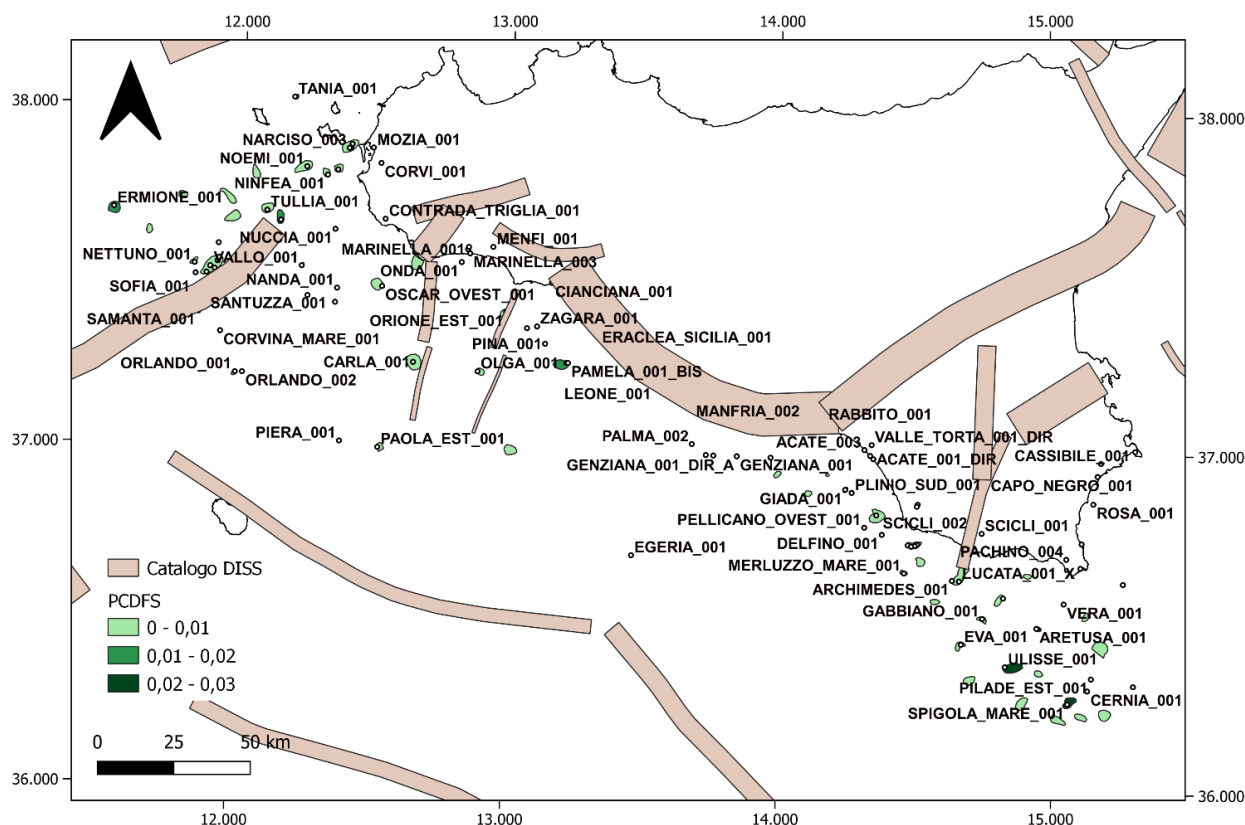


Figure 18. Summary chart representing the values obtained from the PCDFS classes for the whole sector of the Channel of Sicily.

The statistical analysis of the distribution of classes obtained for each site investigated is represented here by pie charts showing the percentage distribution of classes for each parameter (Fig. 19, 20). This

preliminary analysis shows that the Sicilia Channel is an area relatively rich in sites suitable for geological storage with respect to stratigraphy; in fact, 82% of the sites surveyed show adequate depth of reservoir formation. However, the value to be observed more closely is certainly the distance from the seismic sources, since 71% of the sites investigated are located at a distance < 35 km from the sources identified by the official DISS catalogue of the INGV.

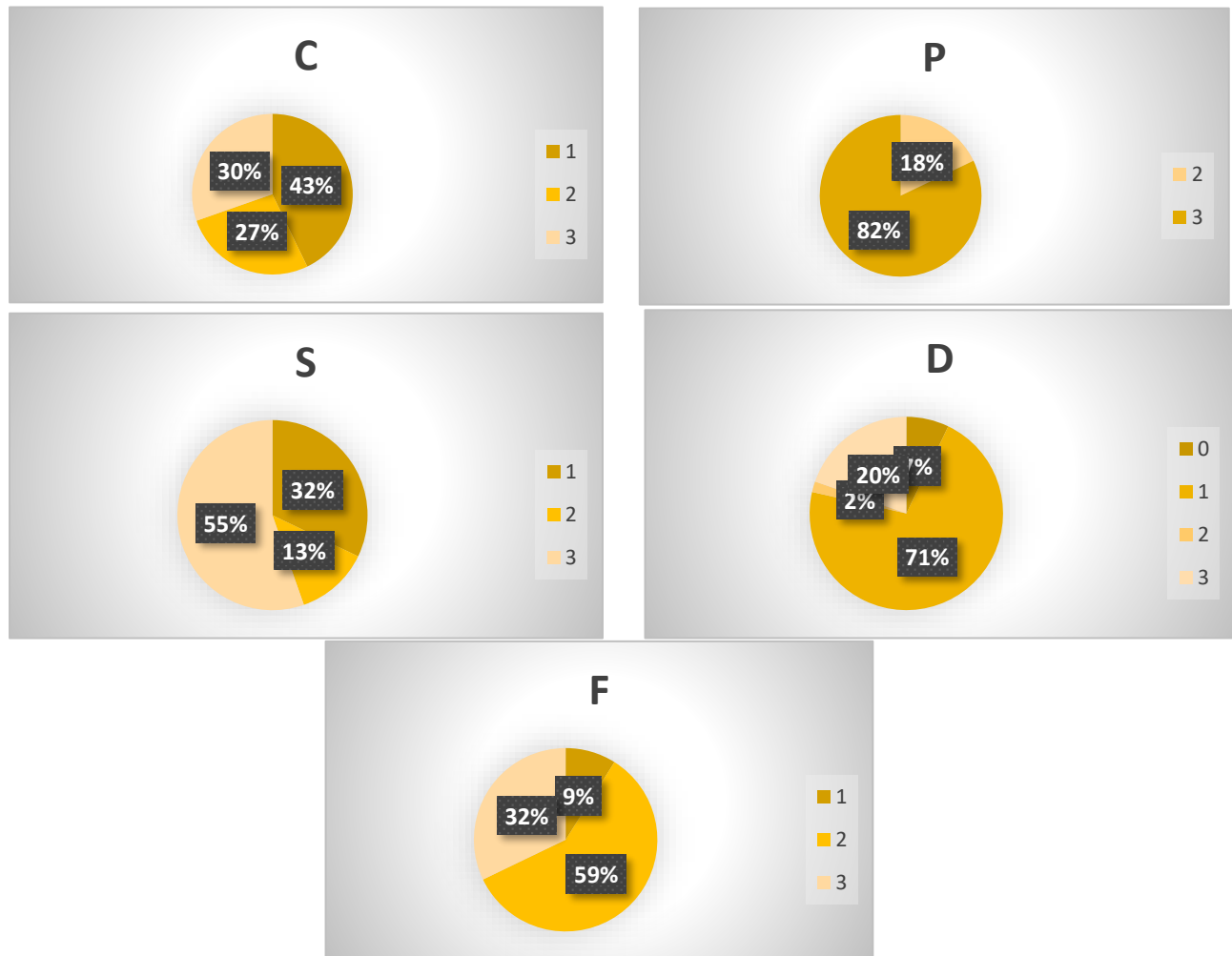


Figure 19. Representative pie charts of the percentage of parameter classes C, P, D, S, F.

Considering the contributions of each individual index, 47 % of the investigated sites were found to be unsuitable for CO₂ storage, while the remaining 53 % had potentially suitable values that could be better characterised through correlation with more high-resolution data. In fact, of the sites identified using public data, only 5 % were found to be potentially suitable. As can be seen in Fig. 20 these are mainly distributed in the Malta Plateau and are close to the Ulisse, Spigola mare and Aretusa wells.

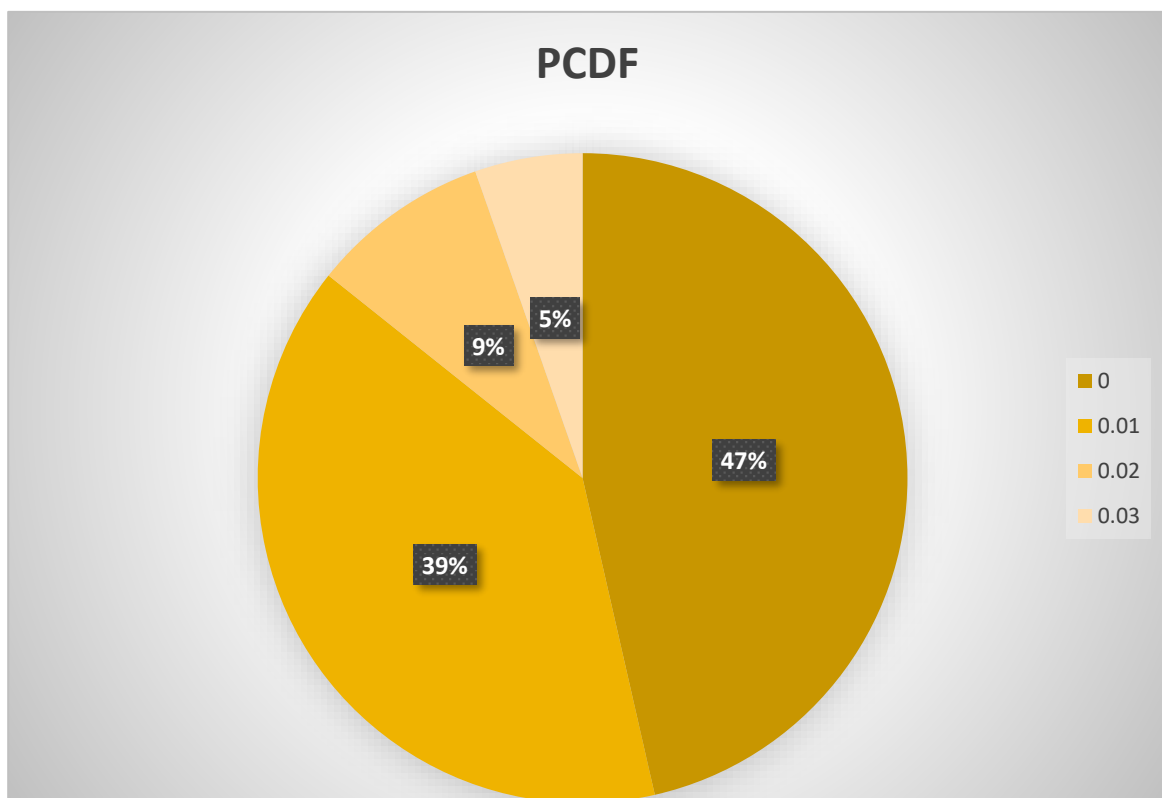


Figure 20. Pie chart representing the percentage of PCDF parameter classes

4.8 Conclusions

This preliminary study has allowed us to understand the geological and structural framework of the area, as well as the parameters that contribute to the selection of sites suitable for the geological storage of CO₂ in the studied area.

The results show that, in the first place, the use of public data may cause an underestimation of the quality of the reservoirs studied. This shows that the selection of parameters must also be calibrated to data of greater detail and resolution. Considering this background, the data identify potentially suitable areas located in the Iblean offshore and in the northwest sector of the Adventure Bank respectively. The aim of future surveys and analyses is to produce three-dimensional geological models which will allow a more accurate estimation of thicknesses, depths and potential storage volumes.

5. Geological Modeling of a Prospective CO₂ Storage Site

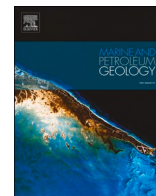
5.1 Introduction

In this chapter, we delve into the geological modeling of a promising CO₂ storage site located in the Gela Foredeep, along the southern coast of Sicily. The following work has been developed in synergy with Halliburton and ENI, who provided the necessary data and instruments.

The Gela Foredeep presents a unique opportunity for carbon capture and storage (CCS) due to its complex geological structure and the presence of saline aquifers. Our comprehensive evaluation of the region involved meticulous analyses of 2D multichannel reflection seismic profiles, which were calibrated with well-to-seismic ties. This approach allowed us to conduct a detailed seismo-stratigraphic analysis, illuminating the tectono-stratigraphic evolution of the Gela offshore area.

Through this rigorous investigation, we identified the Gela Play, characterized by a reservoir formation (Sabbie di Irene Fm.) that is effectively sealed by the primary Argo Formation and potentially by the basal layer of the Gela Gravitational Slide. Our findings underscore the existence of adequate stratigraphic and structural closures within the Gela Foredeep, affirming its potential as a site for further CCS research. Notably, the basal level of the Gela Gravitational Slide exhibits sealing layer characteristics that could serve as a regionally significant sealing unit, making this area a key focus for future geological assessments and sustainable energy solutions.

5.2 GEOLOGICAL CHARACTERISTICS OF A POTENTIAL CO₂ STORAGE SITE IN THE GELA OFFSHORE (SOUTHERN SICILY) AND THE ROLE OF GRAVITATIONAL SLIDES



“Geological characterization of a potential CO₂ storage play in the Gela offshore (southern Sicily) and the role of a gravitational slide”

Mariagiada Maiorana^{a,*}, Attilio Sulli^a, Matteo Marelli^b, Mauro Agate^a

^a Department of Earth and Marine Science - University of Palermo, Italy

^b Halliburton - Via del Marchesato, 25- Ravenna, Italy

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ABSTRACT

In a context where European policies mandating a 55% reduction in CO₂ emissions by 2030, Carbon Capture Storage (CCS) presents a viable solution for achieving substantial emissions cuts. Identifying existing and new potential sites for CCS in offshore southern Sicily is crucial to meeting this goal.

The Gela offshore region is predominantly characterized by the Gela Thrust System (GTS) and its associated Gela Foredeep (GF), a narrow (less than 20 km) and elongated (approximately 100–120 km) depozone that comprises the thicker Plio-Pleistocene sandy sediments of the offshore Sicilian sector. This area is covered by the Gela Slide, a 1500 km² gravitational slide.

The potential of Plio-Pleistocene clastic deposits in this region for CCS implementation has not been previously explored. In this study, we investigated a potential caprock-reservoir system covering around 840 km² in the Gela offshore area. Our analysis involved interpreting key horizons from a dense grid of 2D seismic reflection profiles, conducting well-to-seismic tie analysis and developing a refined velocity model.

The study reveals a promising storage play within the foredeep basin-filling deposits. This potential storage play consists of Lower Pleistocene foredeep turbidite sands of Sabbie di Irene Fm. (reservoir) and of the Middle-Upper Pleistocene pelitic deposits of the Argo Fm. (primary seal). Additionally, the basal shear level of the Gela Slide has been investigated as a potential secondary seal. Analyzing its extent, age, and interaction with the GTS offers valuable insights into the relationships between tectonics and sedimentation, which could lead to the identification of suitable sealing layers for CCS purposes.

This study thus provided new data on the thickness, depth, facies and rock volumes of the main reservoir and seals, highlighting their potential suitability for CCS applications.

1. Introduction

From 1997 to 2017 Carbon Capture and Storage (CCS) initiatives facilitated the storage of a cumulative total of 30.4 million tonnes of CO₂ (Global CCS Institute, 2019; National Academies of Sciences Engineering Medicine, 2019; Kelemen et al., 2019). Given these achievements and the future projections, CCS is poised to play a crucial role in meeting the global Carbon Dioxide Removal (CDR) goal of about 10 gigatons per year by 2050 (United Nations Environment Program (UNEP), 2017; National Academies of Sciences Engineering Medicine (2019); Kelemen et al., 2019). CCS is particularly important for hard-to-abate industries, aiding in emissions reductions and contributing to European Green Deal's objectives: reducing net greenhouse gas emissions by at least 55% by 2030 and achieving climate neutrality by 2050.

Currently, most captured CO₂ is injected into depleted hydrocarbon reservoirs, occasionally for CO₂-enhanced oil recovery (CO₂-EOR) (Global CCS Institute, 2019). However, these reservoirs offer limited capacity compared to saline aquifers, which have the highest geologic storage capacity due to their extensive nature (Hughes, 2009).

Sleipner (offshore Norway) was the world's first commercial CO₂ storage project in saline aquifers. It involves injecting CO₂ into the Utsira Formation, a vast shallow marine sandstone of Miocene age, with a CO₂ storage capacity ranging from 1 to 60 gigatons at the basin scale (Ringrose et al., 2021).

The Sicily Channel is known for its many geological traps, but most are in a carbonate context (e.g., carbonate builds-up, Frixia et al., 2000), which may offer limited capacity for CCS or CO₂-EOR projects (Civile et al., 2013).

* Corresponding author.

E-mail address: mariagiada.maiorana@unipa.it (M. Maiorana).

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Since the most suitable aquifers are typically found in sedimentary basins (Hughes, 2009), this study focuses on a portion of the largest sedimentary basin in the Sicily Channel, the Gela Foredeep, to assess its potential as a CO₂ storage. The strategic advantage of targeting aquifers for CO₂ injection is their capacity to accommodate larger volumes compared to depleted oil and gas fields (Hughes, 2009). Moreover, given the extent of the Gela Foredeep, it is possible that suitable reservoir identified in this study might also be present in other areas of the foredeep, warranting future exploration.

Since the Gela Foredeep is covered by a 1500 km² gravitational slide following the tip of the Gela Thrust System (Trincardi and Argnani, 1990), we examined this feature in order to detect a potential sealing layer. Gravitational complexes can form kilometre-scale deposits resulting from gravity-induced deformation of strata on continental slopes (Mangano et al., 2023). These features typically develop over a long-lasting overpressured basal detachment, often shaly, which acts as a rheologically weak zone (Morley et al., 2011) and thus, potentially serve as a seal (Sun et al., 2021). Given that ongoing fluid can weaken the basal detachment and reduce its friction, fluid seepage and slope instability often occur together. This association has been observed in the central Mediterranean (Crotone Basin) where, slope instability since the Pliocene has coincided with the development of gas-bearing traps (Zecchin et al., 2018; Mangano et al., 2023a, 2023b).

