

Research Article

Morphostructural Setting and Tectonic Evolution of the Central Part of the Sicilian Channel (Central Mediterranean)

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The Plio-Quaternary tectonic evolution of the central sector of the Sicilian Channel and the resulting morphostructural setting have been analyzed using a large geophysical dataset consisting of multichannel seismic profiles, which some of them never published, and available bathymetric data. This area hosts two regional-scale tectonic domains that registered the complex pattern of deformation occurred since the Early Pliocene: (1) the Sicilian Channel Rift Zone (SCRZ), which can be divided into a western sector formed by the Pantelleria graben (PG) and in a eastern one represented by the Linosa and Malta grabens (LG and MG) and (2) the Capo Granitola-Sciacca Fault Zone (CGSFZ), a NNE-oriented lithospheric transfer zone that crosses the Sicilian Channel from the Sicily coast to the Linosa Island, of which only its northern part has been studied to date. Data interpretation has allowed achieving the following outcomes: (i) the presence of an alternation of basins and structural highs forming a NNE-oriented separation belt between the western and eastern sectors of the SCRZ, and interpreted as the shallow expression of the southern part of the CGSFZ; (ii) a NE-oriented tectonic lineament separating the MG in a northern and southern part, and interpreted as the southern prosecution of the Scicli-Ragusa Fault System; (iii) the presence of syn-rift deposits in the Plio-Quaternary fill of the grabens, suggesting that the opening of the grabens of the SCRZ was coeval, and started since Early Pliocene in the framework of a NW-oriented right-lateral transtensional mega-shear zone; (iv) continental rifting ended around the Early Calabrian, during which extensional tectonics dominated along the separation belt; (v) the CGSFZ conditioned the SCRZ configuration at a regional scale, leading to the development of the PG in the western sector and of the LG and MG in the eastern one; and (vi) after the Early Calabrian, the PG and the southern MG followed a different tectonic evolution with respect to the LG and northern MG. The syn-rift deposits of the PG and southern MG were sealed by an undeformed post-rift succession, while the LG and the northern MG suffered a basin inversion that ended around the Latest Calabrian time. During this stage, the separation belt was affected by a transpressional tectonics. At present, the grabens of the Sicilian Channel seem to be tectonically inactive, while the CGSFZ represents an active tectonic domain.

1. Introduction

The Sicilian Channel belongs to the North Africa continental margin and hosts a foreland-foredeep-chain system consisting of the offshore part of the Neogene-Quaternary Sicilian-Maghrebian chain, the Gela foredeep basin, and the Pelagian foreland (Figure 1). Despite foreland domains are relatively stable areas affected by a weak deformation [1], the Pelagian foreland includes two regional-scale tectonic domains: (1) the ~300 km long and 100 km wide Sicilian Channel Rift

Zone (SCRZ) developed in the central part of the Sicilian Channel since Early Pliocene and consisting of three NW-oriented deep tectonic grabens (Pantelleria, Linosa, and Malta; PG, LG, and MG; Figure 1) [2–6] and (2) the Capo Granitola-Sciacca Fault Zone (CGSFZ) [7], a NNE-oriented lithospheric transfer zone that crosses the Sicilian Channel for at least 200 km from the Linosa Island to the Sicily coast between Capo Granitola and Sciacca Town (Figure 1) [4, 7–11].

The central part of the Sicilian Channel, far from the coasts, remains as a large, mostly unexplored area on which,

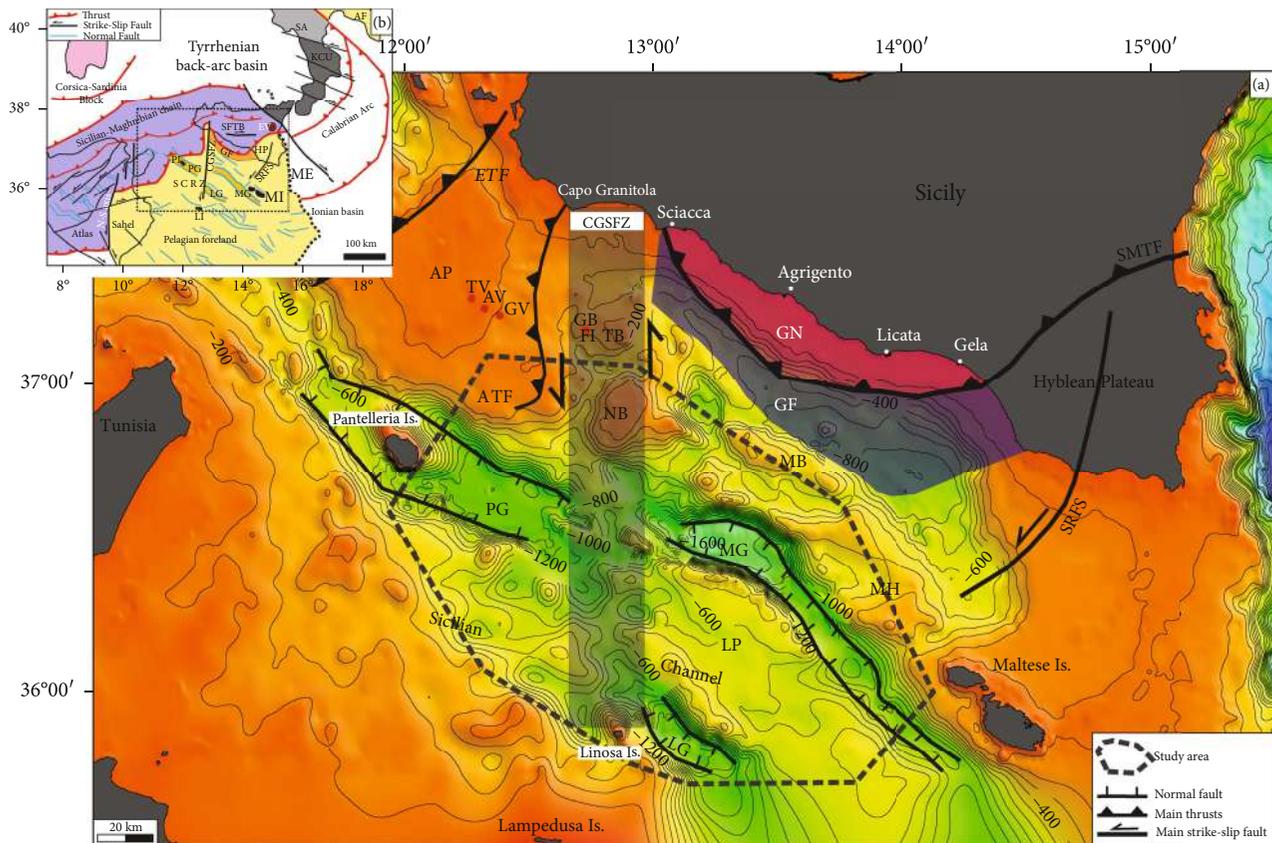


FIGURE 1: (a) Simplified structural map of the Sicilian Channel. Bathymetric data derived from EMODnet (<http://www.emodnet-bathymetry.eu/>) Digital Terrain Model (1/16*1/16 arc minutes). The position of the Gela Nappe and Gela foredeep derives from various authors [38, 66, 68]. AP: Adventure Plateau; ATF: Adventure Thrust Front; AV: Anfitrite Volcano; CGSFZ: Capo Granitola-Sciaccia Fault Zone; ETF: Egadi Thrust Front; GB: Graham Bank; GF: Gela foredeep; GN: Gela Nappe; GV: Galatea Volcano; LG: Linosa graben; LP: Linosa Plateau; MB: Madrepora Bank; MG: Malta graben; MH: Malta High; NB: Nameless Bank; PG: Pantelleria graben; SMTF: Sicilian-Maghrebian Chain Frontal Thrust; SRFS: Scicli-Ragusa Fault System; TB: Terrible Bank; TV: Tetide Volcano. (b) Box in the upper left corner indicates the main geodynamic features of the Central Mediterranean area. The dotted rectangle is the area reported in (a). AF: Apulian foreland; CGSFZ: Capo Granitola-Sciaccia Fault Zone; EV: Etna Volcano; FI: Ferdinanda Island; GF: Gela foredeep; KCU: Kabilo-Calabride tectonic units [102]; LG: Linosa graben; LI: Linosa Island; ME: Malta Escarpment; MI: Maltese Islands; MG: Malta graben; PI: Pantelleria Island; PG: Pantelleria graben; SA: Southern Apennines; SCRZ: Sicilian Channel Rift Zone; SFTB: Sicilian Fold and Thrust Belt; SRFS: Scicli-Ragusa Fault System.

due to the paucity of the available seismic profiles and borehole data, few and dated papers were published. These studies mainly focused on the development of the three grabens, whose origin still remains an open question, and on their deformation age.

The present study investigates the central part of the Sicilian Channel (Figure 1(a)) with the following objectives: (1) to analyze the morphobathymetric features of the PG, LG, and MG produced by the continental rifting process; (2) to define the spatial distribution of the main magmatic manifestations; (3) to identify the main tectonic structures and their kinematics, focusing in particular on the CGSFZ, which is well known only in its northernmost part; (4) to investigate the role of the CGSFZ as a potential separation belt between two independent sectors of the SCRZ, the PG to the west and LG and MG to the east; (5) to reconstruct the Plio-Quaternary tectonic evolution of the central part of the Sicilian Channel, focusing on the three grabens containing the most complete and continuous sedimentary record;

and (6) to relate the tectonic evolution of the study area in the general context of the Central Mediterranean geodynamics.

For these purposes, several multichannel seismic profiles collected by OGS of Trieste during geophysical campaigns conducted between 1970s and 2000s (MS and PANT datasets), which some of them never published, have been reprocessed and interpreted, in combination with available morphobathymetric data (Figures 2 and 3). The OGS seismic dataset has been integrated by CROP lines, seismic profiles and borehole data made available by the Italian Ministry of the Economic Development, and the CS89-01 seismic profile published by Torelli et al. [12] (Figure 2).

Although the density of the available seismic dataset does not allow to reconstruct a complete and exhaustive structural framework of the study area, it was still possible to identify the main structural lineaments bounding the grabens and the minor basins, and to highlight some important differences in their geometry and kinematics, the configuration

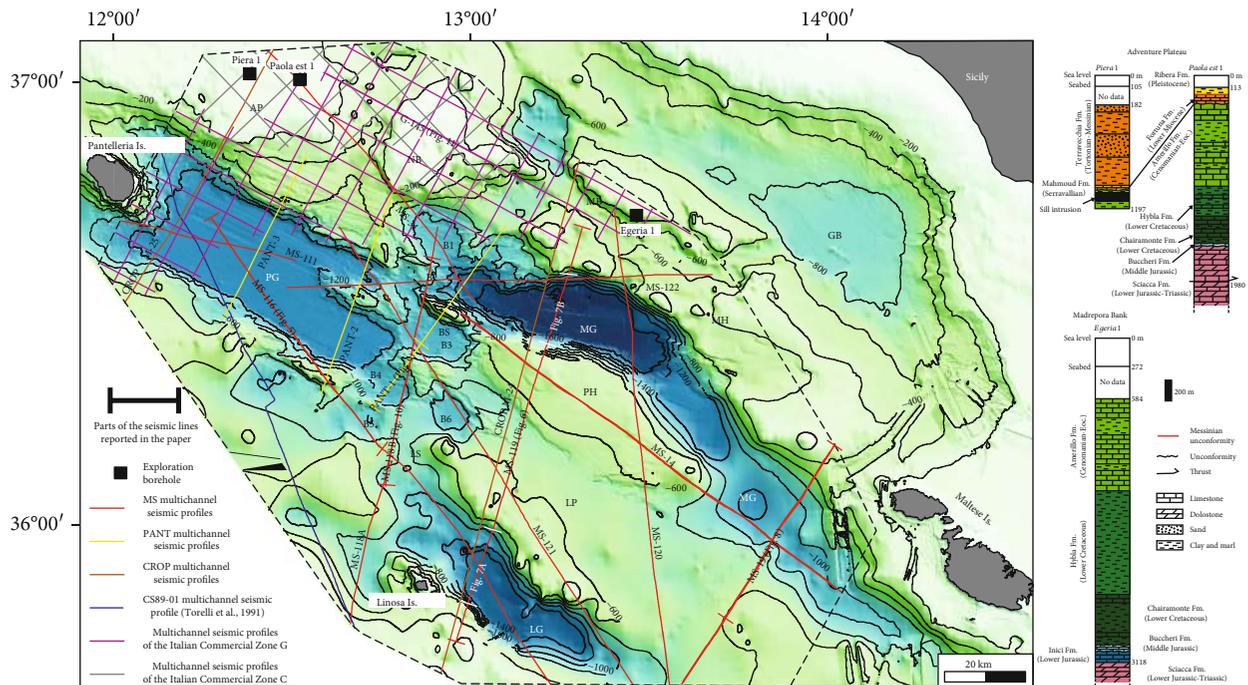


FIGURE 2: Position of the exploration boreholes and multichannel seismic reflection profiles used in this study. The parts of the seismic lines presented in this paper are also indicated. Bathymetric data extracted from EMODnet (<http://www.emodnet-bathymetry.eu/>) Digital Terrain Model (1/16*1/16 arc minutes). AP: Adventure Plateau; BS: Bannock seamount; GB: Gela Basin; LG: Linosa graben; LP: Linosa Plateau; LS: Linosa III seamount; MB: Madrepora Bank; MG: Malta graben; MH: Malta High; NB: Nameless Bank; PG: Pantelleria graben; PH: Pelagian High.

and internal deformation of the Plio-Quaternary basin fills, and the distribution of the magmatic bodies. These aspects have allowed to propose a tectonic evolution that significantly differs for the PG and the southern MG with respect to the central part of the SCRZ comprising the LG and the northern MG, being separated by lithospheric discontinuities.

2. Tectonic Background

The tectonic evolution of the Central Mediterranean, where the Sicilian Channel is located, is related to the NNW-oriented Neogene convergence between African and European plates [13–15], which led to the closure of the Neo-Tethys Ocean and the coeval collision between the European and African continental margins.

In this geodynamic context, a chain-foredeep-foreland system was developed today consisting of the Sicilian-Maghrebian chain, the Gela foredeep, and the Pelagian foreland, respectively. These tectonic domains can be identified in the Sicilian Channel (Figure 1(b)): (1) the Pelagian foreland, mainly made of shallow and deep water Mesozoic carbonates; (2) the Plio-Pleistocene Gela foredeep, filled by over 2 km of clastic sediments; and (3) the frontal part of the Sicilian-Maghrebian chain, a complex orogen mainly generated during the Neogene times and developed from Southern Italy to North Africa across the Sicilian and Sardinia Channels [16–18].

The Pelagian foreland, which includes the study area, occupies most of the Sicilian Channel (Figure 1(b)). It is part

of the northern continental margin of the African plate (the so-called Pelagian Block of [19]) and represents the area not affected by the emplacement of thrust sheets of the Sicilian-Maghrebian collisional system (Figure 1(b)). The crustal thickness of the Pelagian foreland ranges from 25 to 35 km [20], except in the Pantelleria Island area where the crust does not exceed 17 km [21] due to continental rifting processes. The foreland succession, which outcrops in SE Sicily (Hyblean Plateau) and in Tunisia (Sahel) (Figure 1(b)), has been mainly analyzed by seismic and well data. On a crystalline basement [22] rests a sedimentary succession consisting of a thick, up to over 5 km, Triassic and Lower Jurassic shallow water carbonates overlain by Jurassic-Eocene pelagic, slope, and open-shelf carbonates, up to 2 km thick, followed by Oligocene-Miocene open-shelf clastic deposits [3, 18, 23, 24]. The Plio-Pleistocene sedimentary cover consists of terrigenous, pelagic, and hemipelagic sediments, which generally does not exceed a thickness of 500 m [24–26]. Several extensive depositional hiatuses have been recognized in the carbonate successions, as well as tuff and pillow lavas deposited during a number of volcanic episodes [27].