The criteria for selecting suitable CO₂ storage sites vary based on the type of storage (EOR, depleted fields or Saline aquifer storage). Most European projects follow the guidelines established by the Geo-capacityProject (<http://www.cgseurope.net/Sections.aspx?section=491.492.494>), which identify key characteristics for reservoirs and seals. An ideal reservoir should exhibit high permeability, porosity and be mainly composed of sandstone. It should be located at a depth between 800 and 2500 m b.s.l. The ideal seal should have low permeability and porosity, preferably composed of mudstone, with a thickness exceeding 50 m. In CCS projects, both primary and secondary seals are critical for preventing CO₂ leakage from underground storage. The so-called “primary seal” is the main geological barrier directly above the CO₂ storage reservoir, preventing the upward migration of injected CO₂. The

“secondary seal” is an additional layer of impermeable rock located above the primary seal (not necessary directly), providing extra protection against CO₂ leakage and acting as a backup if the primary seal fails or is compromised. Identifying multiple seals (e.g., primary, secondary, etc.) is essential for maximizing storage efficiency and minimizing risk, especially in large-scale storage operations (Chadwick et al., 2008).

This paper addresses (i) the identification of new storage sites, comparing them to previous regional assessments (Donda et al., 2011; Civile et al., 2013) and (ii) an analysis of interactions between Gravitational Slide and Gela Thrust System to investigate the potential formation of secondary sealing layers.

2. Geological setting

The structural configuration of Sicily Channel (Fig. 1) has been significantly influenced by the Neogene active convergence between European and African plates (Carminati et al., 2012). The Sicily Channel is part of the northern African continental platform and is crossed by three NW-trending, relatively deep troughs: Pantelleria, Malta and Linosa grabens (Civile et al., 2021) (Fig. 1). A passive rifting process is widely accepted to explain these extensional structures accompanied by a local crustal thinning of the Sicily Channel (Finetti, 1984; Civile et al., 2010, 2021; Maiorana et al., 2023). The rifting process, which began in the Early Pliocene, led to the opening of the Pantelleria, Malta and Linosa Grabens and was accompanied by extensive volcaninc activity. This volcanism produced both subaerial and submarine volcanic features, often linked to fluid flow processes (Spatola et al., 2023; Maiorana et al., 2024). The active convergence between European and African plates also resulted in the development of three key regional-scale elements (Roure et al., 1990; Lentini et al., 1996; Catalano et al., 2013; Butler et al., 2019).

a) The Iblean-Pelagian foreland, part of the African plate, which is exposed in the southeastern corner of Sicily (Iblean Plateau) and is

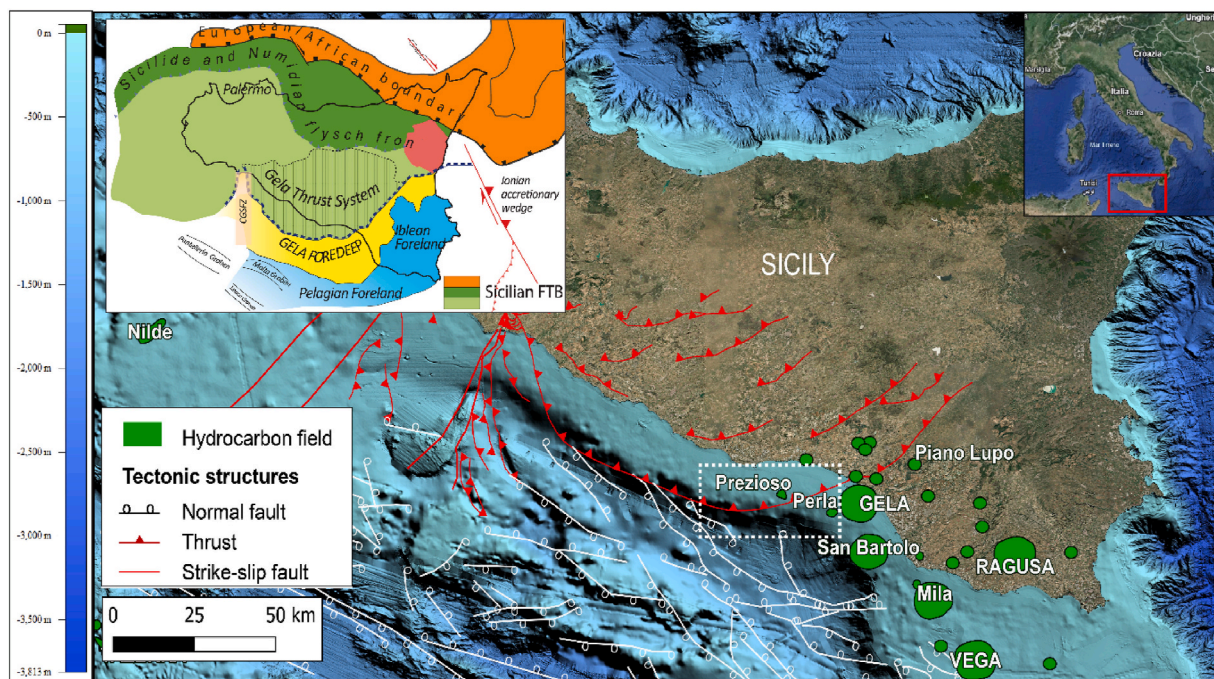


Fig. 1. Map showing the Sicilian onshore and offshore tectonic lineaments (courtesy of Neftex® Halliburton) with in indication of the study area (white dotted square); on the top right the geographic location of the Sicilian area is shown; on the top left the tectonic domains are shown (mod. after Catalano et al., 2013; Civile et al., 2018). Bathymetric base map from GEBCO (https://www.gebco.net/data_and_products/gridded_bathymetry_data/).

- submerged in the Pelagian Sea with its African basement (i.e. the Pelagian–Iblean foreland) (Catalano et al., 2013).
- b) The south to southeast-vergent Sicilian Fold and Thrust Belt (SFTB), which includes: i) a “European” element (Kabalian-Calabrian tectonic units), exposed in north-eastern Sicily and continuing in the southern Tyrrhenian; ii) a “Tethyan” element (Sicilide units); iii) an “African” element, composed of carbonate thrust systems (Sicilian-Maghrebian units), with a frontal thrust wedge called Gela Thrust System (GTS) (Fig. 1) composed of Cenozoic terrigenous, evaporitic and clastic-carbonate deformed rocks (Argnani, 1990; Butler et al., 1992; Catalano et al., 2013; Lickorish et al., 1999; Sulli et al., 2021). In the Early Pleistocene, the last stage of advancement of the GTS is recorded at 0.8 Ma (late Calabrian) (Di Stefano et al., 1993; Cavallaro et al., 2017; Maiorana et al., 2023)
- c) The Late Pliocene-Quaternary Gela Foredeep (GF), a narrow and elongated foredeep basin located along the frontal sector of the Sicilian thrust belt in southern Sicily and its offshore region (Sulli et al., 2021) (Fig. 1). This depocenter represents a significant Plio-Quaternary foredeep basin. Since the Early Pliocene a basin wide event, linked to a regional uplift, affected this area, later inducing a gravitational collapse involving the Gela Basin deposits (Trincardi and Argnani, 1990). The head of the produced slide (involving more than 700 m of the GF deposits) follows the tip of the GTS.

3. Stratigraphic setting

The Gela Foredeep (GF) is characterized by a substantial sedimentary sequence composed of Pleistocene turbidite sandstones and mudstones, which contains several multiple depositional sequences (Di Stefano et al., 1993; Catalano et al., 1996; Patacca and Scandone, 2004). In the shelf zone, Pleistocene deposits show well-developed prograding

complexes that correlate with the turbidites found in the basin (Di Stefano et al., 1993).

Ghielmi et al. (2012) proposed a lithostratigraphic scheme for the GF, which includes the following informal units (Fig. 2).

- Trubi Formation (Lower Pliocene): This formation consists of upper Zanclean-basal Piacenzian marly limestone. Thin layers (10–20 m) of transgressive grey-whitish fossiliferous marls of Trubi Fm. were deposited only in a relatively limited onshore area.
- Ponte Dirillo Formation (middle Pliocene-to-Holocene): This formation consists of grey and grey-green clays deposited by fall-out with draping geometry on the foreland ramp and foreland of the Gela Basin. The thickness, laterally very variable, usually ranges from 20 to 50 m.
- Argille Basali Formation (Lower Pleistocene): This formation consists of foredeep turbidite sediments, including grey and grey-green clay and silty clay. The maximum thickness reaches approximately 110 m.
- Sabbie di Irene Formation (Lower Pleistocene): Composed of foredeep turbidite sands and clays, the Sabbie di Irene Fm. is characterized by a highly efficient Type I turbidite system (sensu Mutti et al., 1999), featuring a notable basin-scale tabular geometry.
- Argo Formation (Middle-Upper Pleistocene to Holocene): This formation consists of foredeep turbidite sands and clays, with a maximum thickness of around 1300 m. It is frequently intercalated with mass-transport deposits, particularly along the inner foredeep margin. Their size and frequency increase in the middle-upper part of the Argo Formation. Most of the chaotic deposits are represented by slumps produced by submarine failure of slope sediments of the Pleistocene progradation originally deposited on the Gela Nappe. These deposits, developed along the northern margin of the Sicily Channel, were produced by submarine failure of slope and shelf

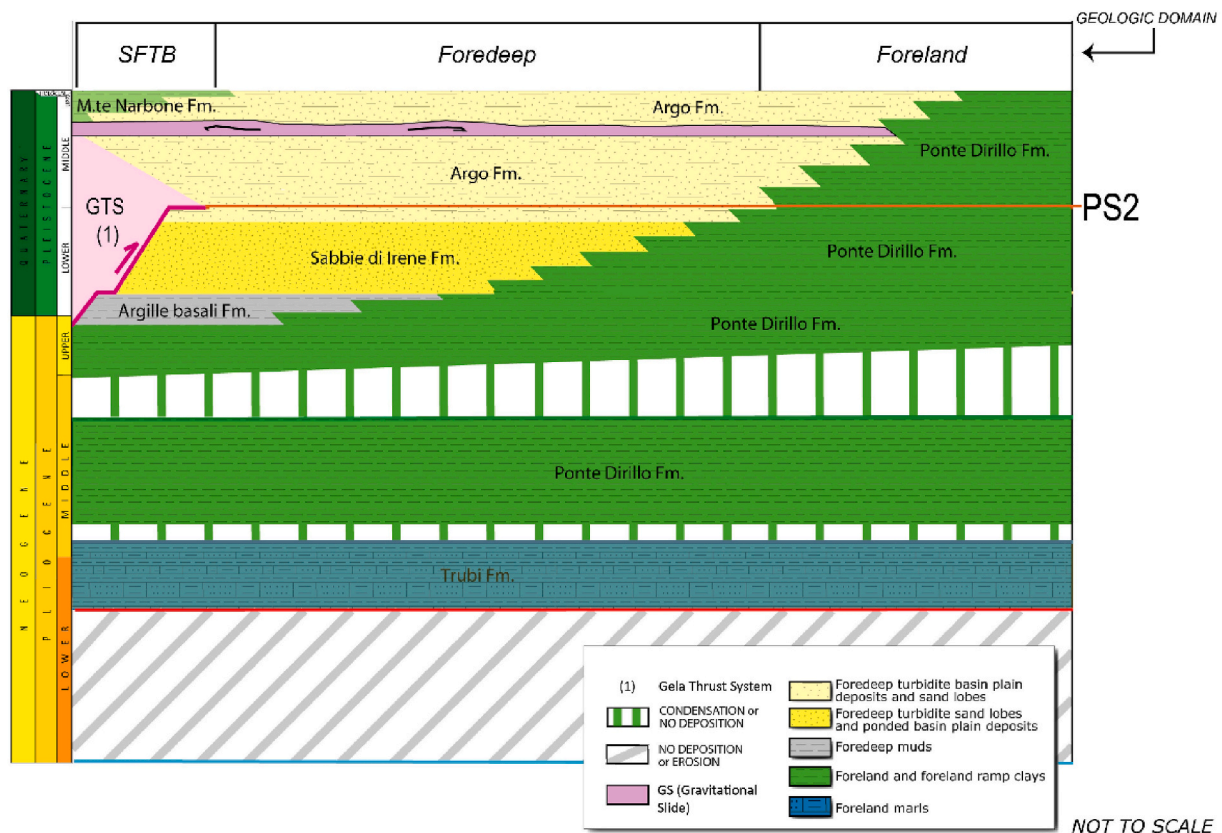


Fig. 2. Stratigraphic scheme of the Plio-Pleistocene Gela Basin succession (mod. after Ghielmi et al., 2012) along the SFTB (Sicilian Fold and Thrust Belt), foredeep and foreland domains. PS2: Pleistocene Sequence 2, a pelitic level from Ghielmi et al. (2012).

deposits of the Pleistocene Prograding Complex, consisting of slope, shelf, and coastal deposits.

In their study, Ghielmi et al. (2012) also identified an interval termed “PS2”, which corresponds to a clayey layer found in the study area and located at the top of the Sabbie di Irene Fm. The acronym “PS” stands for “Pleistocene Sequence”. Ghielmi et al. (2012) distinguished PS1 (older) and PS2 (younger) in the Plio-Pleistocene foredeep succession, noting that these are bounded by tectonic or eustatic-controlled boundaries, generally corresponding to abrupt changes in depositional systems type and distribution. In the foredeep (Gela Basin), PS2 corresponds to turbiditic deposits (pelites) of the Argo Fm., while in the ramp, it aligns to pelites of the Ponte Dirillo Fm. The upper boundary of PS2 is associated with the advancement of the GTS toward the foreland, which led to the deformation of the underlying turbiditic succession.

4. Materials and methods

For this analysis, we utilized a dense grid of 2D seismic reflection profiles along with data from 8 exploration wells (Fig. 3), sourced from the ENI database. Exploration boreholes (Figs. 3 and 4) were employed to calibrate the seismic profiles. The interpretation of key horizons was conducted using the seismo-stratigraphic methods outlined by Vail et al. (1977).

The Landmark DecisionSpace Geosciences package was used to perform the seismic interpretation of key horizons and main faults, well-to-seismic tie, velocity model, depth conversion, to create depth and isopaque maps (in-depth domain) and to generate a 3D view in-depth domain. The well-to seismic tie was necessary to calibrate the well log data response to two-way time seismic generating new time-depth curves in the process and also a single synthetic seismic trace along the well bulk shifting and/or stretching and squeezing the well data. This way the horizons interpreted on the seismic in TWT (Two Way Time) should match the surface picks in TVD (True Vertical Depth). The well to seismic tie was done for 8 wells, on an individual basis, covering the whole study area.

4.1. Well-to seismic tie and velocity model

The velocity model is a crucial step to convert seismic two-way time into depth domain, enabling the calibration of seismic response with well data. This was achieved by integrating well check-shots and logs (sonic and density) and performing well-to seismic tie generating new time-depth curves in the process and a single synthetic seismic trace at each well location.

For each well, the sonic and density logs were multiplied and then convolved with a seismic wavelet (close to a 20 Hz zero phase Ricker, representative of the seismic frequencies) to provide a preliminary synthetic log in the time domain, using the original check-shot curve for the depth to time conversion of well data. The sonic log was also used to integrate the check-shot velocities. All the above steps were performed by the DecisionSpace® Geosciences software.

Subsequently, the synthetic log was shifted and/or stretched to match the seismic responses; this was mainly done manually moving the data points (check-shot stations) interactively. This means modifying the time-depth relationship (i.e. velocity) along the well so a new check-shot was created for each well (example in Fig. 5). Available logs data do not cover the upper part of the well-data.

The well-tie process was guided by geophysical principles to avoid unreasonable interval velocities and ensure that seismic horizons in time matched three key surface picks in the depth domain.

The new time-depth curves from the well-to seismic tie process served as the first type of information for the construction of a preliminary velocity mode, which represents both vertical and lateral variation of velocities. Velocity changes reflect variation in lithology and/or fluid contents, compaction and might also identify, with the correct resolutions, significant faults and fractures.

To take advantage of new calibrated time-depth curve relatively fine resolution, a vertical sampling of 5 m has been chosen with 100 m in X and Y. To ensure uniform velocity distribution along wells located 5 and 50 km apart, 3 significant time surfaces have been selected.

Kriging was used as proved to provide smoother interpolation of velocity values laterally accounting for the different distance of well locations.

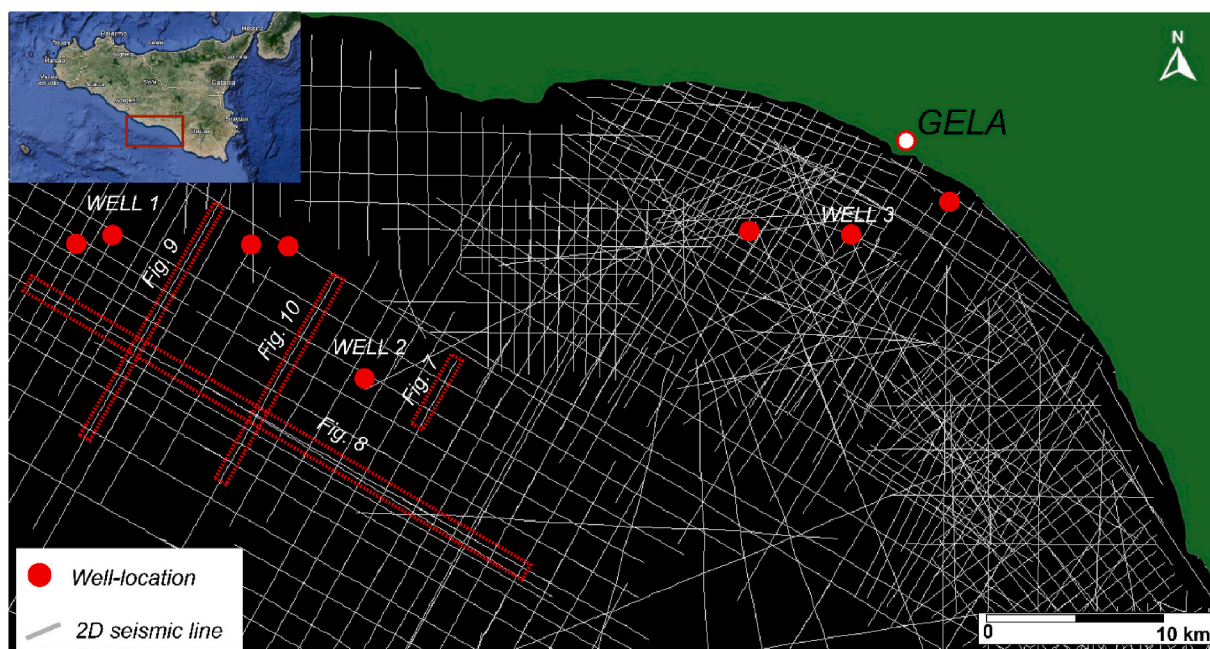


Fig. 3. Dataset location with 2D seismic reflection profiles and wells.