Water depth of the Sicilian Channel is in general less than 200–250 m, except in its central part where a continental rifting process, started since Early Pliocene, generated three NW-oriented deep tectonic grabens (PG, LG, and MG) (Figure 1), leading to the development of the SCRZ [2, 3, 5, 6, 12, 21, 28]. These grabens, where water depth ranges from 1300 m to more than 1700 m, are filled by up to 2000 m thick Plio-Pleistocene deposits and are bounded by NW-trending subvertical normal faults [6]. Three hypotheses have been

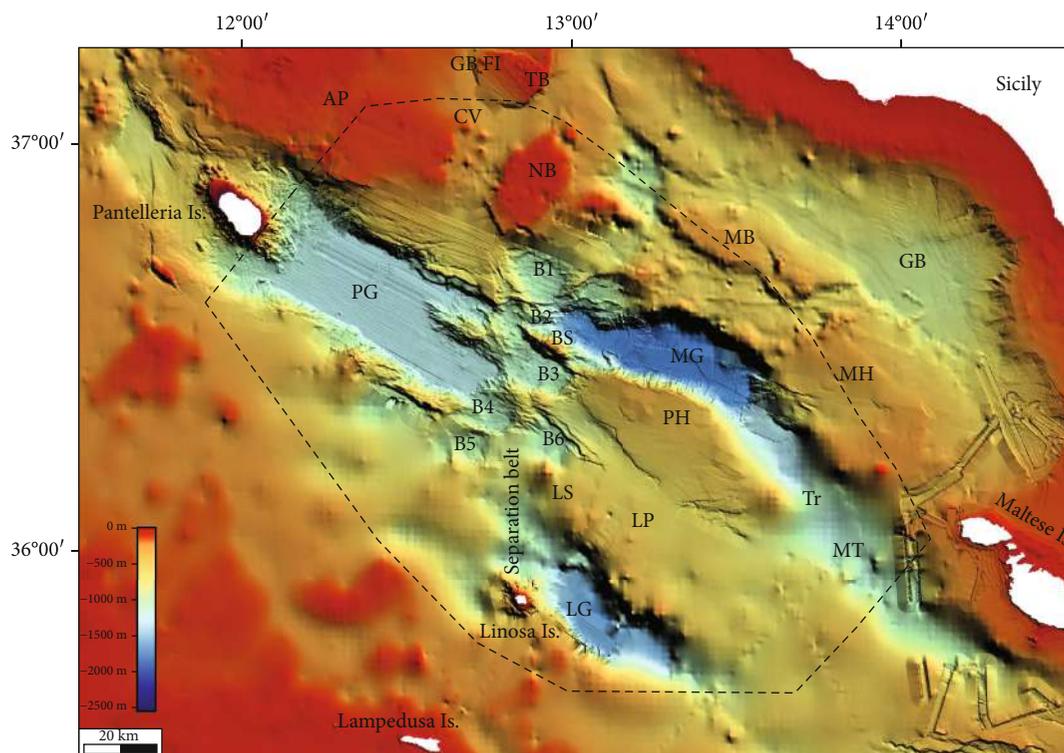


FIGURE 3: Detailed morphobathymetric map of the central part of the Sicilian Channel, including the study area (dashed line), extracted from EMODnet (<http://www.emodnet-bathymetry.eu/>) Digital Terrain Model (1/16*1/16 arc minutes). The study area. AP: Adventure Plateau; B1: Basin 1; B2: Basin 2; B3: Basin 3; B4: Basin 4; B5: Basin 5; B6: Basin 6; BS: Bannock seamount; CV: Cimotoe Volcano; FI: Ferdinandea Island; GB: Graham Bank; GB: Gela Basin; LG: Linosa graben; LP: Linosa Plateau; LS: Linosa III seamount; MB: Madrepora Bank; MG: Malta graben; MH: Malta High; NB: Nameless Bank; PG: Pantelleria graben; TB: Terrible Bank; Tr: morphological threshold.

formulated to explain the origin of the SCRZ: (1) the grabens are large and discrete pull-apart basins developed along a major dextral wrench zone [3, 28–33]; (2) the rifting is associated with mantle convections developed during the roll-back of the African lithosphere slab beneath the Tyrrhenian Basin [4, 34]; and (3) a mechanism of intraplate rift, related to NE-directed displacement of Sicily away from the African continent [35–37].

The central part of the Pelagian foreland is also crossed by the Capo Granitola-Sciaccia Fault Zone (CGSFZ), a roughly NNE-oriented, lithospheric strike-slip fault zone or “separation belt” of [4, 7–11, 24, 38, 39] (Figure 1). It is interpreted as a transfer zone separating tectonically independent sectors of the Sicilian-Maghrebian chain, and mainly developed during Early Pliocene [7]. Some authors suggested that the CGSFZ might be responsible for the Sicilian Channel continental rift configuration between the western sector, marked by the PG, and the eastern one, where the rift is splitted into the LG and MG [4, 10, 24]. Therefore, the CGSFZ might extend for 200 km from the Linosa Island to the Sicily coast between Capo Granitola and Sciaccia Town (Figure 1). Its northern part consists of two major fault systems, the Capo Granitola Fault System to the west (CGFS) and the Sciaccia Fault System to the east (SFS) ([7]; Figure 4), both dominated by a transpressional tectonics [7, 11]. The CGFS and SFS show clear evidence of Quaternary tectonic activity [7, 11]. A currently left-lateral strike-slip

component of movement along the CGSFZ has been supposed [28, 34, 38–40].

A scattered anorogenic volcanism is widespread in the Sicilian Channel mainly occurred during Plio-Pleistocene times [41], but eruptive events are documented until the historical time, as testified by the 1831 submarine eruption of Ferdinandea Island on the Graham Bank (Figures 3 and 4) [42] and by the 1891 eruption occurred about 5 km off the NW coast of Pantelleria Island [43, 44]. Part of this volcanism is related to the rifting process, and it includes the Quaternary alkaline volcanic islands of Linosa and Pantelleria, the submarine volcanic centers (Anfitrite, Tetide, and Galatea) located in the central part of the Adventure Plateau (Figure 1(a)), and other manifestations observed along the PG and LG [21, 41, 45–51]. The several submarine volcanic manifestations recognized on the Graham and Terrible Banks and in the nearshore of Capo Granitola-Sciaccia coast of Sicily, together with Cimotoe Volcano (Figure 4) [41, 42, 52–59], are located within of a nearly NS-oriented belt bounded by the faults of the CGSFZ, and their origin has been related to the rising of magmas along its lithospheric master faults [7]. Finally, at the eastern termination of the Nameless Bank (Figures 3 and 4), a volcanic manifestation with an inferred age of 9.5 ± 0.4 Ma has been identified [60].

The Gela foredeep or Gela Basin is a WNW-ESE-trending, narrow, and weakly deformed elongated depocenter formed during Plio-Quaternary times. This basin was

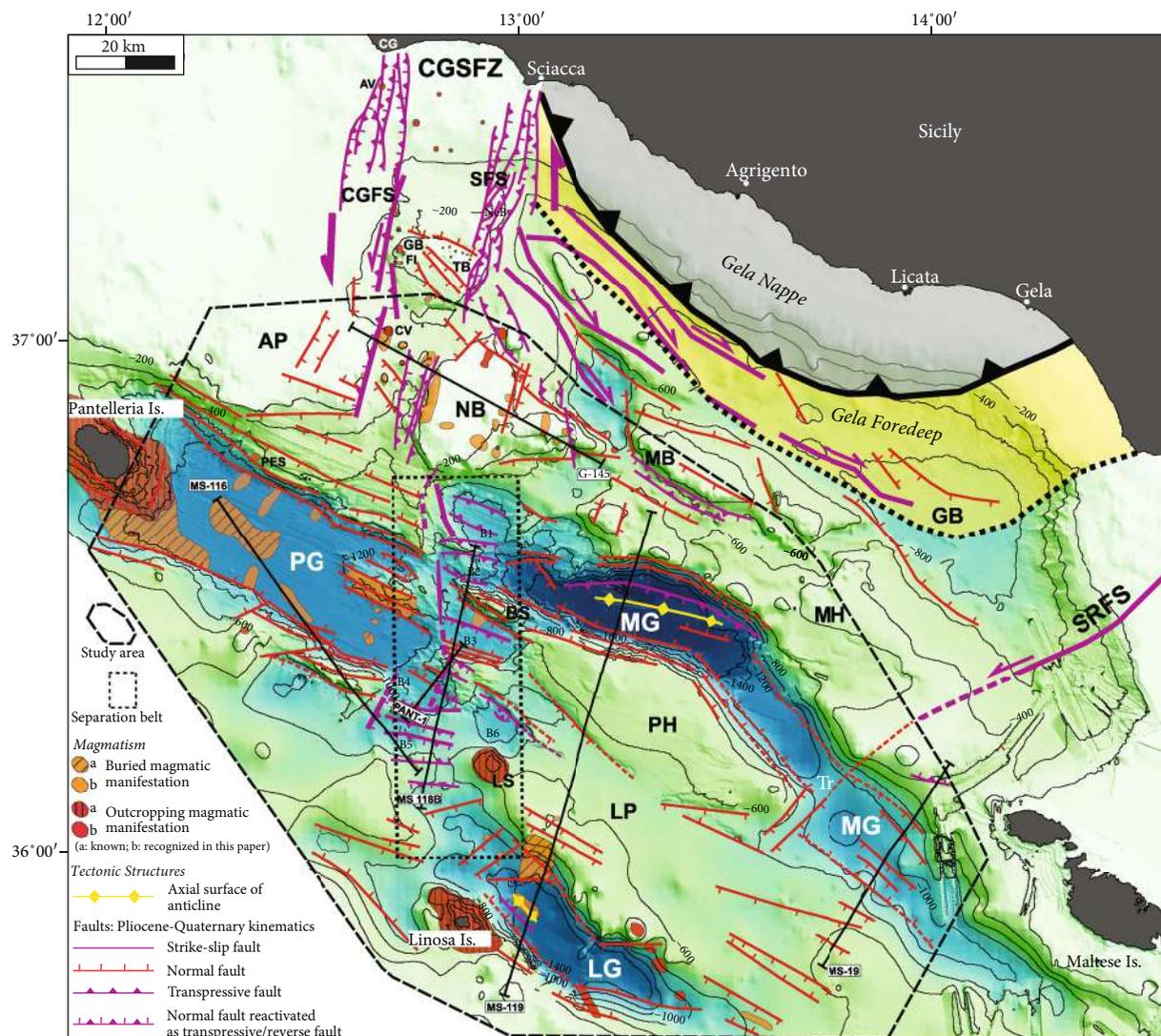


FIGURE 4: Structural map of the central part of the Sicilian Channel and distribution of the magmatic manifestations. The structural lineaments and magmatic manifestations reported outside the study area (dashed line) derive from Civile et al. [7], for the Capo Granitola-Sciacca Fault Zone (CGSFZ), and Cavallaro et al. [64]. For the Scicli-Ragusa Fault System (SRFS) has been reported the present-day supposed kinematics [81]. The position of the Gela Nappe and Gela foredeep derives from various authors [38, 66, 68]. The position of the interpreted seismic lines is also reported (black lines). AP: Adventure Plateau; B1: Basin 1; B2: Basin 2; B3: Basin 3; B4: Basin 4; B5: Basin 5; B6: Basin 6; BS: Bannock seamount; CGFS: Capo Granitola Fault System; CGSFZ: Capo Granitola-Sciacca Fault Zone; CV: Cimotote Volcano; FI: Ferdinanda Island; GB: Graham Bank; GB: Gela Basin; LG: Linosa graben; LP: Linosa Plateau; LS: Linosa III seamount; MB: Madrepora Bank; MG: Malta graben; MH: Malta High; NB: Nameless Bank; NeB: Nerita Bank; PES: Pantelleria Est seamount (after Pantelleria graben); PH: Pelagian High; SFS: Sciacca Fault System; SRFS: Scicli-Ragusa Fault System; TB: Terrible Bank; Tr: morphological threshold.

developed in the offshore of SE Sicily, parallel to the coast in front of the south-verging Plio-Pleistocene Gela Nappe [61] (Figure 1), which represents the outermost and youngest thrust sheet of the Sicilian-Maghrebian chain [16, 18, 38, 62–64]. The formation of the Gela foredeep has been associated with the flexure of the foreland, due to loading of the Gela Nappe [16]. The CGSFZ separates the Gela foredeep and the offshore part of the Gela Nappe by a western offshore sector of the Sicilian-Maghrebian chain that includes the Adventure Plateau (Figure 1(a)). This western sector hosts the Tortonian-Lower Messinian deposits (Terravecchia

Fm.) of the NE-oriented Adventure foredeep lying on a Mesozoic-Cenozoic carbonate substrate [8, 65–67]. This sector of the chain was affected by a Late Miocene compressional phase [9, 66–69], which produced ESE-verging thrusts and associated back thrusts deforming also the Adventure foredeep [24, 49, 70]. This offshore sector of the chain is limited to the east by the Adventure Thrust Front [8] (Figure 1(a)).

On the basis of the available well data (Figure 2) and literature information [7, 24, 11, 38, 64, 71, 72], the sedimentary succession of the study area can be summarized as

follows: the lower part consists of Upper Triassic (Sciacca Fm.) and Lower Jurassic (Inici Fm.) carbonate platform deposits covered by a Jurassic-Eocene pelagic succession, composed of limestones with marly and clayey intercalations up to over 2500 m thick (Buccheri, Chiaramonte, Hybla, and Amerillo Formations); on this succession rests an Oligocene-Middle Miocene shallow water to pelagic carbonate succession, up to 700 m thick, with siliciclastic intercalations (Bonifato, Ragusa, Fortuna, Nilde, and Mahmoud Formations) covered by the siliciclastic foredeep deposits of the Late Tortonian-Early Messinian Terravecchia Fm. characterized by considerable thickness variations from about 250 m to over 2000 m; some tens of meters of Messinian evaporites of the Gessoso-Solfifera Group can be locally present. The Late Oligocene-Lower Messinian succession presents different lithological features in the Maltese area [73, 74]. This succession, which can reach a thickness of 1000 m, consists of shallow-water bioclastic limestones (Lower Coralline Limestone Fm.), marly limestones (Globigerina Limestone Fm.), hemipelagic clays, and marls (Blue Clay Fm.) that area unconformably overlain by a shallow water reef deposits (Upper Coralline Limestone Fm.). The lower part of the Plio-Quaternary succession is composed of pelagic marls and marly limestones correlated with the Zanclean Trubi Fm. in Sicily. The succession ends with the Piacenzian-Pleistocene shelf clayey deposits with sandy and carbonate intercalations of the Ribera Fm.

3. Materials and Methods

The results presented in this paper are based on the seismostratigraphic and structural interpretation of a seismic dataset (Figure 2) that has been uploaded and analyzed using the Kingdom Suite® seismic package. Morphobathymetric data have been also uploaded to better constrain the position of the tectonic structures (Figure 3). The latter data largely derive from EMODnet Digital Terrain Model (grid-size: 1/16*1/16 arc minutes) and extracted from the following link: <http://www.emodnet-bathymetry.eu/>. The morphobathymetric data also include the high-resolution multibeam data collected in May 2009 by the R/V OGS Explora in the area of the PG and in the sector that separates MG and PG (published in Civile et al. [6]).

The seismic dataset consists of multichannel seismic reflection profiles collected during several seismic survey campaigns realized over a long period of time (between 1960s and 2000s) in the Sicilian Channel. It includes the following:

- (i) Three multichannel seismic reflection profiles, for a total length of about 170 km, collected in May 2009 by the R/V OGS Explora within the central-eastern part of the PG (PANT-2 and 3 already published in Civile et al. [6]) and in the separation belt between PG and MG (PANT-1) (Figure 2 and Table 1). Specific processing of these data consisted of (1) multiple removal using both the surface-related multiple elimination (SRME) and the wave equation multiple attenuation (WEMA) methods, (2) predictive decon-

volution, and (3) prestack time migration (by an iterative velocity analysis). Finally, the post-migration processing steps applied were (1) FX deconvolution, (2) time-variant filter (TVF), and (3) an amplitude balancing

- (ii) Ten MS seismic lines acquired in the framework of the project Mediterranean Sea (MS project; [75, 76]) (Figure 2 and Table 1). This geophysical investigation was performed by OGS from 1969 to 1982. The MS lines used in this paper are the only available seismic data that allow to investigate the geological setting of the extensive area of the Pelagian foreland including LG and MG, the Linosa Plateau, and (together with the seismic line PANT-1) the sector that separates the LG and MG from the PG (Figure 2)

The re-processing workflow carried out for the MS lines can be summarized in the following steps: (1) trace editing, (2) geometry assignment, (3) deghosting, (4) shot and receiver interpolation, (5) multiple attenuation (SRME followed by WEMA), (6) Q factor compensation, and (7) amplitude recovery and surface consistent predictive deconvolution. Deghost algorithm allowed to recover the lost frequencies (due to source and streamer depth) and consequently increase temporal resolution. The interpolation in shot and receiver domains was done in order to reduce the spatial aliasing effects, so that the fold coverage of the MS lines was increased to 2400% before the SRME application. Prestack Kirchhoff time migration (PSTM) was done iteratively while updating the velocity field: after several residual velocity analysis iterations, the final optimum velocity field was obtained. The final post-migration processing steps applied were (1) FX deconvolution, (2) TVF, and (3) trace equalization.

- (iii) A densely spaced network of 2-D multichannel seismic reflection profiles and borehole data made available by the Italian Ministry of the Economic Development in the framework of the project “Visibility of Petroleum Exploration data in Italy” (ViDEPI database; <http://www.videpi.com>). The used dataset includes 25 seismic profiles belonging to the Italian commercial zones C and G (Figure 2 and Table 2). These data were acquired by AGIP (now ENI E&P) for hydrocarbon exploration during the 1960s and 1980s, respectively, in expired mining permits and concessions. These lines have been mainly used to define the geological setting of the northern sector of the study area that includes the SE part of the Adventure Plateau and the Nameless and Madrepora Banks (Figure 2)

These seismic lines available as raster files were converted to SEG-Y format files using Seismic Unix free software.