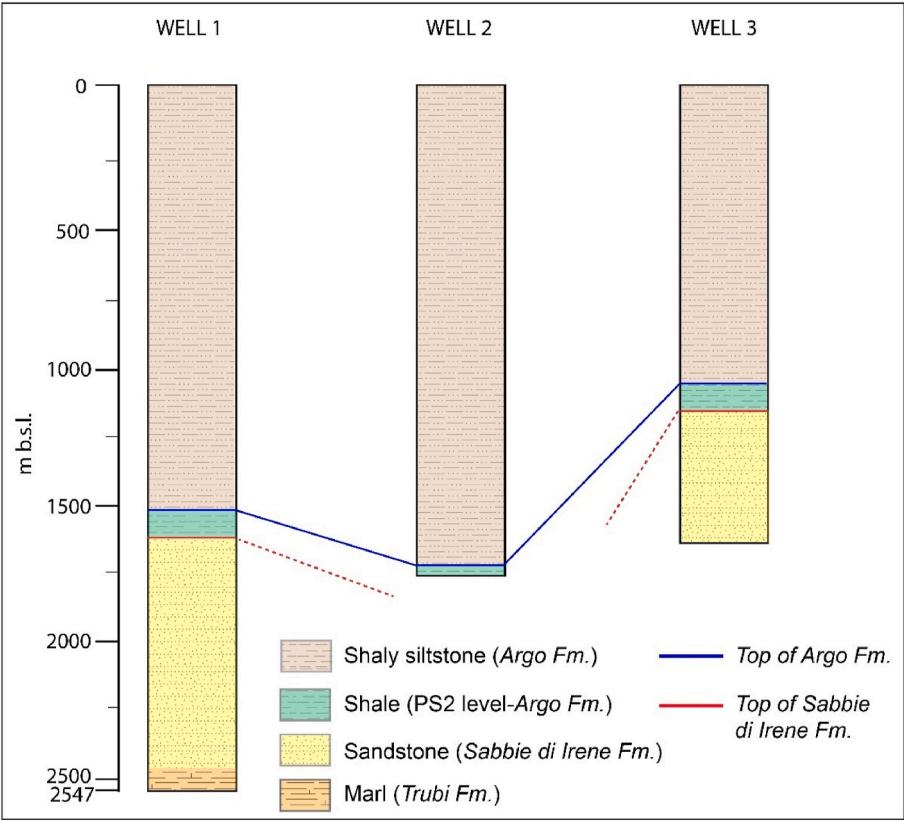


Fig. 4. Simplified stratigraphic columns of the main exploration boreholes used in this study and their stratigraphic correlation (location of boreholes in Fig. 3).

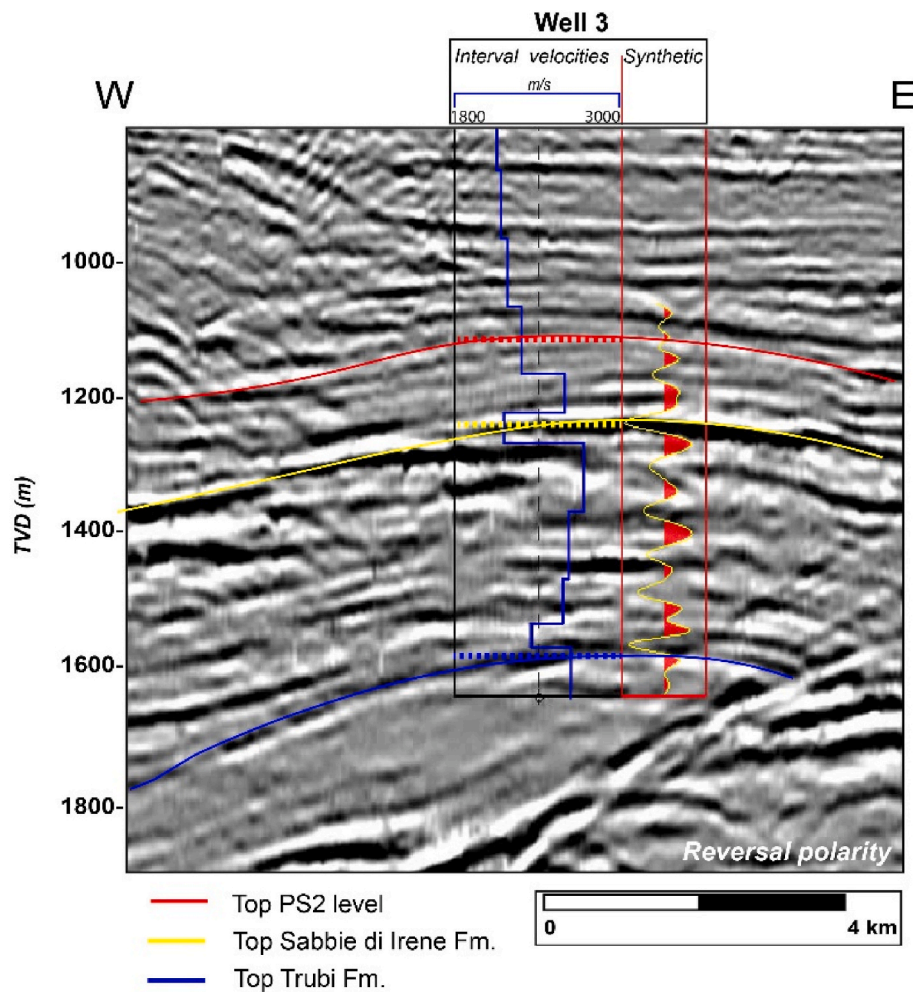


Fig. 5. Example of the computed single synthetic trace and the resulting time-depth curve for Well 3 (see location in Fig. 3). Well surface picks are indicated with dotted line matching the horizons colours (continuous line).

The resulting velocity model (Fig. 6) was used for time-to-depth conversion of the main horizons. These were ultimately gridded with a 250×250 m resolution introducing conformance rules so that there would be no overlap between the horizons and flexed to match the well surface picks, marking the top of the main units (residual fit operation).

Additionally, the thickness of reservoir and seal layers were calculated. Using that data, the software DecisionSpace® Geosciences automatically generated the Gross Rock Volume for each layer.

5. Results

5.1. Seismic stratigraphy (time domain)

The interpretation of the TWT seismic reflection profiles was based on the identification of key surfaces limiting the seismic units, identified as follows, bottom to top (Fig. 7):

Unit 1: is represented by a low reflectivity interface showing a high lateral continuity. This unit shows some interruption attributed to normal faults and a thickness increasing towards south. It is limited at

the top by a low amplitude reflector and at the bottom by a high amplitude reflector with low lateral continuity (Fig. 7) interpreted as the “Messinian Unconformity”; Unit 2: the reflectors within this unit exhibit good lateral continuity, high frequency, and tabular geometry. The unit shows a decrease in thickness toward the south, where the reflectors onlap with onlap geometries on the Unit 1 (Fig. 7). Toward the north, instead, the reflectors cut-off on the GTS basal thrust; Unit 3: characterized by high amplitude reflectors with medium frequency, good lateral continuity and tabular external shape (Fig. 7). Onlap termination on the Unit 1 are observed to the south and on the GTS to the north (Fig. 7); Unit 4: it exhibits reflectors with amplitudes varying from low to high, all characterized by high lateral continuity and tabular external shape (Fig. 7). Locally onlap terminations are observed on Unit 1; Unit 5: this unit shows a tabular external shape and high frequency reflectors, locally with an intercalation of chaotic levels with low amplitude reflectors marked at the base by a high amplitude reflector. Reflectors show gradual decrease in amplitude upwards (Fig. 7). The top of the unit is a high amplitude reflector corresponding to the seafloor (Fig. 7).

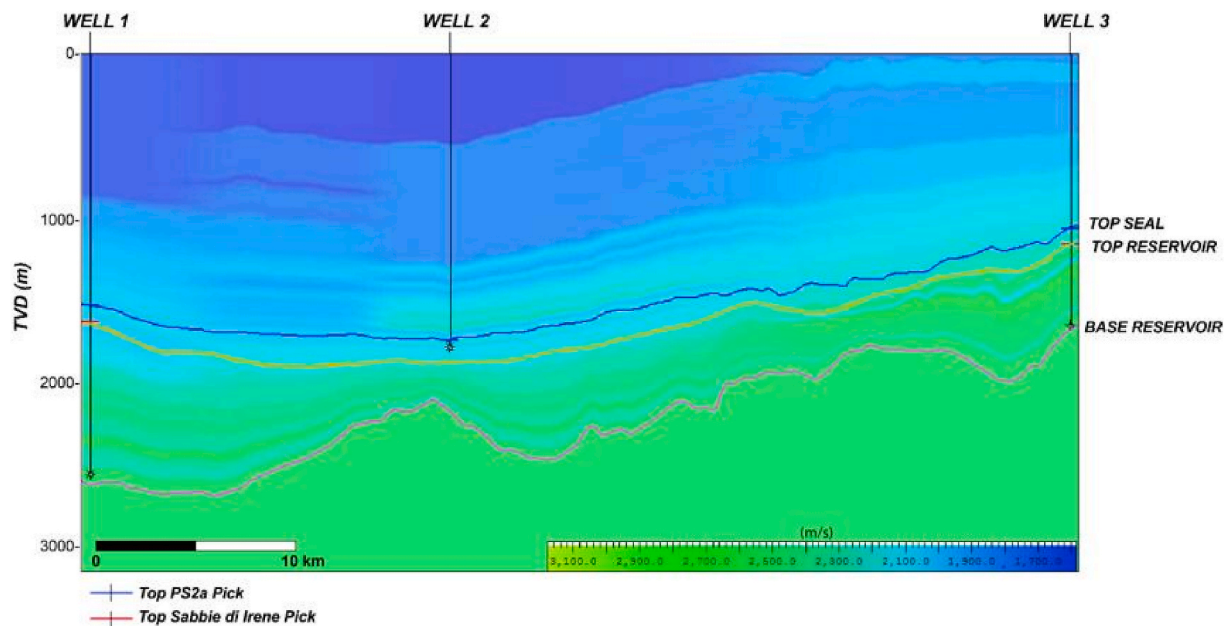


Fig. 6. Velocity model represented along well cross-section between wells 1, 2, 3 (see Fig. 3 for location). See the velocity distribution following the significant interpreted reflectors and the matches with the surface picks.

5.2. Lithological significance of interpreted seismic units

After the well-to-seismic tie process, formation tops indicated in the well-logs data were associated to the corresponding horizons. The correlation between seismic units and formations (for which the top is indicated by well surface picks) is described in Table 1.

The well surface pick marking the top of the Trubi Fm (Figs. 4 and 5), corresponds to the top of the Unit 1 (Fig. 7). The unit consists of marls and turbidite clays of the Early Pliocene (Zanclean) and covers, with variable thickness and lateral pinch-out terminations, the Messinian Unconformity (Todaro et al., 2021; Lofi et al., 2011). The deposition of pelagic marls of Trubi Fm. indicates an aggrading sedimentation controlled by a relative sea level rise; the net reduction of acoustic impedance contrast generates semi-transparent seismic facies that makes this deposit well recognizable, as observed by Civile et al. (2018). The synthetic of the Well 1 in Fig. 5 shows peaks reducing their amplitude at the top of Trubi Fm.; this amplitude reducing is similar to the one observed in the southern Pyrenees turbidite system at the transition between mud-dominated to sandstone-dominated unit (Falivene et al., 2010). The well surface pick marking the top of the Sabbie di Irene Fm (Figs. 4 and 5), corresponds to the top of the Unit 2 (Fig. 7). The unit consists of Lower Pleistocene thick-bedded coarse-to fine-grained sands of proximal and distal sand lobes facies association. Well bottom cores analyzed in Ghielmi et al. (2012) show a number of turbidite typical sedimentological features, such as: (1) unusual thick clay layers associated to the thicker sand layers; (2) uncommon thick laminated sand intervals; (3) presence in the same sand layer of current ripples with opposite directions. Sabbie di Irene Fm. turbidites have been attributed to a highly efficient Type I turbidite system (sensu Mutti et al., 1999) characterized by remarkable basin-scale tabular geometry.

The strong reflections imaged in the synthetic of the Well 1 in Fig. 5, could be related to the turbidite typical sedimentological features mentioned above, which reflects in acoustic impedance variations as also shown by Falivene et al. (2010). Well surface pick at the top of the PS2 level (Figs. 4 and 5), located at the base of the Argo Fm., corresponds to the top of the Unit 3 (Fig. 7). The PS2 mainly consists of fine-grained basin-plain turbidite deposits of the Early Pleistocene (about 0.9 Ma). With a remarkable basin-scale tabular geometry, the PS2 turbidites have also been attributed to Type I highly efficient turbidite systems sensu Mutti et al. (1999). The largest acoustic impedance in the synthetic of the Well 1 in Fig. 5 is located between sandstones and mudstones, so at the base of the PS2 level; the top of PS2 is instead marked by a weak transition to a lower amplitude peak. Above the PS2 level, the Argo Fm., composed of foredeep turbidite sands and clays of Middle-Late Pleistocene (Ghielmi et al., 2009), has been attributed to Unit 4 (Fig. 7) given the alternation of levels with different reflection coefficients which generate variable amplitudes reflectors.

The variable amplitude reflectors with chaotic configuration highlighted in the Unit 5 is typically indicative of presence of a disturbed material (Lee et al., 2004). This level, located in the middle-upper part of the Argo Fm., has been so attributed to a Gravitational Slide (GS) as reported by Trincardi and Argnani (1990) and Ghielmi et al. (2012), since its typical chaotic feature due to sediment mixing and deformation (Fig. 7). Trincardi and Argnani (1990) and Ghielmi et al. (2012) correlate these signals to slumps produced by submarine failure of slope sediments of the Pleistocene prograding deposits originally covering the GTS. However, the available data did not cover the top of Argo Fm. and it is therefore not possible to describe the trend of the synthetic signal.

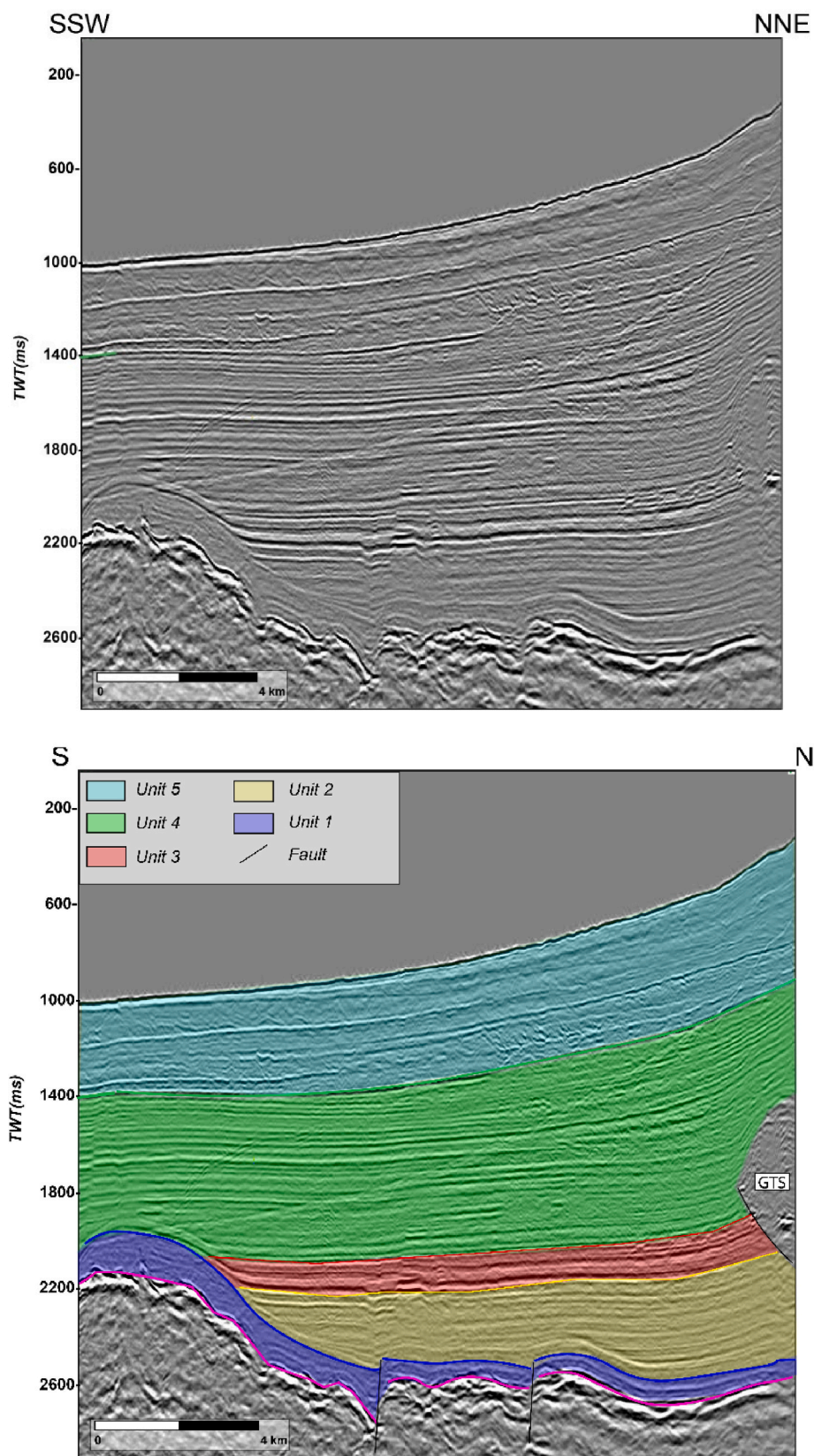


Fig. 7. (a) Uninterpreted (above) and (b) interpreted (below) seismic reflection profile showing the main seismic units from 1 to 5 for of the study area. GTS: Gela Thrust System. See location in Fig. 3.

Table 1

Interpretation of the main seismic units on the basis of well analysis. The age refers to the surface that marks the base of the unit.