- (iv) Part of the multichannel seismic lines M-25 and M-24 acquired during the 1995s in the framework of the Italian Deep Crust Project (CROP) and the profile CS89-01 (Figure 2)

TABLE 1: Acquisition parameters of the multichannel seismic profiles MS and PANT used in this study.

| Project name | MS | | PANT |
|--------------------|------------------------------|---|-------------------------------|
| Line name | MS-14, MS-19, MS-34 | MS-111, MS-116, MS-118A/B, MS-119, MS-120, MS-121, MS-122 | PANT-1, PANT-2, PANT-3 |
| Vessel | Marsili | Marsili | OGS Explora |
| Recording date | 1970/1972 | 1980/1982 | 2009 |
| Sample rate (ms) | 4 | 4 | 2 |
| Record length (s) | 10 | 8.0/10.0 | 9.0 |
| Fold (%) | 1200 | 1200 | 3000 |
| Recording filters | 10-72 Hz | 8/12-62 Hz | Anti-alias |
| Energy source | Flexotir | Flexotir | Sleeve guns |
| Source array | 3 guns, microcharges of 50 g | 2 guns, microcharges of 50 g | 8 sleeve guns of 2450 cu. in. |
| Streamer (m) | 2400 | 2400 | 1500 (1200) |
| Channel | 24 | 48 | 120 (96) |
| Group interval (m) | 100 | 50 | 12.5 |
| Shot interval (m) | 200 | 100 | 25 |

TABLE 2: Acquisition parameters of the multichannel seismic profiles of the ministerial lines of the zones G and C.

| Survey | Zone G | Zone C |
|----------------------------|----------------|---------------|
| Vessel | M/V Artic Seal | Not available |
| Recording data | 1982 | 1968 |
| Sample rate (ms) | 2 | 2 |
| Record length (s) | 8 | 5 |
| Fold (%) | 4800 | 1200 |
| Recording filters | 8-128 Hz | 10-80 Hz |
| Energy source | Airgun array | AquaPulse |
| Source array (charge size) | 2000 cu.in. | Not available |
| Streamer (m) | 2400 | 1600 |
| Channel | 96 | 24 |
| Group interval (m) | 25 | 67 |
| Shot interval (m) | 25 | 134 |

Three AGIP exploration boreholes are located in the study area. Two wells (Piera 1 and Paola 1) are positioned on the south-eastern sector of the Adventure Plateau, while the Egeria 1 well is located on the top of the Madrepora Bank (Figure 2).

Seismic lines are displayed in a two-way time (TWT) except for two prestack depth-migrated (PSDM) parts of the seismic line MS-119 that cross orthogonally LG and the northern MG. The PSDM has been done using a 2D grid tomography approach in order to obtain an accurate velocity-depth model. The iterative workflow for the grid tomography approach can be summarized into three main steps:

- (1) The starting velocity field was obtained by the conversion of the RMS velocity field (previously obtained for PSTM) into interval velocities through Dix equa-

tion [77]; the velocity field was smoothed to avoid artefacts due to strong lateral variations and was used to perform the first PSDM.

- (2) The grid tomography was used to update the velocity model; it tends to minimize the travel time errors between modeled and real ray paths changing trajectory and velocity of seismic waves in each cell of the grid.
- (3) New PSDM with the updated velocities and quality control on the common image gathers (CIG) were carried out. Steps 2 and 3 have been repeated until the CIG showed a satisfactory flatness of the reflections.

The seismic velocity field obtained for the Plio-Quaternary sedimentary fill of the LG and the northern MG ranges from roughly 1550 m/s in the uppermost part of the grabens to over 3500 m/s in the deepest one of the northern MG. The time vs. depth charts and the associated interval velocity functions for the PG and the northern MG are included in the Supplementary Material.

A velocity analysis has been performed on the Plio-Quaternary succession of the PG along the seismic line MS-116, where the maximum thickness of the sedimentary cover is reached. The interval velocity profile was derived from the Dix formula [77] and used for the time-to-depth conversion. It is reported in the Supplementary Material, along with the corresponding table.

The time-to-depth conversion was used to calculate the maximum thickness of the Plio-Quaternary sedimentary fill of the grabens in order to evaluate the average sedimentation rate for the last 5.33 Ma (Miocene-Pliocene boundary [78]) and thus hypothesize the age of the main observed unconformities. The interval velocities obtained for the northern MG have been also used as a reference for the southern part of the MG.

The seismostratigraphic interpretation of the seismic lines was made through the recognition of key reflectors, corresponding to lithological changes and/or unconformities, bounding seismic units characterized by distinctive seismic features (e.g., amplitude, lateral continuity, and frequency of internal reflectors), and then by correlating them with the stratigraphy derived by the hydrocarbon wells and literature information. Since the main focus of the present work was the Plio-Quaternary tectonic evolution, the zones of greatest interest were the PG, LG, and MG (Figures 5–8), characterized by the most complete and continuous Plio-Quaternary sedimentary record. The unconformities visible in the basins have been recognized on the basis of the reflection terminations as onlap, downlap, and truncation.

The magmatic manifestations have been inferred on the basis of the following features: (a) distinctive geometry, which generally consists of dome-shaped and discordant intrusive bodies; (b) seismic facies consisting of discontinuous and chaotic reflectors that interrupt the continuity of the seismic reflectors associated with the sedimentary succession; (c) reflective and high-amplitude top that precludes acoustic penetration and showing diffraction hyperbola; (d) possible presence of acoustic velocity jumps; and (e) tilting/folding of the reflectors around the potential magmatic intrusions.

4. Data Interpretation

The morphobathymetric and structural maps of the investigated area are shown in Figures 3 and 4, respectively. The structural setting of the northern sector of the Sicilian Channel located outside the study area is derived from the data reported in Civile et al. [7] (Capo Granitola-Sciaccia Fault Zone) and in Cavallaro et al. [64] (north of Madrepora Bank-Gela foredeep) (Figure 4).

The distribution of the magmatic manifestations is also reported in Figure 4, and it includes the bodies identified in this work and those already known in literature. However, it is necessary to emphasize that the evidence of most of the magmatic bodies remains uncertain because of the lack of available magnetic data in the study area and of detailed seismic velocity analysis on the used dataset. Therefore, the recognition of magmatic intrusions is essentially supposed on the basis of their seismic facies and shape. Finally, the areal extension and plain-view geometry of the mapped magmatic bodies is in some cases indicative.

4.1. Morphobathymetric Analysis. The study area hosts three prominent NW-trending grabens (PG, LG, and MG) constituting the core of the SCRZ, and a series of wide and shallow flat-topped structural banks, composed of Meso-Cenozoic carbonate and siliciclastic successions covered by thin Plio-Quaternary deposits (Figure 3). A narrow, roughly N-trending separation belt, about 15–25 km wide, with a complex morphobathymetry, separates the western sector of the SCRZ hosting the PG from the eastern sector occupied by the LG and MG (Figure 3).

The PG develops for about 125 km reaching a maximum width of over 40 km in the area of the Pantelleria Island

(Figure 3). The latter represents the emergent summit of a large submarine volcanic complex (Figures 3 and 4). The eastern part of the PG, which presents a rectangular shape, is bounded by N115°–120° trending linear margins (Figures 3 and 4). This sector is characterized by a flat bottom with a maximum water depth of 1350 m. The NE margin of the PG consists of a steep scarp up to 700 m high, while along the SW margin, several structural highs are recognizable.

The Adventure Plateau, characterized by a flat top with water depth between 50 m and 150 m, shows a slope gently inclined towards the PG affected by several NW-oriented tectonic scarps (Figures 3 and 4).

A NNE-oriented depression, about 12 km wide, separates the Adventure Plateau from the Nameless Bank. This depression hosts several small semicircular-shaped morphological highs, the largest of which is the Cimotoc Volcano (Figure 3). The Nameless Bank is a large plateau up to 40 km wide and 30 km long, with water depth around 120–150 m, that rapidly narrows to the east (Figure 3).

The MG and LG show a more articulated shape and a smaller width compared to the PG (Figure 3). The MG develops for over 160 km with a sigmoidal shape (Figure 3). It presents a variable trend from ~N110° in the northwestern sector to ~N140° in the remaining part of the graben. A maximum width of about 22 km is observed in the northwestern part of the graben, while in the southern one, the MG widens up to 30 km at the SE edge of the Pelagian High [after 28] (Figure 3). The maximum water depth of roughly 1700 m is reached in the northwestern part of the MG that is bounded by scarps up to over 1300 m high.

MG and LG are separated by the over 50 km wide Linosa Plateau, whose maximum elevation is the Pelagian High (Figure 3). The SE edge of this high consists of a 650 m high steep tectonic scarp, which might extend to the NE forming a morphological threshold (“Tr” in Figure 3) that separates into two parts of the MG.

The LG is the narrower depression of the SCRZ (Figure 3), and it develops for about 45 km. The LG presents a maximum width of about 20 km and a variable orientation from N140° in its northern part, where the maximum water depth of over 1550 m is reached, to about E-W in the southern one. The largely submerged Linosa volcanic complex occupies the northern part of the southwestern margin of the LG (Figure 3).

The separation belt between the PG to the west and MG and LG to the east is characterized by the presence of shallow basins (numbered 1 to 6 from north to south) of different shape and extension separated by structural highs (Figures 3 and 4). The most prominent reliefs are the 900 m high-carbonate Bannock seamount [50] and the seamount of volcanic origin called Linosa III [53] (“BS” and “LS”, respectively, in Figures 2–4). This separation belt is limited to the north by the Nameless Bank and to the south by the Linosa volcanic edifice (Figure 3).

4.2. Seismostratigraphic Analysis. The oldest seismostratigraphic unit recognizable in the seismic profiles consists of a Meso-Cenozoic pelagic carbonate succession (Figures 6 and 8–11) composed of a generally well-layered seismic

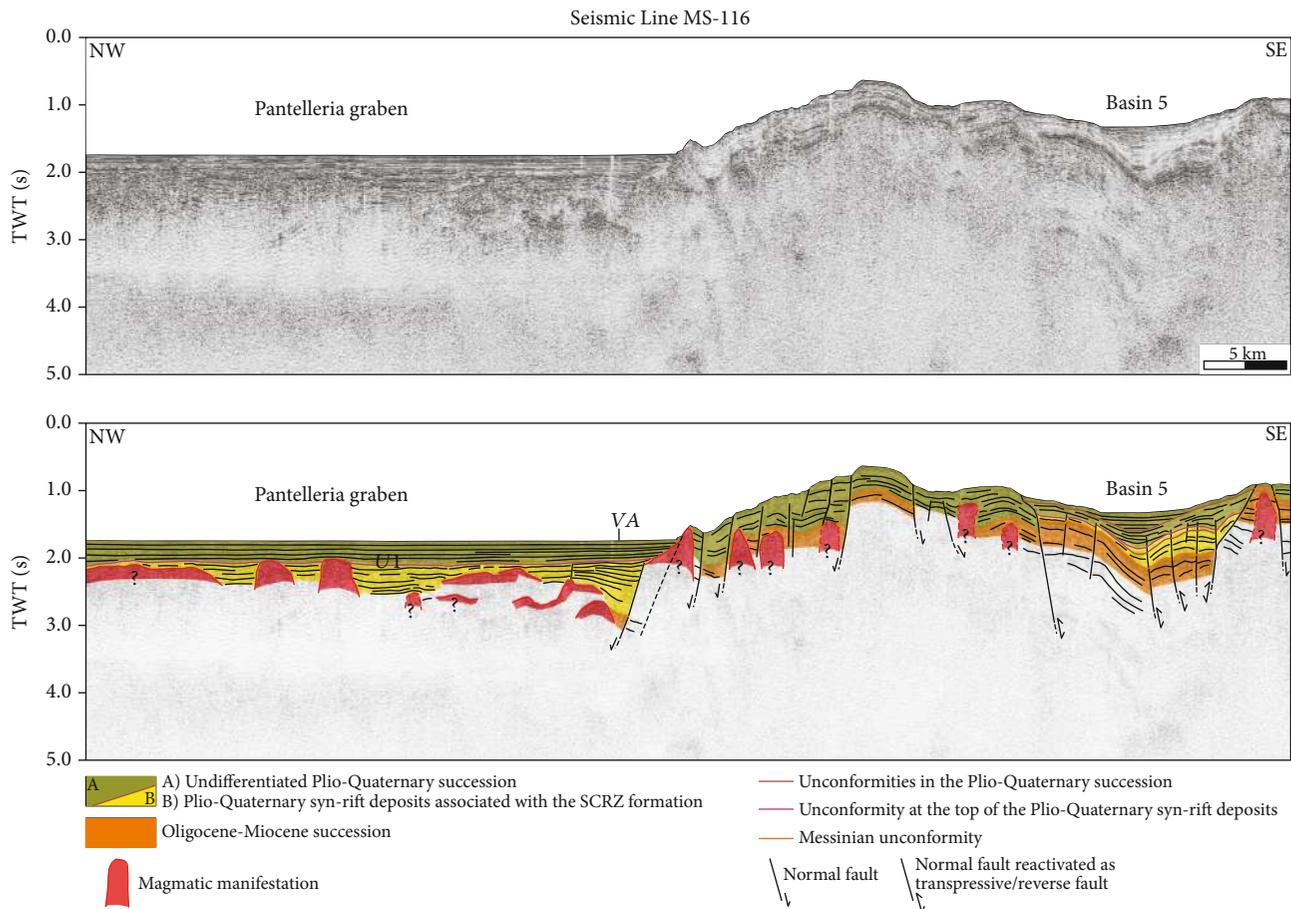


FIGURE 5: Part of the multichannel seismic reflection profile MS-116 and interpreted line drawing (location in Figure 2). Vertical exaggeration about 3.5X. U1: unconformity at the top of the syn-rift deposits of the Pantelleria graben; VA: velocity analysis site of the Plio-Quaternary succession of the Pantelleria graben (see Supplementary Material (available here)).

facies with low- to high-amplitude discontinuous reflectors. This succession can be locally chaotic. The top of the carbonate succession (top of the Amerillo Fm.) is not always recognizable in the seismic data. Where it is identified, it consists of a high-amplitude and laterally discontinuous reflector dissected by faults (Figures 6 and 8–11). The mixed siliciclastic-carbonate Oligocene-Miocene succession shows a considerable variability in terms of seismic facies and thickness. It generally consists of an upper part characterized by high-amplitude reflectors resting on an alternation of low-to-moderate amplitude seismic reflectors (Figures 6 and 8–11). The reflectors are usually discontinuous and locally chaotic. This succession is well-layered and characterized by continuous reflectors with low to high amplitude in the MG (Figure 6) and in the Adventure Plateau (Figure 11). The top of the Oligocene-Miocene succession, which also represents the base of the Plio-Quaternary deposits, is a prominent reflector associated with the Messinian unconformity. It is seismically expressed by an undulated, high-amplitude, and continuous reflector that is generally well recognizable on all seismic lines. The Plio-Quaternary deposits of the grabens consist of an alternation of sandy, pelitic, and more rarely gravelly layers produced by the interaction of several processes including gravity-driven flows, hemipelagic sedimen-

tation, mass wasting, and bottom currents [79]. The seismic facies of the sedimentary fill of the grabens is characterized by well-layered, laterally continuous, and parallel reflectors with a generally high frequency (Figures 5, 6, and 8). It is possible to identify an alternation of packages showing low to moderate or high amplitude. On the plateau areas, the Plio-Quaternary succession is generally thin and characterized by laterally continuous and parallel reflectors (e.g., Figures 6, 8, and 9). The lower part of the Plio-Quaternary succession of the basins often shows a growing wedge-shaped geometry produced by a syn-tectonic deformation associated with extensional processes (Figures 5, 6, 8, and 10). Finally, a buried seismic body characterized by a chaotic facies has been identified within the northern MG (Figure 6). This large body might be a mass wasting deposits produced by landslides generated along the fault scarps bounding the western part of the MG.