Seismic Unit	Formation	Facies	Age (Ma)
Unit 5	Argo Fm.	Foredeep turbidite sands and clays with GS intercalation	0.6
Unit 4	Argo Fm.	Foredeep turbidite sands and clays	0.3
Unit 3	PS2a- Lower Argo Fm.	Turbidites pelites	0.8
Unit 2	Sabbie di Irene Fm.	Turbidite sands and clays (Type I) Average porosity 33.9 %	0.98
Unit 1	Argille Basali Fm.	Turbidite clays	1.79
	Trubi Fm.	Marls and turbidite clays	5.33

5.3. Seismic interpretation of Gela offshore (depth domain)

The interpreted 2D seismic reflection profiles (Figs. 8 and 9) are distinguished by a wide depocenter (16 km long, filled by at least 2 km of deposits) limited at its northern part by a tectonic wedge well defined by the presence of a basal thrust that tips out towards SSW (Maiorana et al., 2023) and in its southern part by a regional monocline (Figs. 8 and 9). The basin filling host at its base a high-amplitude reflection associated with the M-reflector, which corresponds to a widespread irregular erosional surface (Figs. 8 and 9). This surface cuts through the underlying units and is interpreted as the top of the Messinian evaporitic sequence. Over the M reflector, the Trubi Fm. is observed, highlighted by its typical semi-transparent acoustic facies associated to the marly deposits; its deposition records the onset of the deep basinal conditions following Catalano et al. (1996), Lofi et al. (2011) and Ghielmi et al. (2012). The Trubi Fm. is covered by a ~700 m thick level of variable

amplitude reflectors, related to the Sabbie di Irene Fm. deposits consisting of a Lower Pleistocene sandy turbidites with basin-scale tabular geometry (Figs. 8 and 9). Laterally, onlap terminations of the deposits are observed to the north towards the GTS and to the south towards the regional monocline covered by the Trubi Fm. A ~200 m thick level of turbidite pelites interpreted as PS2 level overlies the Sabbie di Irene Fm. with a tabular geometry (Figs. 8 and 9). It is marked at the top by a high amplitude reflector and show internally, onlap termination on the GTS to the north and to the regional monocline to the south. The PS2 level is covered by a ~600 m thick unit attributed to the foredeep turbidite sand and clays of the Argo Fm., showing variable amplitude reflectors (due to its variable lithofacies) with a tabular geometry (Figs. 8 and 9). Figs. 8 and 9 highlight the presence of a chaotic signal in the lower part of this unit. A high amplitude reflector is found at the top of this, marking a shear surface indicating the passage to the GS unit. Fig. 9 shows the chaotic signal of this unit, ~800 m thick, while Fig. 9 shows the same unit with semi-transparent facies, a difference attributed to the high lithological variability of the sediments involved in deformation.

5.4. Gela Gravitational Slide (Gela GS)

Unit 5, comprising the Argo Fm. deposits, host a wide body, at least 800 m thick, delimited at the base by a high amplitude reflector. This body has been firstly identified in 2D seismic reflection profiles by Trincardi and Argenti (1990), who called it "Gela Gravitational Slide-Gela GS". The analysis of a 3D seismic reflection profile derived from Ghielmi et al. (2012) (Fig. 10) allowed us to obtain a better characterization on the Gela GS geometry and configuration.

Following Lewis (1971) the conceptual model for units resulting from slope failure, a systematic distribution of strain is exhibited in Gela GS with extensional structures in the upslope region, and compressional structures in the downslope region. The Gela GS exhibits a typical

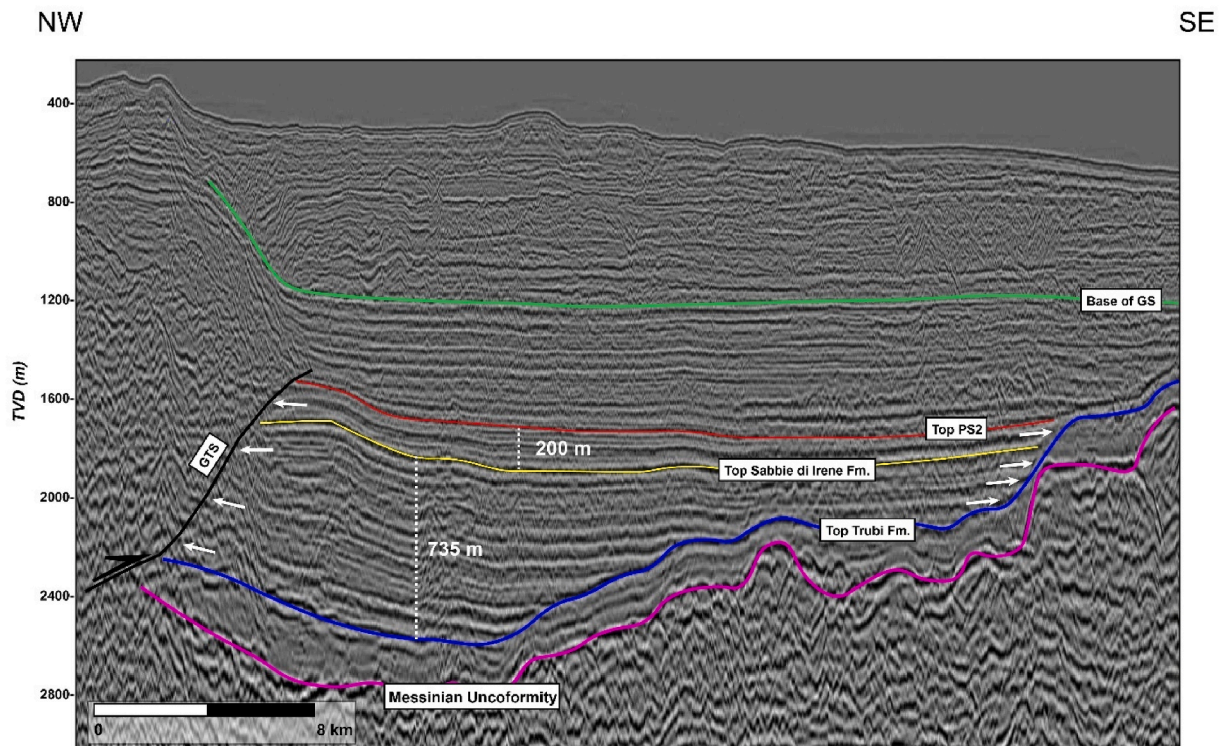


Fig. 8. Interpretation of the seismic reflection profile A converted in depth domain (see Fig. 3 for location). White arrows indicate the main onlap terminations.

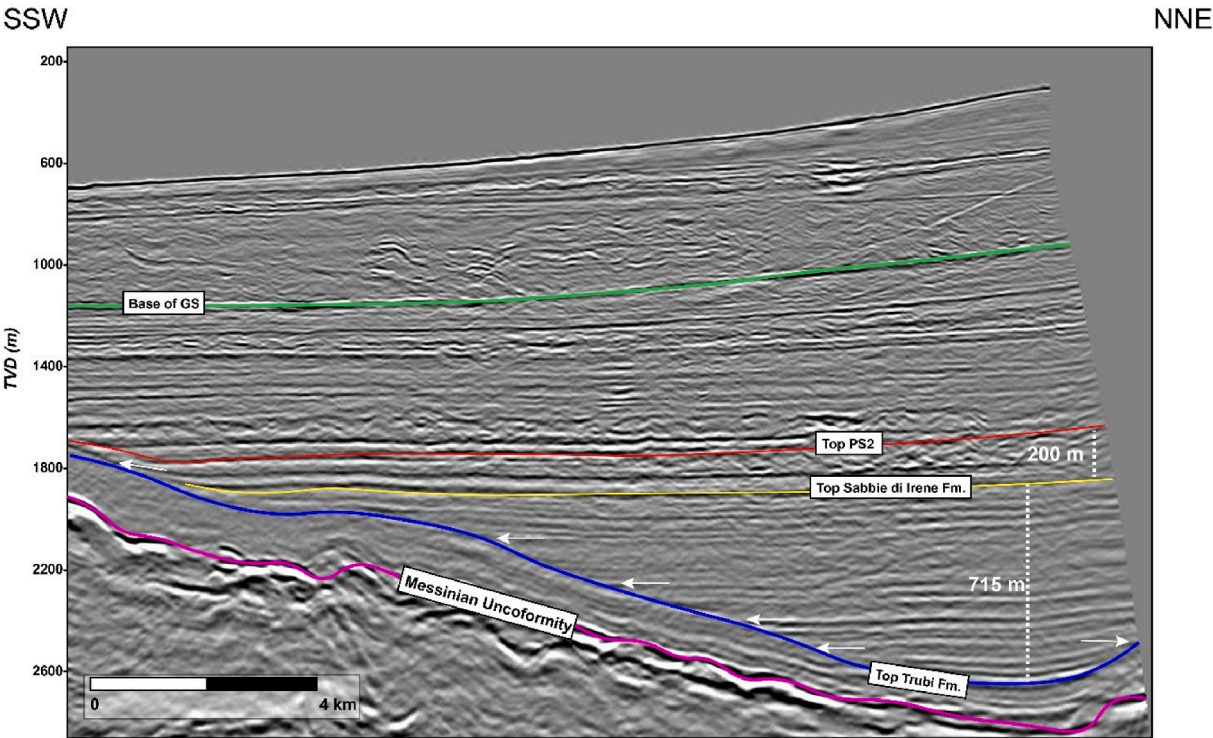


Fig. 9. Interpretation of the seismic reflection profile B in depth domain (see Fig. 3 for location). White arrows indicate the main onlap terminations.

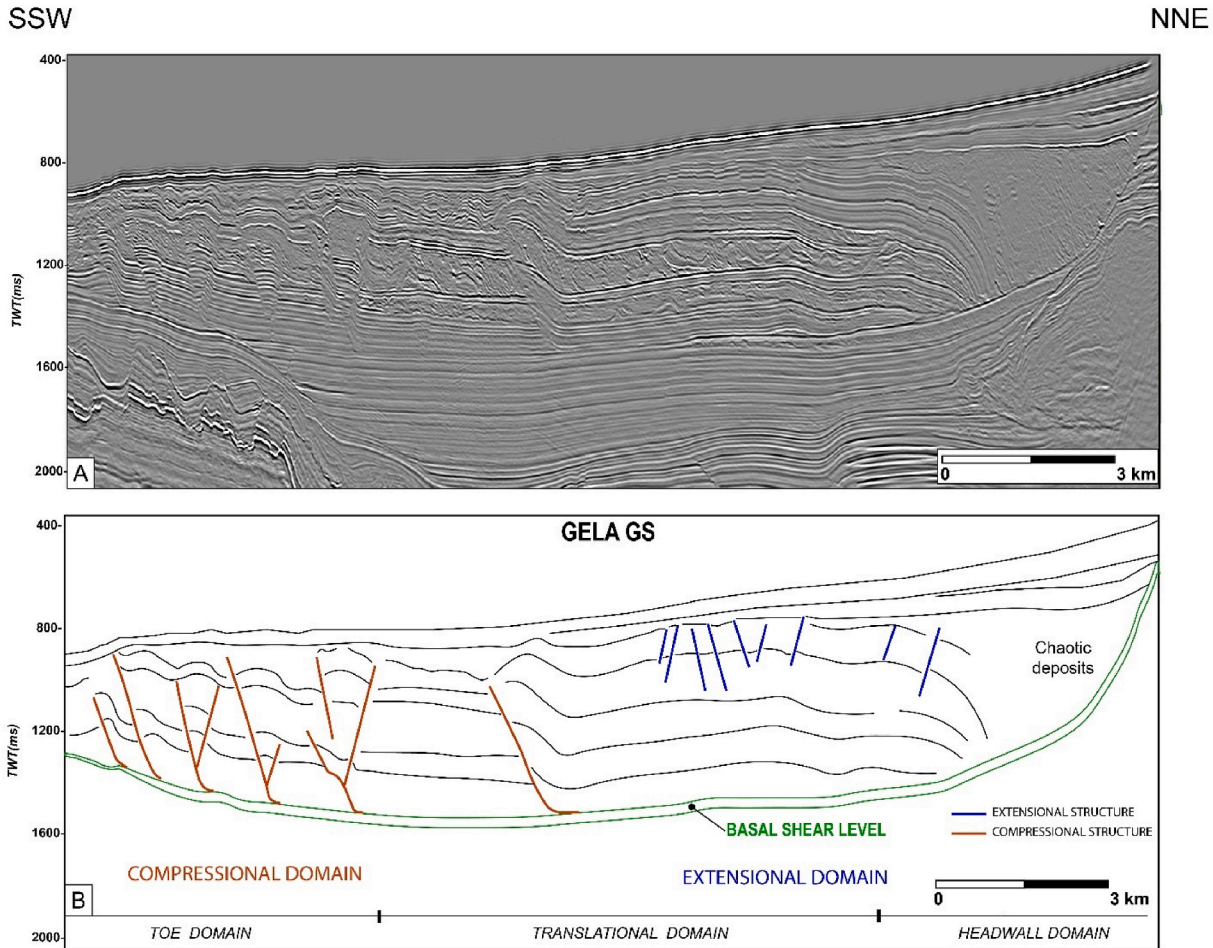


Fig. 10. (A) 3D seismic reflection profile along the Gela GS (Gela Gravitational Slide) after Ghielmi et al. (2012); (B) line drawing showing the internal geometry (see Fig. 3 for location).

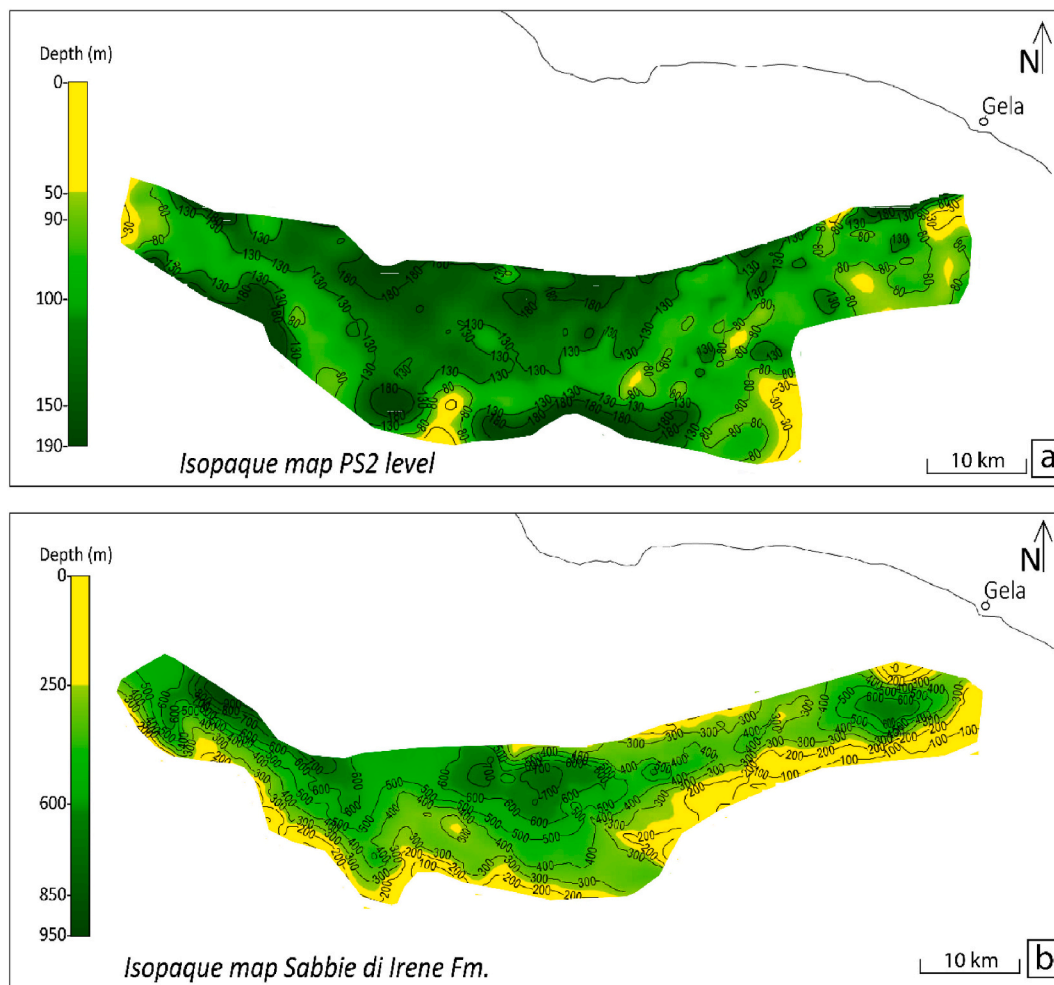


Fig. 11. Isopaque maps of (a) PS2 level and (b) Sabbie di Irene Formation.

‘tripartite’ anatomy (Martinsen, 1994; Lastras et al., 2002): the headwall domain, the translational domain and the toe domain (Trincardi and Argnani, 1990; Bull et al., 2009).

The Gela GS basal shear surface, highlighted by a high amplitude reflector, suggests an abrupt change in acoustic impedance (Fig. 10). This surface forms a laterally continuous, bed-parallel undeformed reflection occurring beneath the disrupted Gela GS.

The headwall domain exhibits a chaotic unit, which occupies the space left by the rollover within the slide head (Fig. 10). Over the chaotic unit, prograding reflectors including the post-LGM deposits are observed, as the ones described by Trincardi & Argnani (1990). A headwall scarp defines the boundary of the upslope margin of the Gela GS. The headwall scarp is steeply dipping, showing an inclination of $\sim 35^\circ$ and is about 700 m high (Fig. 8); the sense of slip is predominantly dip-slip, the material is transported directly downslope and away from the scarp itself (Fig. 10).

The translational domain comprises the main south-oriented translated body of the Gela GS. It is noted that the movement of the failed material downslope across the basal shear surface can lead to intense deformation (Martinsen, 1994). In fact, internally within the body, a series of extensional and contractional structures interfere in the mid-slope area (Fig. 10), as typically observed in similar translational systems (Ge et al., 2019); an upslope migration of the extensional domain and downslope migration of the contractional deformed domain interrupts the continuous seismic reflections and generates a series of convex upward, SW-oriented folds affected by brittle deformations (Fig. 10).

The toe domain represents the downslope region of the Gela GS. This sector is characterized by the development of large-scale “thrust and fold system” frontally confined. Thrusts affect the entire thickness of the Gela GS body in the vicinity of the ramp above the basal shear surface, into which they detach (Fig. 10). The thrust faults occur in pairs of opposite verging, dip up to 40° and define regularly spaced (average 1 km) pop-up structures with maximum displacements of up to 300 m (Fig. 10).

5.5. Thickness and distribution of the Gela offshore units

In order to estimate the Gross Rock Volumes in place, surfaces indicating the depth and thickness of the main levels were constructed as in Figs. 11–13.

The PS2 level (Fig. 11a) isopaque map shows a major thickness in the central sector of the study area, where it reaches an average thickness of 180 m; the lower values in thickness (~ 30 m) are reached in the north-eastern sector of the study area. No major faults were interpreted within these sequences. The isopaque map of the Sabbie di Irene Fm (Fig. 11b) indicates values from ~ 800 m decreasing to ~ 100 m towards south (foreland).

Unfortunately, it was not possible to generate an isopach map for the GS due to the limitations of the 2D data resolution, which does not permit the detailed identification of features comparable to those observed in the high-resolution 3D section provided by Ghielmi et al. (2012).

For the bottom of Gela GS, a depth map has been computed

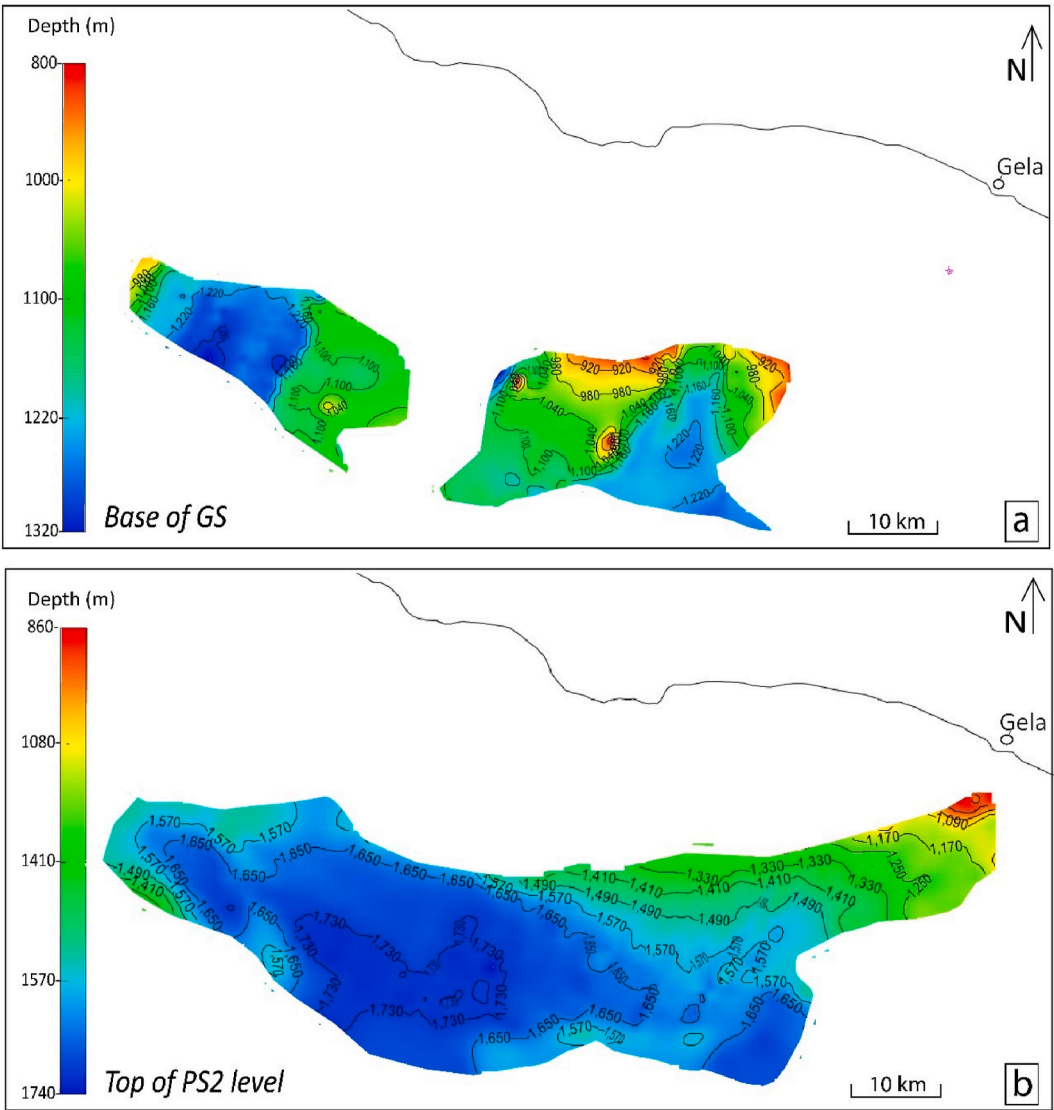


Fig. 12. Depth maps of (a) Base of Gela GS and (b) PS2 level.

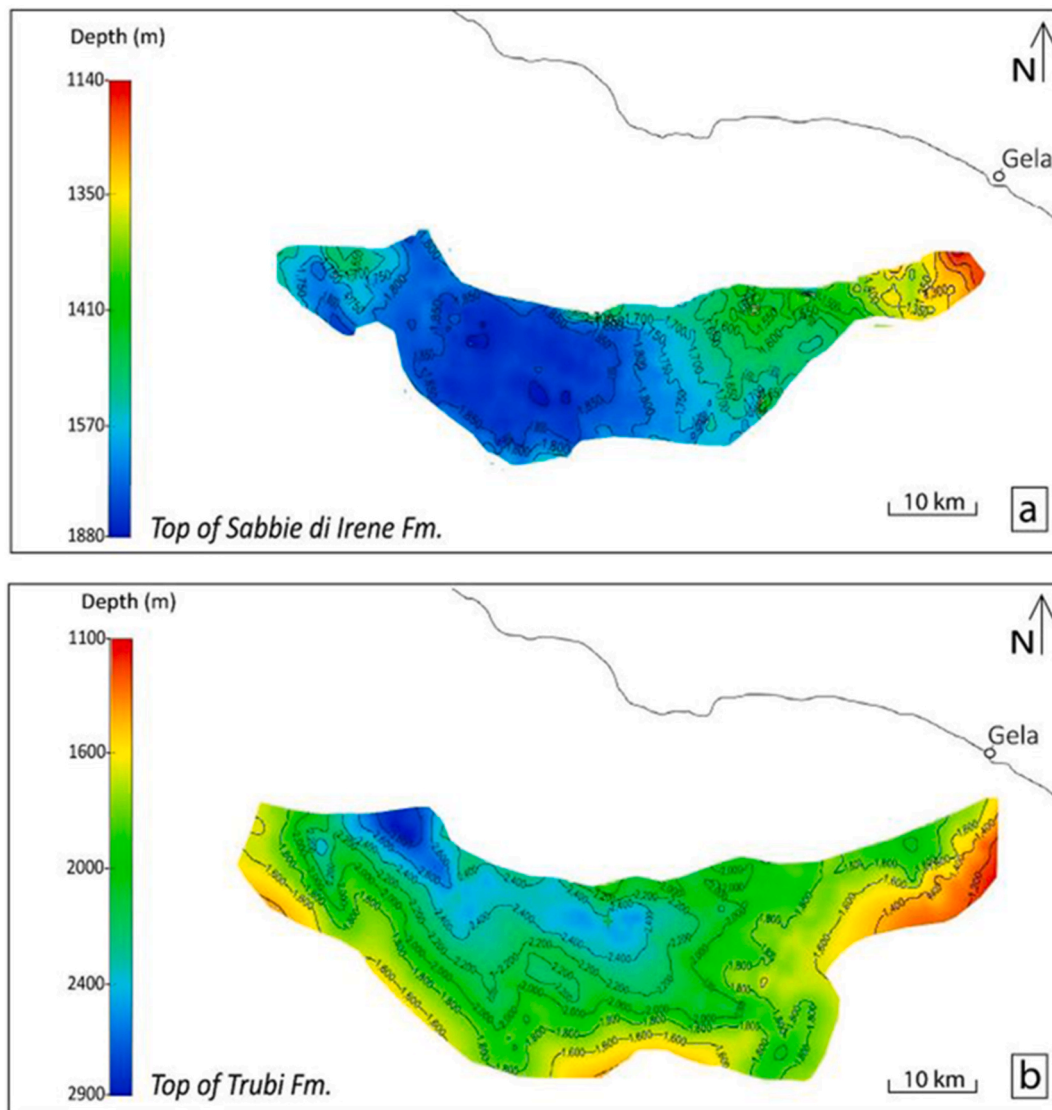


Fig. 13. Depth maps (a) of the top of the Sabbie di Irene Fm. and (b) of the top of Trubi Fm.

(Fig. 12a): the presence of a discontinuity in the surface distribution, localized in the central sector of the study area is highlighted. The depth ranges from 800 to 1320 m. Also, depth maps for the top of PS2 (Fig. 12b) and top Sabbie di Irene Fm (Fig. 13a). confirm that the major depth of the basin is reached in the central part of the study area. Instead, the Trubi Fm (Fig. 13b). shows a minor depth at the southern edges of the study area.

Based on these maps (Figs. 12 and 13), a 3D model of the Gela Foredeep units was reconstructed (Fig. 14). This enabled the estimation of the Gross Rock Volume for the Sabbie di Irene Formation, which extends over approximately 578.4 km², amounting to 3.2832E+11 m³.

6. Discussion

6.1. Tectono-stratigraphic evolution of the Gela offshore

The seismo-stratigraphic interpretation has identified five key geological that shaped the Gela offshore area.

- 1) The Messinian Salinity Crisis (MSC): Occurring around 5.97 to 5.33 Ma, the MSC was a significant geological event marked by the near-complete desiccation of the Mediterranean Sea and the deposition of extensive evaporites (Selli, 1954; Hsü et al., 1978; Lofi et al., 2011; Haq et al., 2020; Zecchin et al., 2020, among the others). The

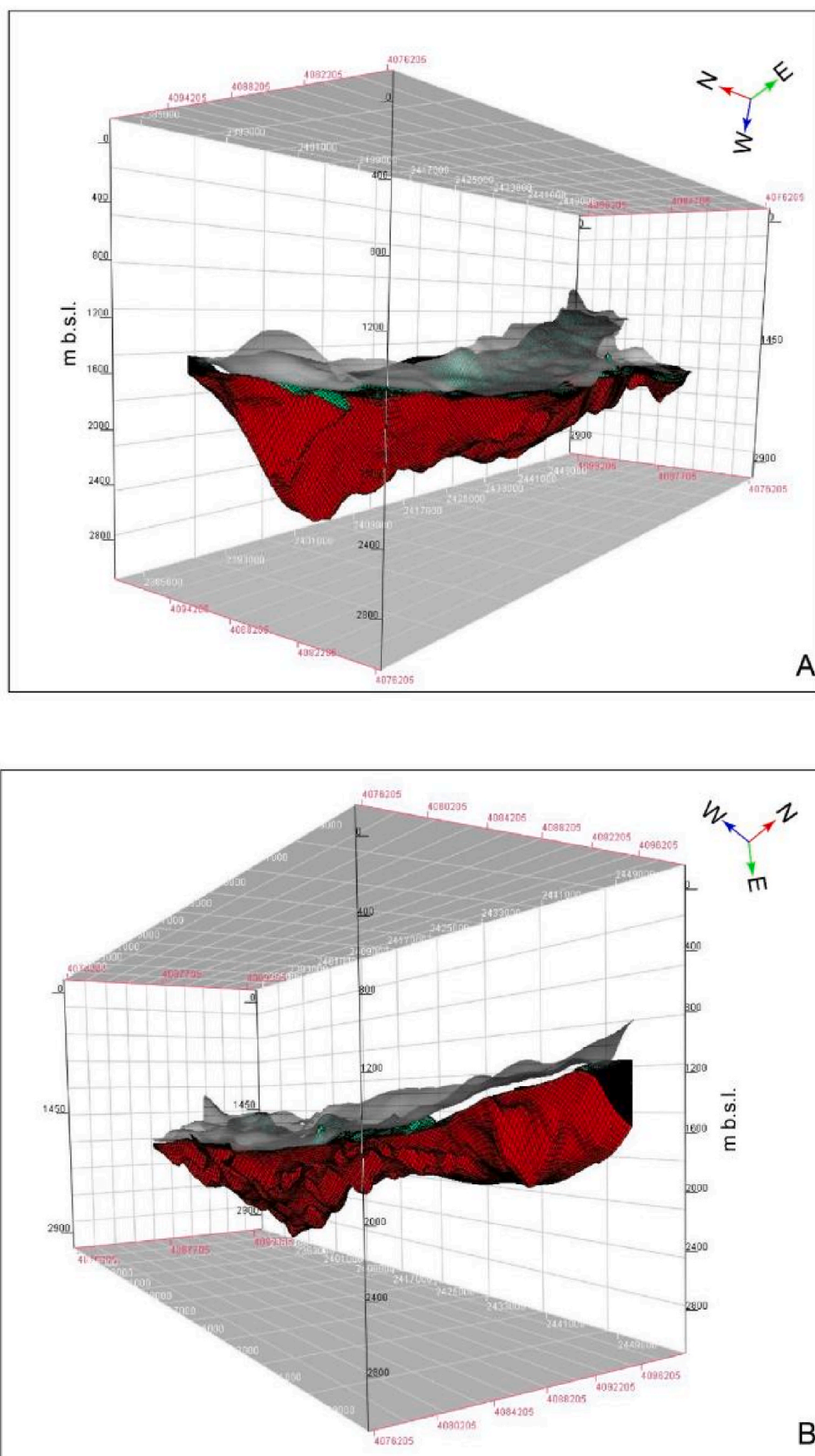


Fig. 14. A, B: 3D views of Gela Foredeep Units identified (x10 vertical exaggeration). In red is represented the Top of Trubi Fm., in green the top of the Sabbie di Irene Fm., and in grey the top of the PS2 level.

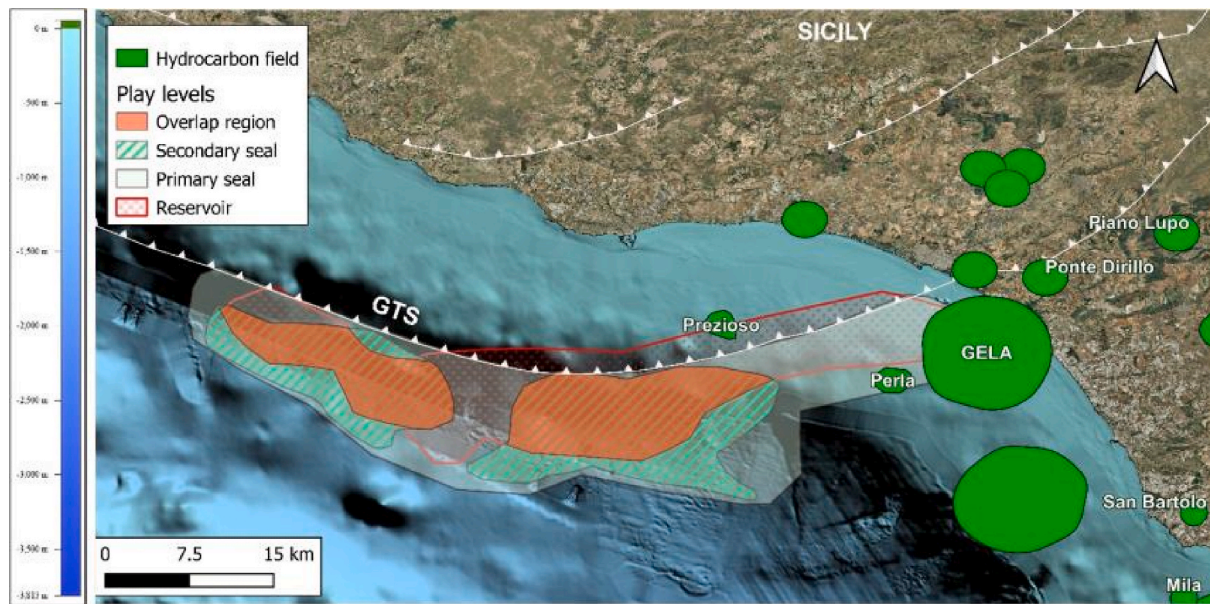


Fig. 15. overlap regions between reservoir and seals levels identifying the best play area for CCS. GTS: Gela Thrust System.

re-opening of the Strait of Gibraltar at the end of the crisis led to the dramatic reflooding of the Mediterranean, known as the Zanclean flood. The Messinian Unconformity, which cuts across various stratigraphic layers and is associated with the retrogressive erosion from the Mediterranean Sea's drawdown.

- 2) Drowning phase and setting up of the GTS: During the Zanclean (5.33 Ma), the return to open marine conditions and progressive subsidence led to the deposition of Trubi Fm. marly limestone (Gennari et al., 2008; Lentini and Carbone, 2014; Riforgiato et al., 2011), the fossil content of which suggests a general deepening over time (Di Grande and Giandinoto, 2002).
- 3) Deposition of Sand Turbidites and Continued Advancement of the GTS: In the Piacenzian (3.6 Ma), as the GTS advanced further, (Cavallaro et al., 20; Maiorana et al., 2023), the Lower Pleistocene turbidite sands and clays of the Sabbie di Irene Formation were deposited. The primary entry point of these turbidite was located at the northeastern apex of the foredeep, near the town of Gela (Ghielmi et al., 2012). Their deposition was influenced by palaeo-currents oriented longitudinally to the basin axis, with W/WSW direction (Ghielmi et al., 2012).
- 4) PS2 Level Deposition and Last GTS Advancement: Around 0.8 Ma, in the Calabrian, the final stage of GTS occurred (Di Stefano et al., 1993), followed by the deposition of the PS2 level. This level is characterized by highly efficient Type I turbidite systems with a clayey composition and shares a common entry point with the Sabbie di Irene Formation (Ghielmi et al., 2012).
- 5) Gravitational Instability: From the Upper Pleistocene to the Holocene mass transport processes developed in the GB (Minisini and Trincardi, 2009). Most of the chaotic deposits are slumps resulting from submarine failure of slope sediments of the Pleistocene progradation originally deposited on the GTS (Ghielmi et al., 2012). A slump of larger volume (500–600 m thick, about 17 km long, about 10 km wide), produced by a submarine slide of exceptional volume, has been documented in the upper part of the foredeep succession (Trincardi and Argnani, 1990).