4.3. Structural Setting and Magmatism of the Sicilian Channel Rift Zone (SCRZ)

4.3.1. *Pantelleria Graben.* The structural setting of the PG reported in Figure 4 derives from the interpretation of the seismic profiles PANT-2 and 3 reported in Civile et al. [6],

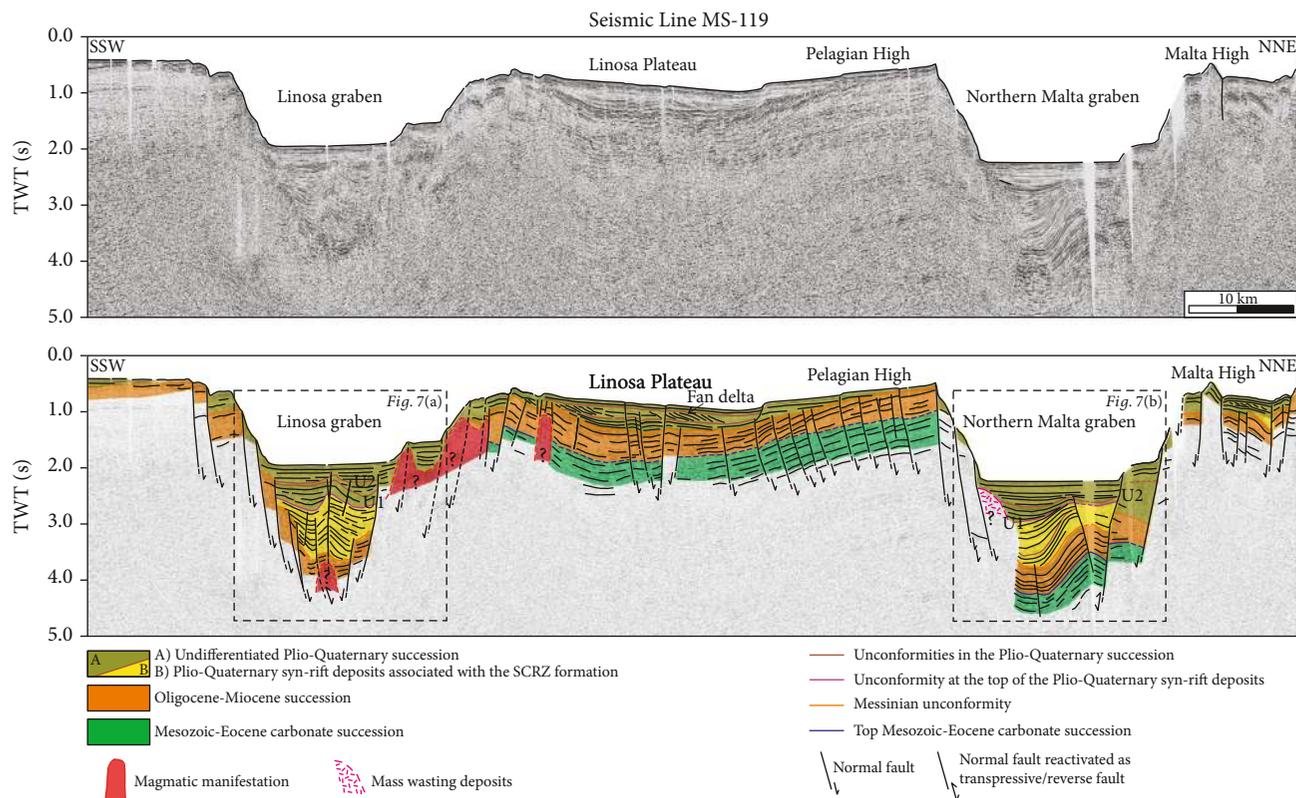


FIGURE 6: Multichannel seismic reflection profile MS-119 crossing the Linosa graben and the Northern Malta graben and interpreted line drawing (location in Figure 2). Vertical exaggeration about 4.5X. U1: unconformity at the top of the syn-rift deposits; U2: main unconformity recognized within the postrift succession.

of the NW-oriented seismic line MS-116 (Figures 2 and 5) and of the ministerial seismic lines belonging to the Italian Commercial Zones G (Figure 2).

The interpretation of the available dataset shows that the SW margin of the PG is composed of structural highs bounded by NW-trending, NE-dipping normal faults, and separated by ENE-oriented normal faults, while the NE margin is controlled by a NW-trending master fault (Figures 3 and 4). The SE termination of the PG consists of two branches separated by a structural high affected by a wide magmatic intrusion and bounded by NW-trending normal faults (Figure 4).

The Plio-Quaternary sedimentary fill of the PG has a maximum thickness of 1200 m (1.1 s TWT), as revealed by the seismic line MS-116 (Figure 5). The base of the basin fill is rarely visible in the seismic lines due to the presence of widespread magmatism (Figure 5). The Plio-Quaternary succession can be divided into two subunits separated by an unconformity (U1 in Figure 5) that is recognizable along the seismic profile as a high-amplitude reflector. The lower part of the basin fill, which is about 900 m thick (0.79 s TWT), is affected by a significant deformation, produced by both modest extensional faulting and by the emplacement of magmatic bodies. The upper part consists of a roughly 250–300 m thick (0.3–0.36 s TWT) succession composed of subhorizontal, continuous, and undeformed reflectors, only marginally affected by magmatism (Figure 5), except for the Pantelleria Island zone. The seismic line MS-116 shows that

the lower part of the Plio-Quaternary basin fill, located at the southern termination of the PG, shows a growing wedge-shaped geometry (syn-rift deposits) with an increasing thickness and divergent fanning strata towards a NW-dipping buried normal fault (Figure 5).

A widespread magmatism is present within the PG (Figures 4 and 5), and its extent is probably underestimated due to the lack of a good seismic data coverage (Figure 2). The largest magmatic body, about 46 km long and 20 km wide, includes the partially outcropping volcanic complex of the Pantelleria Island and its S-E extension (Figure 4).

4.3.2. Linosa Graben and Linosa Plateau-Pelagian High. The maximum thickness of the Plio-Quaternary sedimentary fill of the PG was estimated along the seismic line MS-119 (Figures 6 and 7(a)), with a value of about 2200 m (1.78 s TWT). The LG is bounded on both sides by normal faults, arranged in a staircase configuration, dipping towards the graben (Figures 6 and 7(a)). The pre-Pliocene basement of the LG is affected by fault-block deformation due to normal faults that cut the Messinian unconformity but not involving the Plio-Quaternary succession. A thick Plio-Quaternary succession up to 1550 m thick (about 1.125 s TWT), interpreted as syn-rift deposits that were later folded, rests on the Messinian unconformity (Figures 6 and 7(a)). A thickness (wedge-shaped geometry) of this succession towards the N-NE master fault is recognizable. The post-rift succession, up to 800 m thick (about 0.82 s TWT), can be divided