6.2. The role of the Gela Gravitational Slide

The Gela Gravitational Slide (GS) is a vast 1500 km² slide that covers most of the Gela Foredeep basin with its extensive detachment surface. Its headwall traces the tip of the south-verging Gela Thrust System (GTS;

Argnani, 1990; Butler et al., 1992; Catalano et al., 2013; Lickorish et al., 1999) the youngest tectonic wedge of the Sicilian FTB (Catalano et al., 1993a; Lickorish et al., 1999; Ghisetti et al., 2009) commonly acknowledged as a thin-skinned, accretionary wedge. The last stage of advancement of the GTS is recorded in the Early Pleistocene, at 0.8 Ma (upper Calabrian) (Di Stefano et al., 1993; Cavallaro et al., 2017).

Gardiner et al. (1993) suggested that the deposition of the Gela Slide, as documented by Trincardi and Argnani (1990) was triggered by the uplift of the mainland region during the Quaternary. The movement of the Gela Slide occurred along a decollement level of basin-wide extent, which biostratigraphic analysis dates at 0.6 Ma by (Ghielmi et al., 2012). Trincardi and Argnani (1990) proposed that an abrupt lithologic or diagenetic change at its boundary, potentially linked to fluid overpressure, reduced friction on the basal plane. This suggests that the basal shear level of Gela GS might serve as a seal due to its consolidation and differences in capillary pressure and porosity, as documented in similar geological contexts, as in the Pearl River Mouth Basin (South China) by Sun et al. (2017) and for the Gulf of Squillace by Mangano et al. (2023).

The internal levels and the deformational structures of the Gela GS indicate a SW transport direction, consistent with the GTS primary movement. This suggests a close relationship between the Gela GS and the GTS structure. Identifying the Gela GS as a potential secondary seal highlights its significance and could aid in locating other gravitational slides and potential seals on a regional scale. The Gela GS relation with the GTS structure, extending for at least 200 km within the Gela Foredeep basin, indicates the potential for a widespread distribution of this important sealing layer within the saline aquifer of the Sicily Channel, represented here by the Gela Foredeep.

6.3. The Gela Play characteristics (depth domain)

Based on the performed study, we have linked the interpreted seismo-stratigraphic units to the key elements that characterize the Gela Play and compared them with the depths and thicknesses requirements for CCS (refers to Introduction chapter), retrieved after a time-depth conversion (see Section 4.1). Considering the lithology, depth, thickness and closure of specific units, we identified the primary units of the Gela Play (Table 2), as follows.

- The Reservoir: The Sabbie di Irene Fm. stands out as the unit with the greatest thickness in the study area, reaching up to 950 m (Fig. 11b).

Table 2
Interpreted seismo-stratigraphic units, depth data, and association with the elements of the Gela Play.

Seismic Unit	Formation	Facies	Age (Ma)	Depth range (m)	Max thickness (m)	Interpretation
Unit 5	Argo Fm.	Foredeep turbidite sands and clays with GS intercalation	0.6	800–1320	50	Potential 2 nd seal (base of GS intercalations)
Unit 4	Argo Fm.	Foredeep turbidite sands and clays	0.3	1200–1800	600	Interval level
Unit 3	PS2- Lower Argo Fm.	Turbidites pelites	0.8	860–1740	190	1° Seal
Unit 2	Sabbie di Irene Fm.	Turbidite sands and clays (Type I) Average porosity 33.9 %	0.98	1140–1880	950	Reservoir
Unit 1	Argille Basali Fm.	Turbidite clays	1.79	1500–2600	100	Base reservoir (<i>Top Trubi</i>)
	Trubi Fm.	Marls and turbidite clays	5.33			

Its high porosity values (33.9 %) are due to the sand-dominated turbiditic deposits. Additionally, the unit is found at an ideal depth (below 800 m, Fig. 13a), which is necessary for maintain the CO₂ in a supercritical state upon injection. Onlap terminations of the top of Sabbie di Irene Fm. are observed against the regional monocline covered by the Trubi Fm. and against the GTS (Figs. 9 and 10). The characteristics of this unit, including its thickness, facies and lateral closure, make it a highly suitable reservoir for CCS applications.

- The Primary Seal: The PS2 level is a turbidite pelitic layer, that can serve as a primary seal due to its extensive coverage over the Sabbie di Irene Fm. and its low permeability, given its facies. Its thickness is mostly between 50 and 190 m; the minimum thicknesses, less than 50 m, are found only in the marginal sectors of the area investigated (Fig. 11a). Onlap terminations of the top of PS2 level are observed against the regional monocline covered by the Trubi Fm. and against the GTS (Figs. 9 and 10);
- The Potential Secondary Seal: The basal level of the Gela GS may acts as a secondary seal due to its intensive consolidation in response to differences in capillary pressure and porosity. However, this level is not well-documented by the available well data (and thus by the synthetic), and its exact thickness cannot be precisely defined from the 2D seismic dataset. Nevertheless based on the high-resolution 3D section provided by Ghielmi et al. (2012) (Fig. 10), the basal level is estimated to be between 5 and 10 m thick, assuming a velocity of 2200 m/s. Additionally, an unconformity at ~1200 m depth limits the top of the level (Fig. 10) dated to around at 0.6 Ma by the biostratigraphic analysis of Ghielmi et al. (2012).

6.4. CO₂ storage perspectives

Given the high storage potential of the saline aquifers (Hughes, 2009), we examined the Gela Foredeep, a narrow and elongated basin that, due to its structure and composition, can be deemed as a significant saline aquifer within the Sicily Channel. Buttinelli et al. (2011) identified the Gela Foredeep as a potentially suitable areas for studies on CO₂ geological storage, noting its favourable caprocks far from seismogenic sources and from Diffuse Degassing Structures. Our analysis aimed to evaluate the Gela Foredeep’s suitability for CCS projects based on established criteria (see Introduction chapter). Using 2D seismic reflection profiles, calibrated with well-tie, and time-to depth converted, allowed us to identify the Gela Play as a viable CO₂ storage site.

The Gela Play encompasses Plio-Pleistocene deposits within the Gela Foredeep. It features a reservoir level composed of the Sabbie di Irene Fm. (Early Pleistocene), which is covered by a primary seal, the PS2 level of the Argo Fm. (Middle Pleistocene). Additionally, there is a potential secondary seal corresponding to the basal level of the Gela Gravitational Slide, with its top dated at 0.6 Ma. These layers exhibit suitable thickness and depth for effective storage. The play is confined by both stratigraphic and structural closures: the regional monocline to the south and the GTS to the north. The Gross Rock Volume of the reservoir, calculated at 3.2832E+11 m³, is a critical metric for assessing the storage capacity of the Gela Play (Hedley and Gluyas, 2015).

The results of this study integrate build on the findings of Donda et al. (2011) and Civile et al. (2013), which overview suitable areas for CO₂ geological storage in Italy. Most identified sites are located in carbonate environments (Civile et al., 2013). Sun et al. (2020) highlighted a potential CO₂ storage site in clastic sediments within the Mesopotamian Foredeep Basin, a foreland basin formed from the Cretaceous to the Miocene due to the subduction of the Arabian Plate beneath the Eurasian Plate. In Fig. 13 we mapped two overlapping regions between reservoirs, primary and secondary seal, indicating two potentially suitable zones for CCS investigations. Is is crucial to consider both primary and secondary seal, as each plays a role in preventing or mitigating CO₂ leakage (Ingram et al., 1997).

7. Conclusions

This study provides the first comprehensive evaluation of Gela Foredeep’s filling along the southern Sicilian coast, aimed at identifying potential CO₂ geological storage sites within a saline aquifer in the Sicily Channel.

Utilizing 2D multichannel reflection seismic profiles, calibrated with well-to seismic tie, we conducted a seismo-stratigraphic analysis to reconstruct the tectono-stratigraphic evolution of the Gela offshore area. This analysis let to the identification of the Gela Play, which features a reservoir (Sabbie di Irene Fm.) covered by a primary seal (PS2 level-Lower Argo Fm.) and by a potential secondary seal (the basal level of Gela Gravitational Slide).

This study also highlighted the presence of adequate stratigraphic and structural closures within the Gela Foredeep, indicating that the Gela Play is a potential prospect for further CCS investigations.

The basal level of the Gela Gravitational Slide, exhibiting potential sealing layer characteristics, could serve as a regionally significant sealing unit. However, additional well-logs data and further analysis are necessary to confirm its suitability.

A comprehensive assessment of the CO₂ storage potential in this sector of the Gela Foredeep will require several supplementary data and analysis, such as sedimentological analysis, identification of best sites and migration modelling. Despite this, the current evaluation provides a crucial foundation for understanding the area’s capacity for CO₂ storage.

CRediT authorship contribution statement

Mariagiada Maiorana: Writing – original draft. **Attilio Sulli:** Supervision. **Matteo Marelli:** Methodology. **Mauro Agate:** Validation.

Declaration of competing interest

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

Data availability

The data that has been used is confidential.

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6. Common Chance Maps Workflow

6.1 Introduction

CO₂ storage in geological formations is widely recognized as a crucial carbon abatement technology. An initial common chance screening for CCS has been developed in synergy with Halliburton and ENI. The following chapter outlines the developed workflow that utilizes basin-scale geological parameters to identify suitable rock units, then optimizes the limited subsurface data to estimate storage potential. To demonstrate this approach, the available data from a play in the Gela Foredeep Basin (Gela Play) were used as a data-lean example.

The Gela Play hosts a reservoir within the Sabbie di Irene Formation, a Plio-Pleistocene marine sandstone reservoir overlain by a primary seal (Middle-Upper Pleistocene pelitic deposits of the Argo Formation) and a potential secondary seal formed by the basal level of the Gela Gravitational Slide.

The available data have been analyzed characterizing facies distribution, depth, and thickness for both the reservoir and the seal and conducting a supercritical assessment by extrapolating pressure and temperature data. A chance assignment was applied to each data point, and these were then combined to generate a combined common chance map. This allowed to identify the potential and risks for injectivity (reservoir presence and quality) and containment (seal and possible faults).

This work represents an initial attempt and example of identifying and characterizing subsurface geological sites in the Gela offshore, providing an initial ranking of play potential.

The CO₂ storage technique is well noted for depleted oil and gas fields, thanks to the abundant subsurface data. For saline aquifers these calculations will be more difficult since they may lie outside traditional-well explored petroleum systems. Effective screenings for potential saline aquifer storage may allow them to be rapidly ranked within a region/basin, providing a focus for further data gathering, study and decision making.

Much work has been already done to find and characterize potential storage regions and to develop criteria for screening new areas (Kovscek, 2002; Hovorka et al., 2003; Bachu, 2010; Brennan et al., 2010; Blondes et al., 2013; Halland et al., 2013; Anthonsen et al., 2014; Bentham et al., 2014; Roberts-Ashby et al., 2014; Doe Netl, 2015, 2020; Raza et al., 2016; Trevino and Meckel, 2017).

The geological formations suitable for CO₂ storage must comply with specific criteria, as established in the framework of the EU FP6 Geocapacity Project (Vangkilde-Pedersen et al., 2009). In particular, these criteria include: 1) the presence of a reservoir with adequate characteristics (permeability, porosity, depth, etc.); 2) the presence of an impermeable caprock with suitable thickness to ensure the

structural integrity and to prevent migration of CO₂ from storage site. A caprock thickness less than 20 m is cautionary whereas thickness greater than 100 m is preferable (Chadwick et al., 2008).

Reservoir rocks must have adequate petrophysical properties to be suitable for CO₂ storage. As a general rule, permeability should exceed 1.97×10^{-13} (200 mD) to provide sufficient injectivity (van der Meer, 1993), however, values greater than 2.96×10^{-13} (300 mD) are preferred. Porosity should be greater than 20% (Chadwick et al., 2008), albeit lower values until 10% are acceptable.

The depth of reservoir-caprock boundary (Bachu, 2003) is paramount. In general, CO₂ geological storage takes place in supercritical conditions ($T > 31.1\text{ }^{\circ}\text{C}$ and $P > 7.38\text{ MPa}$). In supercritical condition, CO₂ density is in excess of about 500 kg/m³ that provides the potential for efficient utilization of underground storage volume (U.S Department of Energy-DOE, 2010). In sedimentary basins with an average geothermal gradient of 25 to 30 °C/km, the supercritical condition is generally present at depths of about 800 m (Suekane et al., 2006).

The aim of the following chapter is to present a comprehensive screening criteria for identification of a suitable storage site based on key in situ properties.

6.2 Testing a new CCS screening method applied to the offshore Gela basin Play (central Mediterranean)

The frontal sector of the Sicilian thrust belt, related to the Europa/Africa plate convergence extends in southern Sicily and its offshore, with its associated Gela Foredeep (Sulli et al., 2021). The wide depocenter of the Gela Foredeep is called Gela Basin and is located in the Gela offshore.

The basin is filled by a thick Plio-Pleistocene sequence (up to 2000 m) hosting a reservoir and two sealing layers in stratigraphic relationships within the basin (Maiorana et al., 2024).

The reservoir, constituted by the Sabbie di Irene Formation (lower Pleistocene) is composed of foredeep turbidite sands and clays (Ghielmi et al., 2012). The Sabbie di Irene Formation turbidites have been attributed to a highly efficient Type I turbidite system (sensu Mutti et al., 1999) characterized by remarkable basin-scale tabular geometry. The primary seal is a correlative conformity surface called PS2 that delimits the top of a clayey layer found in the study area and located at the top of the Sabbie di Irene Fm. The PS2a boundary is related to the GTF advancement toward the foreland that involved the deformation of the underlying turbiditic succession (Ghielmi et al., 2012; Maiorana et al. 2024).

At the initial stages, refining storage site selection via screening approach can firstly identify target basins, and secondly, target formation over geological area.

Key criteria to assess suitable target basins include temperature, pressure, reservoir presence/effectiveness and seal presence/integrity.

The present work considered the depth, as a key criterion. This because, in general, the interplay between temperature and pressure determines the depth at which CO₂ reaches a supercritical state (Bachu, 2003). This has been evaluated by assessing key regional depth surfaces identified areas of the target geographies where target formation would be at sufficient depth (>800 m) to store CO₂; depth > 2000 m are considered less viable following Chadwick et al. (2008). By assuming a constant hydrostatic pressure gradient, sediment thickness was used to calculate the depth range (>800 m) which is required for CO₂ to be in a supercritical state (800m = 7.38 mPa). In this case, basin-scale depth maps from Maiorana et al. (2024) were utilized. Also, the Geothermal Gradient, has been evaluated as a necessary criterion; the supercritical temperature value (31.1°C) is predicted to be reached before the pressure threshold (Bachu, 2003).

By assessing the present-day tectonic setting, an assessment of proven reservoir and seal units was conducted. Existing formations that act as reservoir and seals increase the likelihood that CO₂ can be successfully stored.

The following workflow (Fig. 1) is an attempt to predict the likelihood that each of these conditions is met in any given area. Maiorana et al (2024) analysis was used to assess the spatial coverage of key individual geological elements. For each of these elements, the inputs were translated into four chance categories (Likely, Possible, Plausible, Unlikely) based on fixed thresholds. The assigned chance to each lithology (0.2 unlikely, 0.4 plausible, 0.6 possible, 0.8 likely) has been done with DSG calculator, a tool of Decision Space Halliburton software.

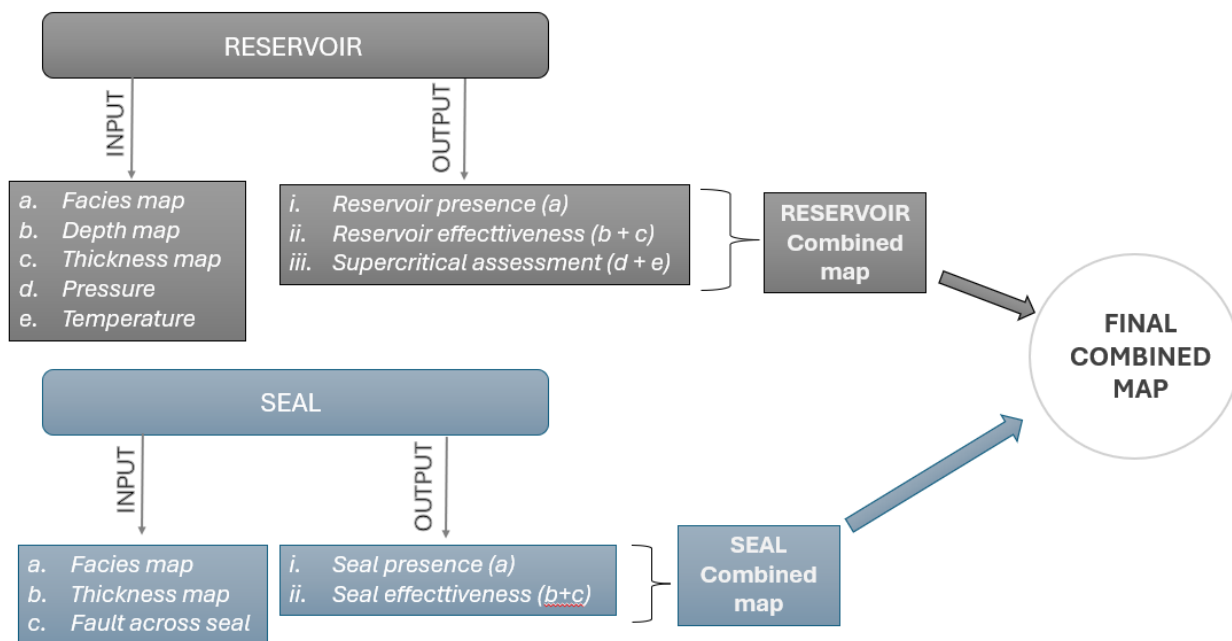


Figure. 1 Proposed screening workflow to construct Common Chance Maps

Following the steps through each element:

1. **Reservoir and Seal Presence:** The spatial distribution of the reservoir (Fig. 2) and seal (Fig. 3) element was assessed using Ghielmi et al. (2012) Gross Depositional Environment (GDE) maps for top reservoir and seal; then scaled by net to gross ratio for 3 wells in the area of interest.

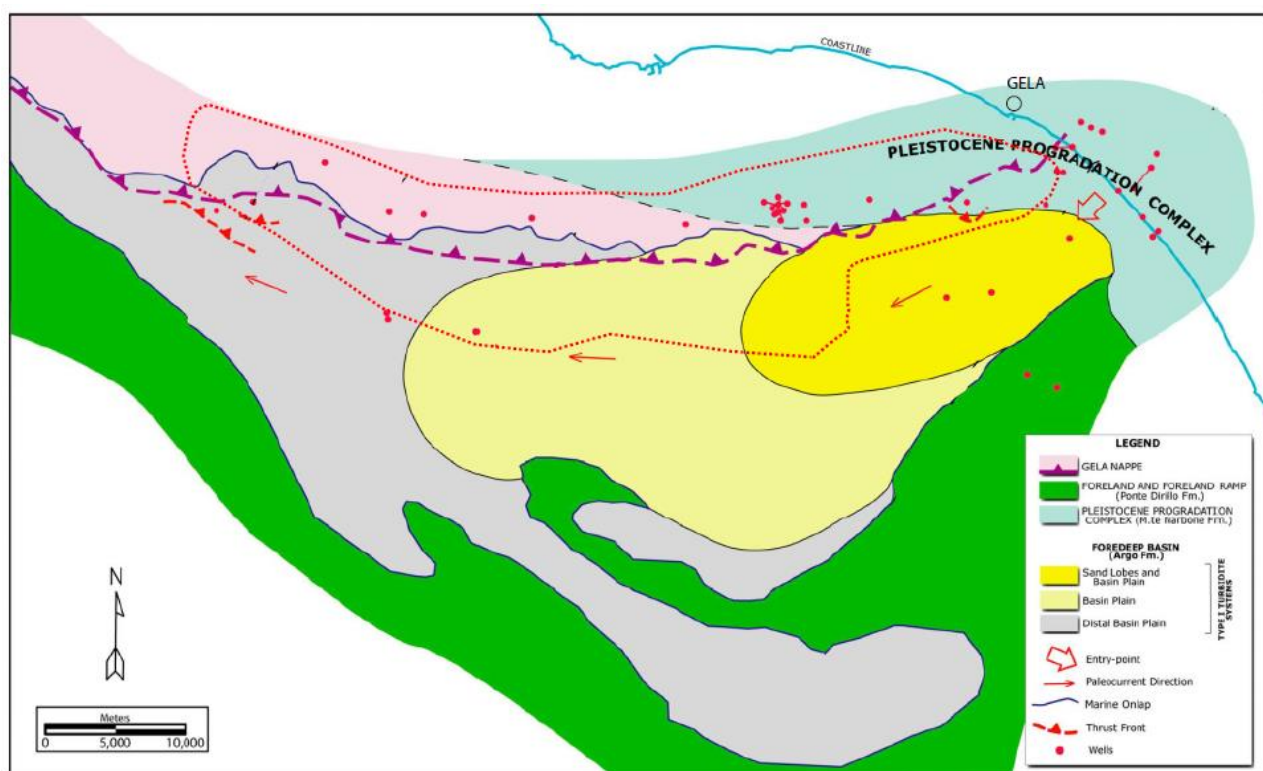


Figure 2. Seal presence retrieved from spatial distribution of the top of seal (modified after Ghielmi et al. (2012)).

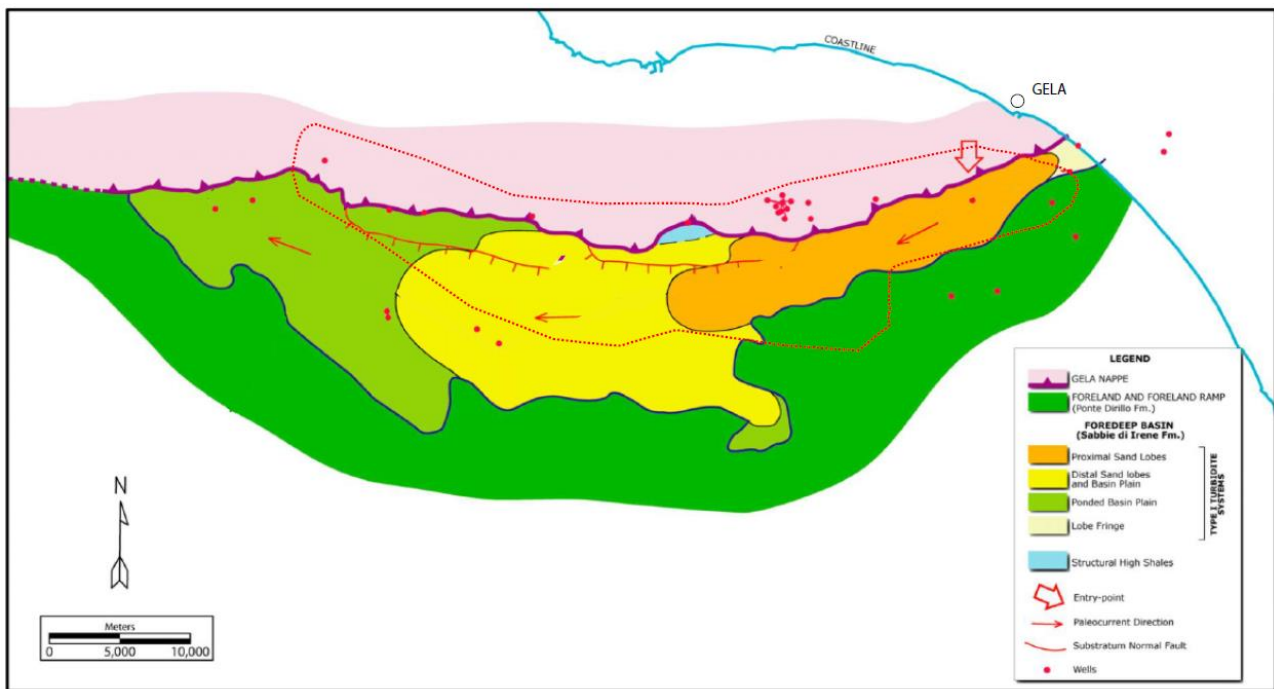


Figure 3. Reservoir presence retrieved from spatial distribution of the top of reservoir (modified after Ghielmi et al. (2012)).

2. **Reservoir effectiveness:** map in Fig. 4 was assessed in relation to three factors: reservoir depth, thickness and well porosity calibration. A basic assumption is that the depth of burial is a primary control on the deterioration of clastic reservoir quality (Ehrenburg et al., 2009). To assess the impact of burial depth on the effectiveness of the selected reservoir interval, depth maps from Maiorana et al. (2024) were used. These covers the whole study area and was generated through the integrated interpretation of numerous geophysical data.

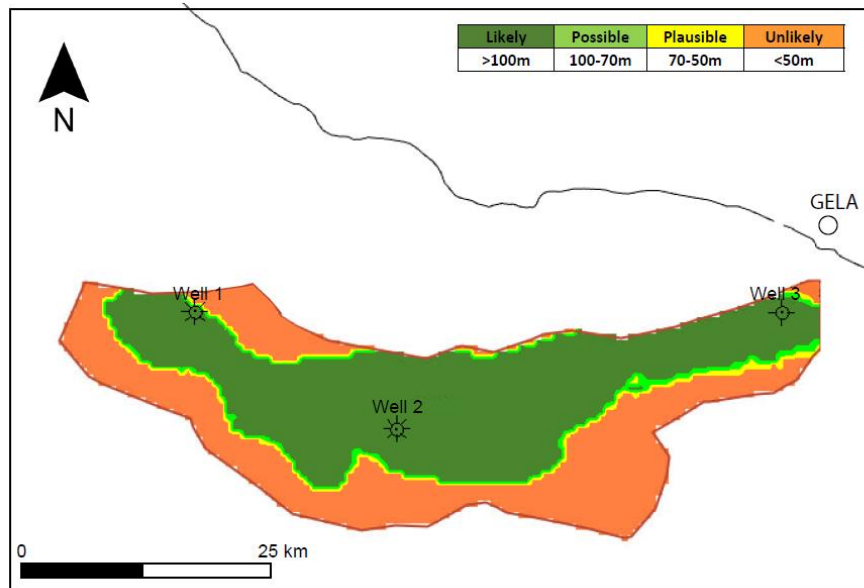


Figure 4. Reservoir effectiveness assessed in relation to three factors: reservoir depth, thickness and well porosity calibration.

3. **Supercritical assessment:** For CO₂ to be stored as efficiently as possible, a supercritical fluid state is required. CO₂ behaves as a supercritical fluid above pressures of 7.38 MPa and temperature of 31.1 °C. In the supercritical state CO₂ behave like a gas, filling all available volume and with a liquid density, reducing buoyancy. This increases an effective storage. The produced temperature map in Fig. 5 shows all the area with temperatures greater than the 29° C, making it adequate for CCS.

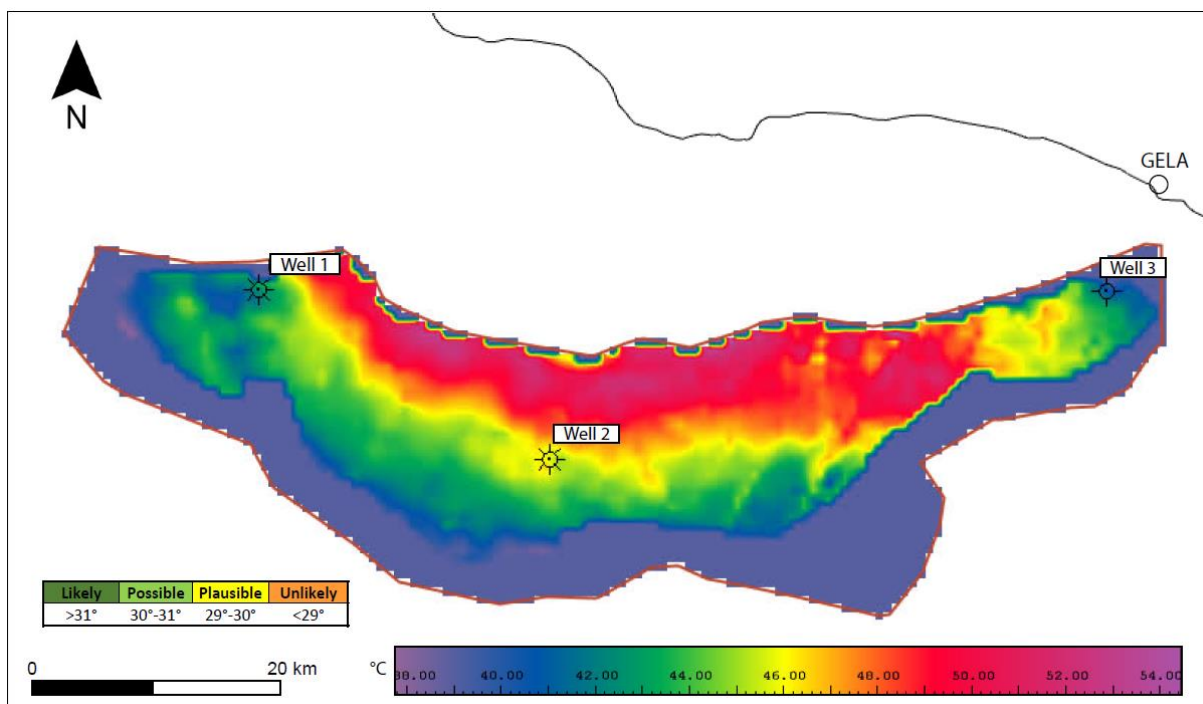


Figure 5. Temperature map derived from interpolation of ENI internal data. Temperatures reaches values greater than the required 29° C for CCS.

4. **Seal effectiveness:** is assessed in relation to two factors: tectonic activity and layer thickness. For tectonic, the assumption being that if a given seal has been subjected to major tectonism, then the seal is less likely to be effective. To assess this, we used Neflex tectonic elements (active fault and folds) to identify area influenced by tectonism.

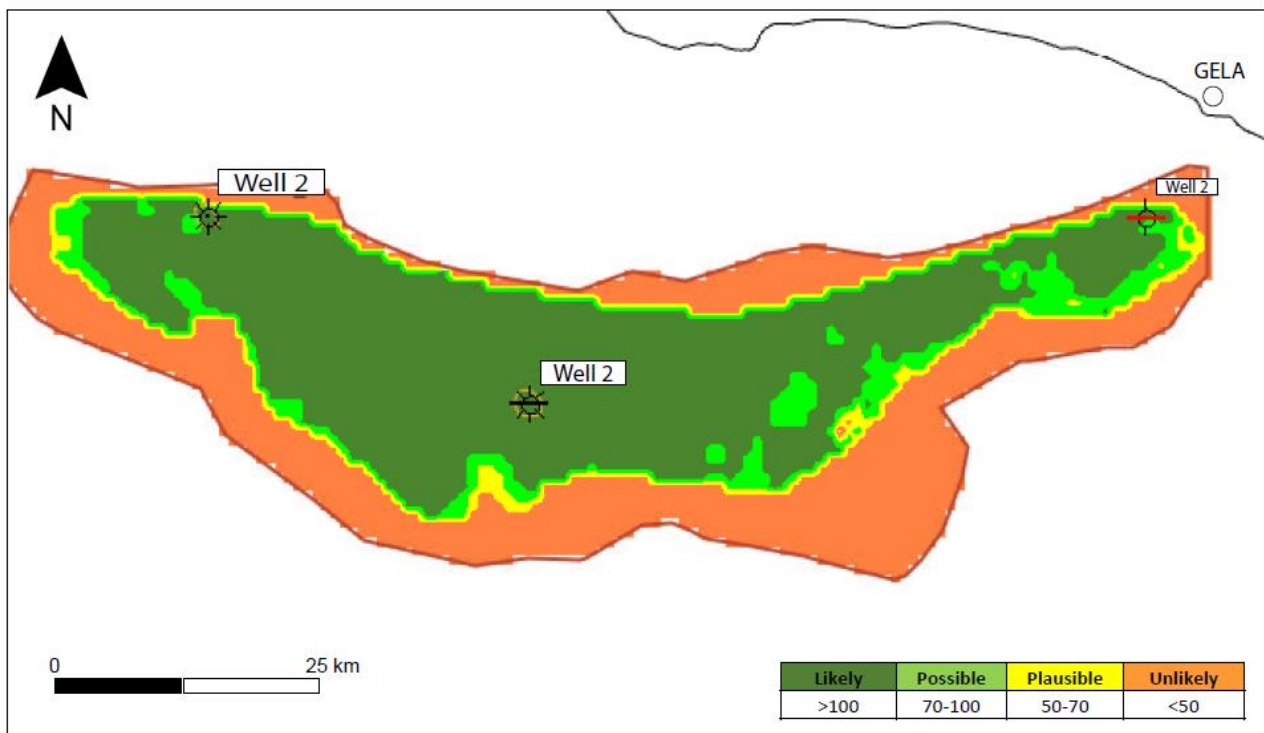


Figure 6. Seal effectiveness from thickness mostly showing the presence of likely areas.

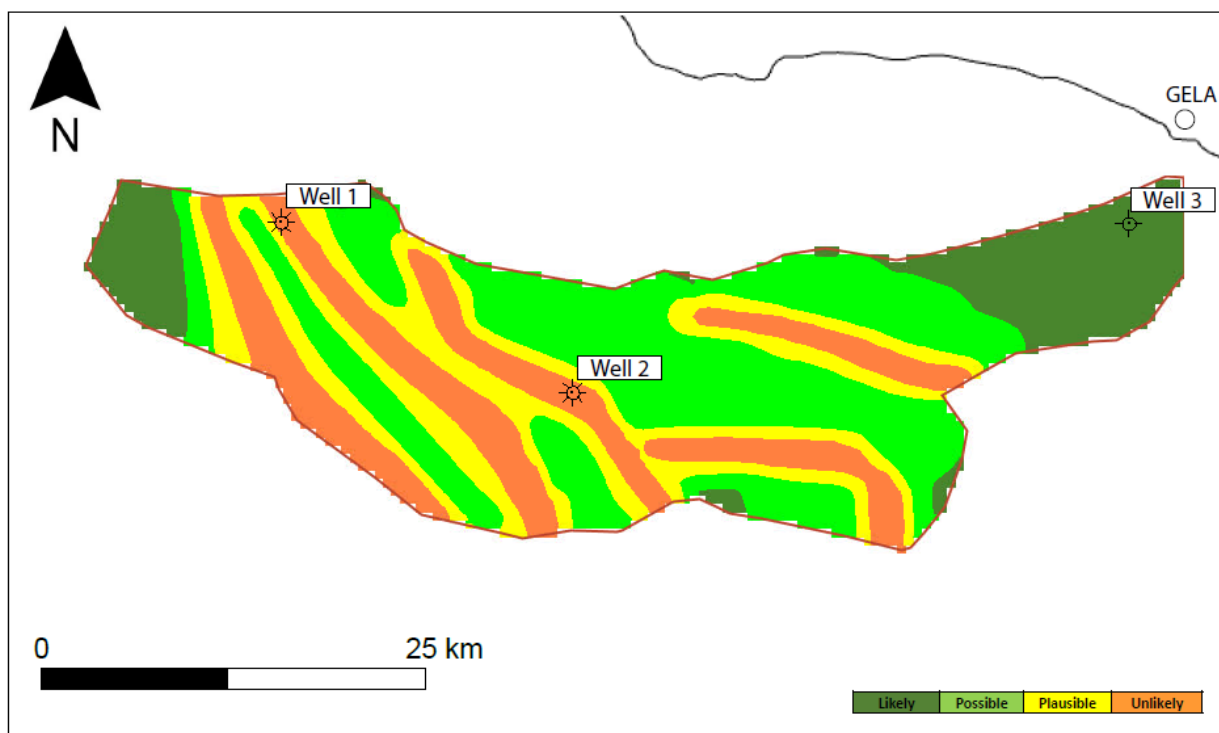


Figure 7. Seal effectiveness from tectonics mostly showing the presence of likely areas NE and NW of the study area.

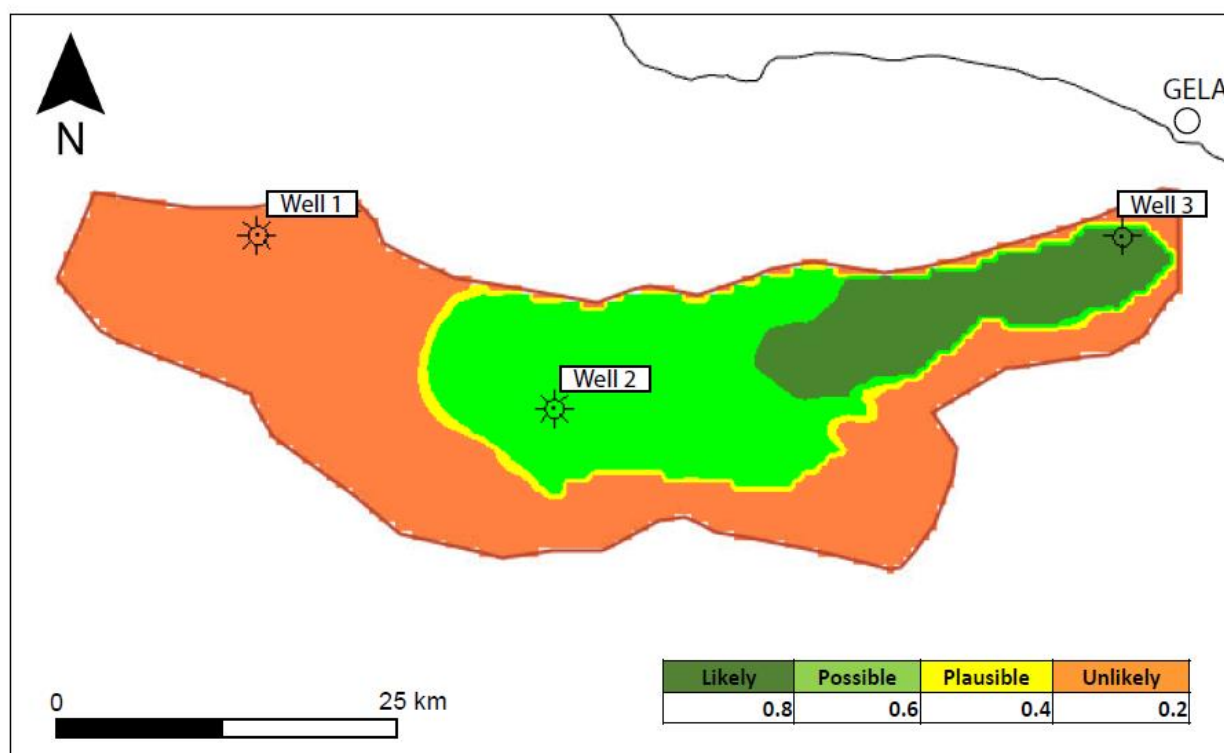


Figure 8. Reservoir combined map showing a likely area in NE sector of study area.

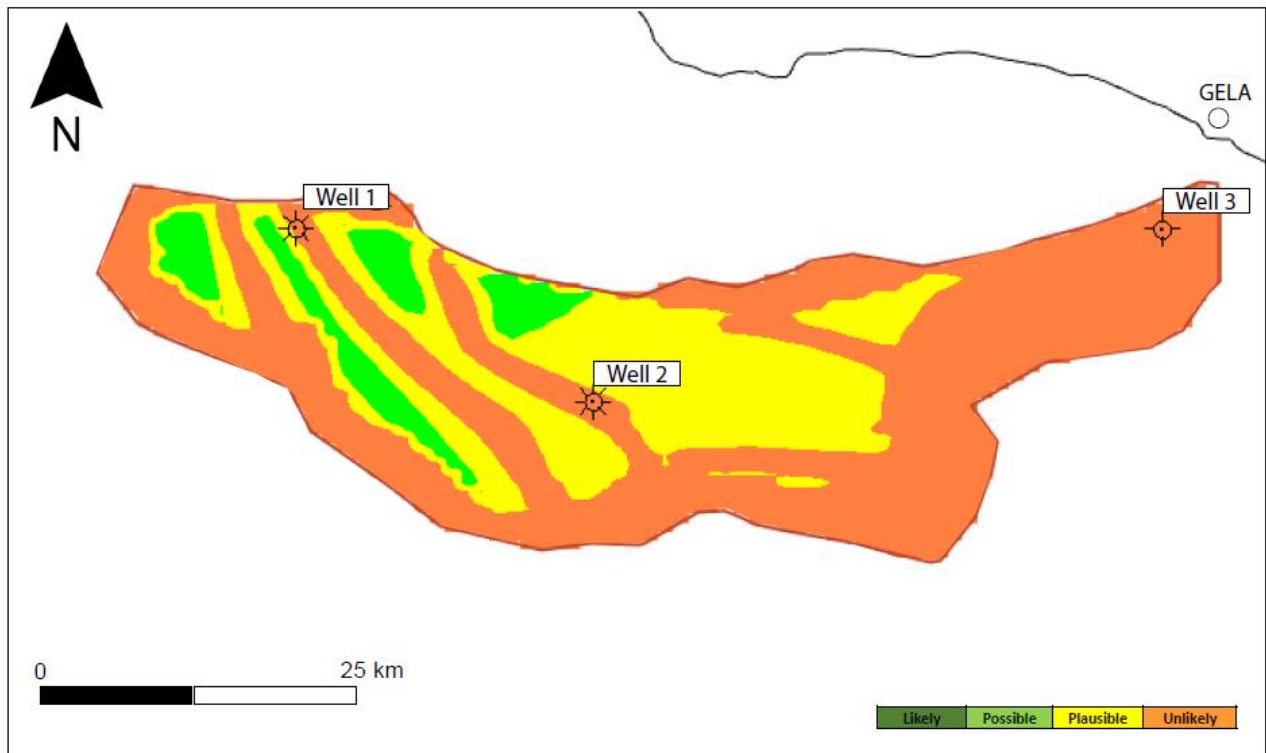


Figure 9. Seal combined map showing no evidence of likely areas.

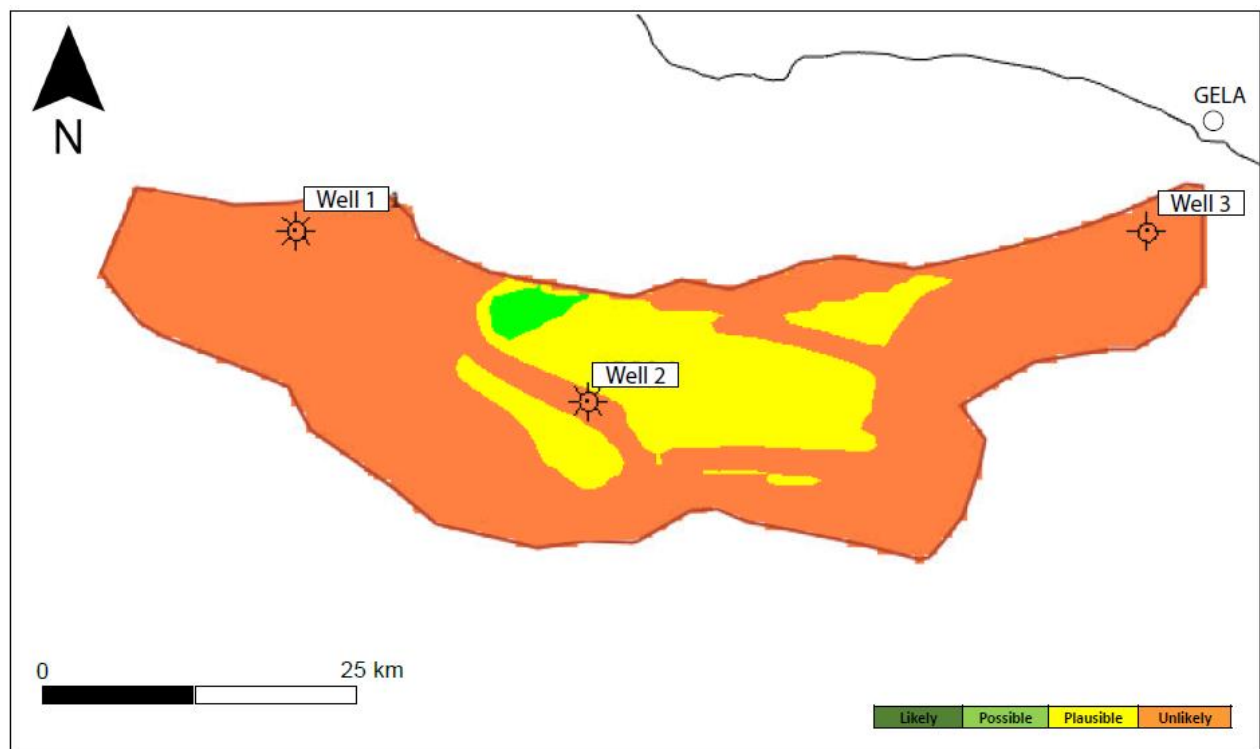


Figure 10. Final combined map for Reservoir and Seal showing no evidence of likely areas, but just a possible area and a plausible.

In the Gela offshore basin one possible target of CO₂ injection has been identified aware of the limited input data availability (especially wells) and of the high heterogeneity of turbiditic deposits.

Some assumptions have been taken to model the facies distribution laterally and vertically and highlight potential and risks for injectivity (reservoir) and containment (seal and possible faults).

The final map of the reservoir chance shows that this can be considered a good reservoir in correspondence of the well 3.

Seal chance map shows a good seal with limited extension in correspondence of well 3, but is a lot conditioned by tectonic faults affecting the lower Pleistocene succession.

The combined final map is therefore conditioned by present day tectonic configuration and facies distribution. Once more interpretations and data become available the final and intermediate chance maps can be refined to highlights risks and opportunities. A similar screening approach could be used to screen other basins in different part of the world.

7. General discussion

This PhD thesis study provided crucial insights into the ongoing tectonic and geological processes in the Sicily Channel and their implications for Carbon Capture and Storage (CCS).

Sicily Channel emerged as shaped by significant tectonic processes, which appears to be ongoing, as indicated by the recent phase of contraction that has resulted in seabed uplifts in the Malta and Linosa Grabens. These structural changes are believed to be linked to a potential shift in the subduction polarity of the African plate, as supported by geodetic data and previous studies in the region. This shift in subduction dynamics, including the rollback of the Calabrian slab and possible slab tear, highlights the complex and evolving nature of the Central Mediterranean geodynamic system. Understanding these tectonic processes is critical when evaluating potential sites for CO₂ storage. Active fault zones, such as the ones identified in the Grabens, play a dual role: they contribute to the creation of natural traps and reservoirs, which can be beneficial for storing CO₂, but they also pose risks, particularly if faults act as pathways for fluid migration, which could result in leakage from CO₂ storage reservoirs. Thus, while tectonic activity creates opportunities for CO₂ storage by forming structural traps, it also necessitates careful assessment of the integrity of these structures to prevent leakage and ensure long-term storage.

One of the most significant findings of this study is the identification of fluid migration mechanisms in the region. Fluid migration—whether through dewatering, compaction, or diffusion through sandy lenses—mirrors the challenges faced in ensuring the safe storage of CO₂ in subsurface reservoirs. The study identifies two distinct fluid types and sources on the Adventure Plateau, providing key insights into the geological layers and their potential role as reservoirs or seals for CO₂. The detection of gas-containing fluids at depths of 700–820 meters and oil at shallower levels highlights the complexity of fluid migration across different geological strata. This complexity is particularly relevant when considering CO₂ injection into the subsurface. The CO₂, after being injected, could potentially follow similar migration pathways as natural fluids, moving through permeable layers or being trapped by impermeable ones. Therefore, understanding the permeability and structural characteristics of formations like the Amerillo and Fortuna Formations is critical for predicting how CO₂ will behave after injection. Impermeable layers, such as those in the Ribera Formation, are of particular interest because they can act as seals that prevent the upward migration of CO₂. These layers serve as barriers that ensure the CO₂ remains trapped within the reservoir, thereby reducing the risk of leakage. However, the presence of structural features like polygonal faults and gas chimneys requires special attention. If these features are not properly accounted for during site selection, they could provide pathways for CO₂ to escape, compromising the storage site's integrity.

The insights gained from this study provide valuable analogies for CO₂ storage projects, particularly regarding the importance of understanding fluid dynamics and subsurface structures. The challenges associated with fluid migration in the Sicily Channel underscore the need for comprehensive geological and geodynamic assessments when selecting CO₂ storage sites. These assessments should include detailed analyses of fault activity, permeability, and the presence of impermeable sealing layers to ensure that CO₂ remains securely stored over the long term. Furthermore, the study demonstrates the necessity of evaluating the potential for leakage through natural pathways such as faults and fractures. In the case of CO₂ storage, even small leaks can have significant environmental and economic consequences, undermining the effectiveness of the storage project and potentially leading to the release of stored CO₂ back into the atmosphere. Therefore, understanding the geological structures that could act as migration pathways is essential for minimizing the risks associated with CO₂ storage.

The screening workflow for Carbon Capture and Storage (CCS) highlighted in this study is a critical tool for the early stages of site selection. This systematic approach to evaluating geological parameters allows researchers and industry professionals to identify and rank potential storage sites based on their suitability for long-term CO₂ containment. By applying this workflow to diverse geological settings, such as the Gela Basin, the study demonstrates its effectiveness in guiding decision-making processes for CCS deployment. The screening workflow involves assessing a wide range of factors, including the presence of natural reservoirs, impermeable seals, fault activity, and fluid migration pathways. By integrating these factors into a comprehensive evaluation framework, the workflow helps to identify sites that are not only capable of storing CO₂ but also pose minimal risk of leakage. This is particularly important in regions like the Sicily Channel, where active tectonics and complex fluid migration dynamics require a nuanced understanding of subsurface conditions.

As CCS technology continues to evolve, the importance of rigorous site selection workflows will only increase. The ability to safely and securely store CO₂ is a critical component of global efforts to combat climate change. Reducing atmospheric CO₂ levels through CCS is seen as one of the key strategies for mitigating the impacts of climate change, particularly as the world transitions to cleaner energy sources.

The differing nature of the reservoirs considered in this thesis introduces critical implications for the feasibility and performance of CO₂ storage strategies. In Chapter 4, the potential reservoirs are identified within Triassic carbonate formations, whereas the case studies in Chapters 5 and 6 focus on clastic successions from more recent geological periods. These reservoirs exhibit substantial

contrasts in permeability, fluid-rock interactions, and overall storage dynamics, which influence both the technical and operational aspects of carbon storage.

Carbonate reservoirs, such as the Triassic formations discussed in Chapter 4, often exhibit high heterogeneity due to their diagenetic history, including fracturing, dissolution, and recrystallization processes. While these features can enhance permeability locally, they can also lead to unpredictable flow pathways and compartmentalization, complicating CO₂ injection and distribution. In contrast, recent clastic reservoirs, as analysed in Chapters 5 and 6, generally display more predictable permeability patterns due to their depositional environments and the limited diagenetic alteration of their pore systems. This predictability can facilitate more controlled CO₂ injection and distribution, reducing the risk of injection-induced pressure anomalies.

The interaction between CO₂ and the host rock significantly affects the long-term stability of the storage system. In carbonate reservoirs, CO₂ dissolution into formation water can lead to the formation of carbonic acid, which may enhance porosity and permeability through dissolution but also risk structural integrity if excessive dissolution occurs. Conversely, clastic reservoirs composed primarily of silicate minerals are less reactive with CO₂, minimizing the risk of reservoir alteration. However, clastic systems may still experience secondary mineralization, such as the precipitation of carbonates, which could reduce porosity over time. The nature of the overlying seal formations also plays a critical role in containment. Carbonate reservoirs often rely on thick evaporitic sequences or marl layers for effective sealing, which, if present, offer excellent containment. On the other hand, clastic reservoirs are frequently sealed by fine-grained shales or mudstones, whose effectiveness depends on their lateral continuity and fracture susceptibility. The choice of reservoir type thus directly influences the overall risk profile for CO₂ leakage.

From an operational standpoint, the differences in reservoir properties also affect the cost and complexity of CO₂ storage projects. Carbonate reservoirs may require extensive characterization and monitoring to address heterogeneity and ensure containment. Meanwhile, clastic reservoirs may benefit from lower costs associated with their relatively homogeneous nature, though they may require larger injection volumes due to lower storage capacity on a per-unit-volume basis.

The contrasting characteristics of carbonate and clastic reservoirs underscore the need for tailored approaches in site selection, modeling, and monitoring for CO₂ storage projects. While carbonate reservoirs offer potential for medium-capacity storage, their complex behavior necessitates advanced management strategies. Clastic reservoirs, with their predictable properties, may provide more straightforward solutions but could be constrained by lower reactivity and higher storage capacities.

The findings in Chapters 4–6 highlight the importance of integrating geological, geophysical, and geochemical data to optimize storage solutions across diverse reservoir types.

8. Conclusions

This PhD thesis has provided critical insights into the tectonic and geological processes of the Sicily Channel and their implications for Carbon Capture and Storage (CCS). The research contributes to our understanding of this region's complex geodynamics, fluid migration mechanisms, and the potential for secure geological CO₂ storage.

The Sicily Channel, as revealed through this study, is shaped by ongoing tectonic activity, including recent contraction phases and seabed uplifts in the Malta and Linosa Grabens. These dynamics are linked to a potential shift in the African plate's subduction polarity, likely influenced by Calabrian slab rollback and slab tearing. Such processes underscore the importance of considering active tectonics in CCS site selection, as fault zones can both create structural traps suitable for storage and pose risks as potential pathways for fluid migration and leakage.

The study's identification of fluid migration mechanisms within the Sicily Channel offers essential analogies for predicting CO₂ behavior post-injection. Fluid migration, facilitated by processes such as dewatering, compaction, and diffusion, highlights the need to carefully assess the permeability and sealing properties of potential reservoirs. The Amerillo and Fortuna Formations were identified as promising reservoirs, while the impermeable Ribera Formation demonstrated potential as a critical seal. However, features like polygonal faults and gas chimneys necessitate rigorous evaluation to avoid compromising storage integrity.

The findings also underscore the varying implications of reservoir characteristics on CO₂ storage strategies. Carbonate reservoirs, such as the Triassic formations discussed in Chapter 4, exhibit high heterogeneity due to diagenetic processes, leading to complex fluid pathways and requiring advanced management strategies. In contrast, the more recent clastic reservoirs analyzed in Chapters 5 and 6 offer predictable permeability patterns and straightforward injection dynamics and may have higher storage capacities. These contrasts highlight the necessity of tailored approaches for site selection, injection modeling, and monitoring based on reservoir type.

The study also emphasizes the importance of a systematic screening workflow for CCS site selection. By integrating geological, geophysical, and geochemical data, this workflow effectively evaluates storage potential and risk factors, as demonstrated in the Gela Basin case study. This

approach provides a robust framework for identifying sites capable of safely and securely storing CO₂ while minimizing risks of leakage and environmental impact.

The implications of this research extend beyond the Sicily Channel, offering valuable methodologies and insights for CCS projects in other geologically active and structurally complex regions. As global efforts to combat climate change increasingly rely on CCS technology, the importance of rigorous site selection workflows and comprehensive geological assessments cannot be overstated.

In conclusion, this thesis contributes to advancing the field of CCS by addressing key challenges associated with tectonic activity, fluid migration, and reservoir heterogeneity. It lays the groundwork for future studies and applications, aiming to optimize CO₂ storage solutions and support global climate change mitigation efforts.

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