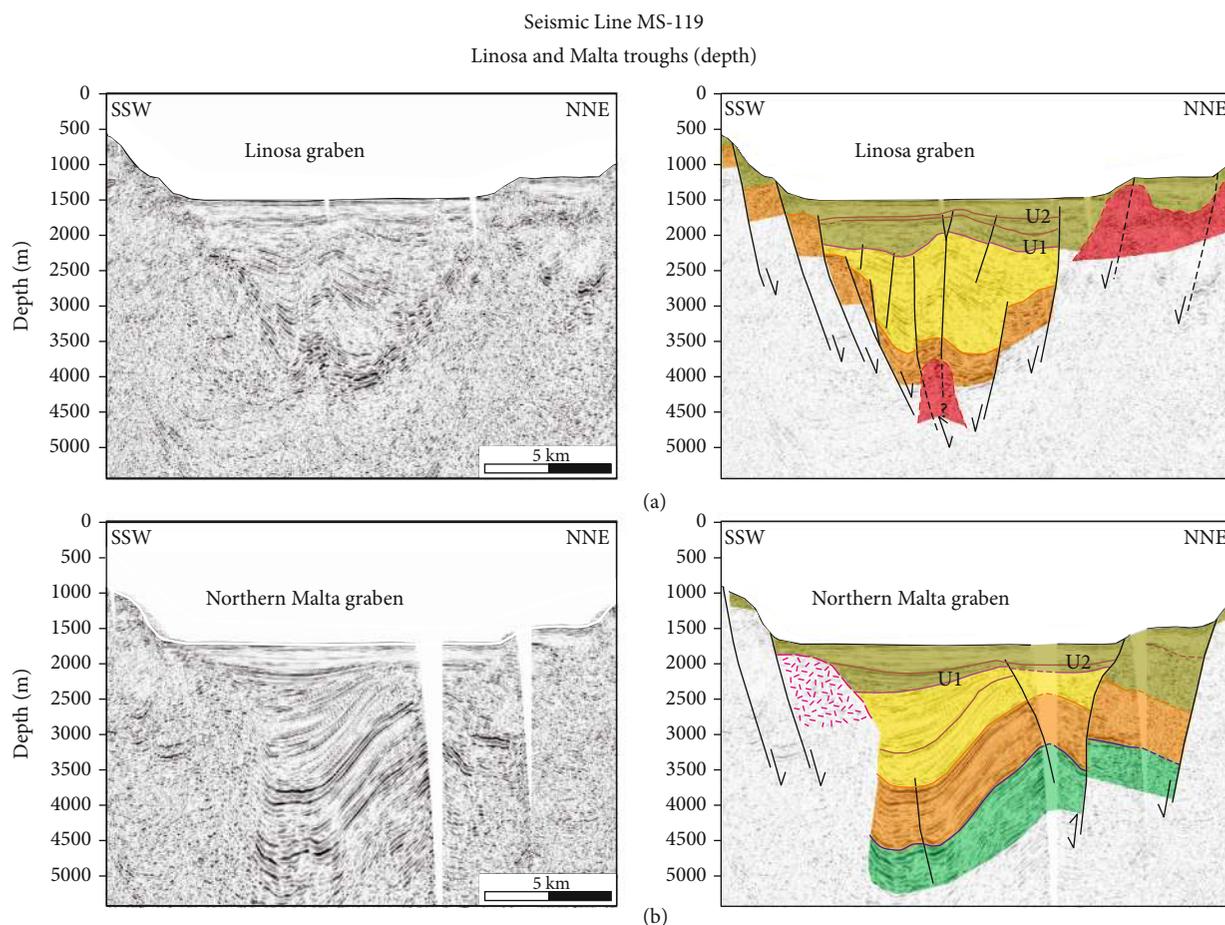


FIGURE 7: (a) Part of the depth-migrated multichannel seismic reflection profile MS-119 crossing the Linosa graben and interpreted line drawing (location in Figure 2). U1: unconformity at the top of the syn-rift deposits; U2: main unconformity recognized within the postrift succession. For the legend, see Figure 6. (b) Part of the depth-migrated multichannel seismic reflection profile MS-119 crossing the Northern Malta graben and interpreted line drawing (location in Figure 2). Vertical exaggeration about 3X. U1: unconformity at the top of the syn-rift deposits; U2: unconformity recognized within the postrift succession. For the legend, see Figure 6.

into an upper undeformed part and a lower folded-faulted part separated by an unconformity (U2 in Figures 6 and 7(a)). The upper succession, up to 250-300 m thick (around 0.3 s TWT), consists of horizontal reflectors with onlap terminations against the basal unconformity. The lower succession, up to over 500 m thick (0.48 s TWT), is in turn divided into two parts by another minor unconformity (Figures 6 and 7(a)).

The Plio-Quaternary sedimentary fill of the LG seems to be affected by two main tectonic stages: (1) a rifting stage starting from the Early Pliocene that led to the opening of the LT and (2) a basin inversion stage.

The major evidence of this inversion is the folding that involved the syn-rift succession and part of the post-rift deposits producing a wide anticline (Figures 6 and 7(a)). The post-rift succession shows a progressive upward decrease in deformation. This anticline extends for about 6-7 km with a NW direction (Figure 4). Evidences of tectonic inversion (normal faults reactivated as reverse/transpressive faults) are visible along the faults affecting the central part of the sedimentary fill (Figures 6 and 7(a)).

The wide shallow bank located between LG and MG, comprising the Linosa Plateau and the Pelagian High (Figure 4), is a gentle syncline covered by a Plio-Quaternary succession with a maximum thickness of 0.52 s (TWT). The syncline might be the result of a gentle downward bending produced by the tectonic activity of the opposite-dipping normal faults bounding the bank. An almost 0.25 s (TWT) thick progradational sedimentary body interpreted as a Late Pleistocene fan delta [72] is also recognizable in the Linosa Plateau (Figure 6). The Linosa Plateau-Pelagian High block is affected by several normal faults with modest throws that were probably produced during the early stages of the opening of the grabens of the SCRZ (Figure 6). The Plio-Quaternary succession shows onlap terminations against the Messinian unconformity, allowing to infer that the Linosa Plateau-Pelagian High was a preexisting structural high.

The magmatism present in the LG is mainly concentrated along the margins of the graben. As in the case of the PG, the extent of the magmatism is almost certainly underestimated due to the lack of a seismic data coverage. The volcanic complex of the Linosa Island (Figure 4), with at least 96% of its

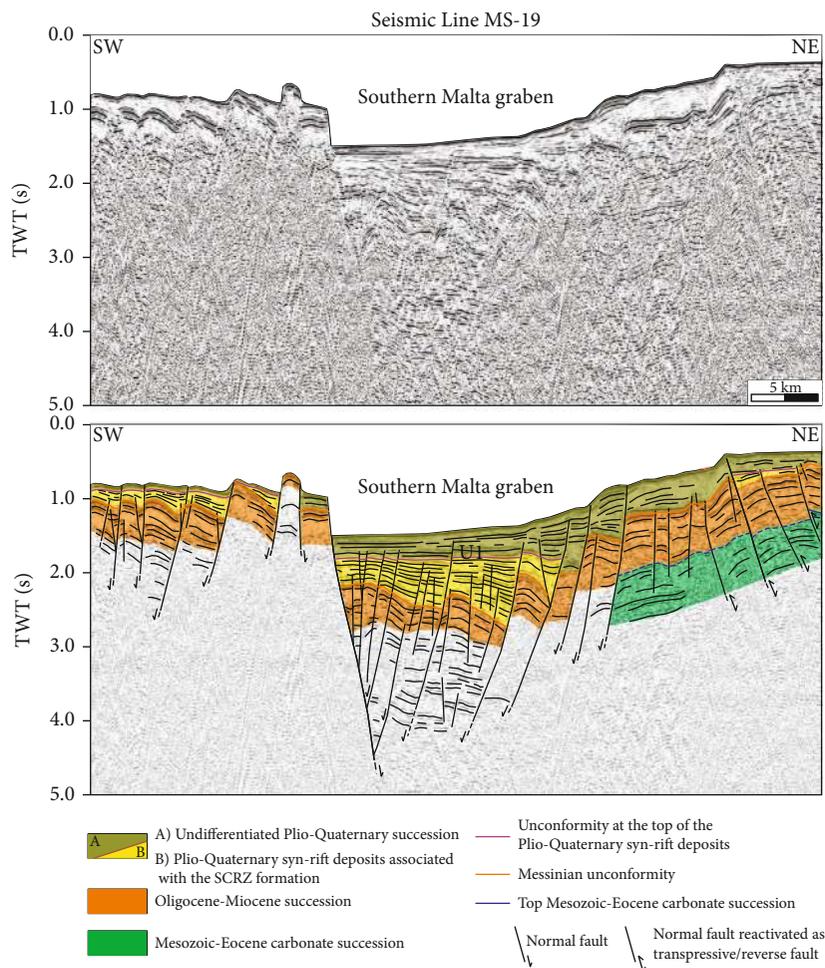


FIGURE 8: Multichannel seismic reflection profile MS-19 crossing the Southern Malta graben and interpreted line drawing (location in Figure 2). Vertical exaggeration about 2.5X. U1: unconformity at the top of the syn-rift deposits.

areal extent lying below sea level [51], is the main magmatic manifestation. On the basis of the seismic facies visible in the central part of the LG along the seismic lines MS-119 (Figure 6), consisting of a high-amplitude and chaotic body of limited extension overlapped by Miocene deposits, the possible presence of magma ascent along the axis of the LG can be inferred (Figure 4).

4.3.3. Malta Graben. It is possible to discriminate two sectors in the MG from a structural point of view (Figure 4): (1) a northern sector running from the Bannock seamount to the SE edge of the Pelagian High and (2) a southern sector comprised between the Pelagian High and the Maltese Islands. These two sectors are separated by a modest morphological high (“Tr” in Figures 3 and 4). The analysis of the available seismic profiles did not allow to recognize evidence of magmatic bodies neither within the MG nor along its margins.

4.3.4. “Northern Sector of the Malta Graben.” The northern sector of the MG, showing an almost symmetric shape, is tectonically controlled by high-angle, WNW- to NW-oriented normal faults dipping towards the graben and arranged in a staircase configuration (Figures 4 and 6). The maximum

thickness of the Plio-Quaternary sedimentary fill is around 2000 m (1.52 s TWT) (Figures 6 and 7(b)). The interpretation of the seismic line MS-119 (Figures 6 and 7(b)) shows that the lower part of the Plio-Quaternary succession of the northern sector of the MG is up to about 1300 m thick (about 0.85 s TWT) and is characterized by a growing wedge-shaped geometry with an increasing thickness and divergent fanning strata toward the SW. Based on these evidences, this part of the basin fill is interpreted as a syn-rift deposit related to the opening stage of the MG. In addition to the unconformity at the top of these deposits (U1), another minor unconformity is visible within the syn-rift succession (Figures 6 and 7(b)). A post-rift succession, up to 700 m thick (about 0.69 s TWT), unconformably covers the syn-tectonic deposits (Figures 6 and 7(b)). It is separated in a lower mildly folded part, up to 300 m thick (about 0.3 s TWT), and in an upper undeformed part, up to about 400 m thick (0.45 s TWT), by an unconformity (U2 in Figures 6 and 7(b)). The lower part of the post-rift succession possibly consists of syn-tectonic deposits associated with the formation of the wide anticline, developed for at least 25 km in a WNW direction (Figure 4), involving also the pre-Pliocene basement of the MG and the syn-rift succession (Figures 6 and 7(b)). The

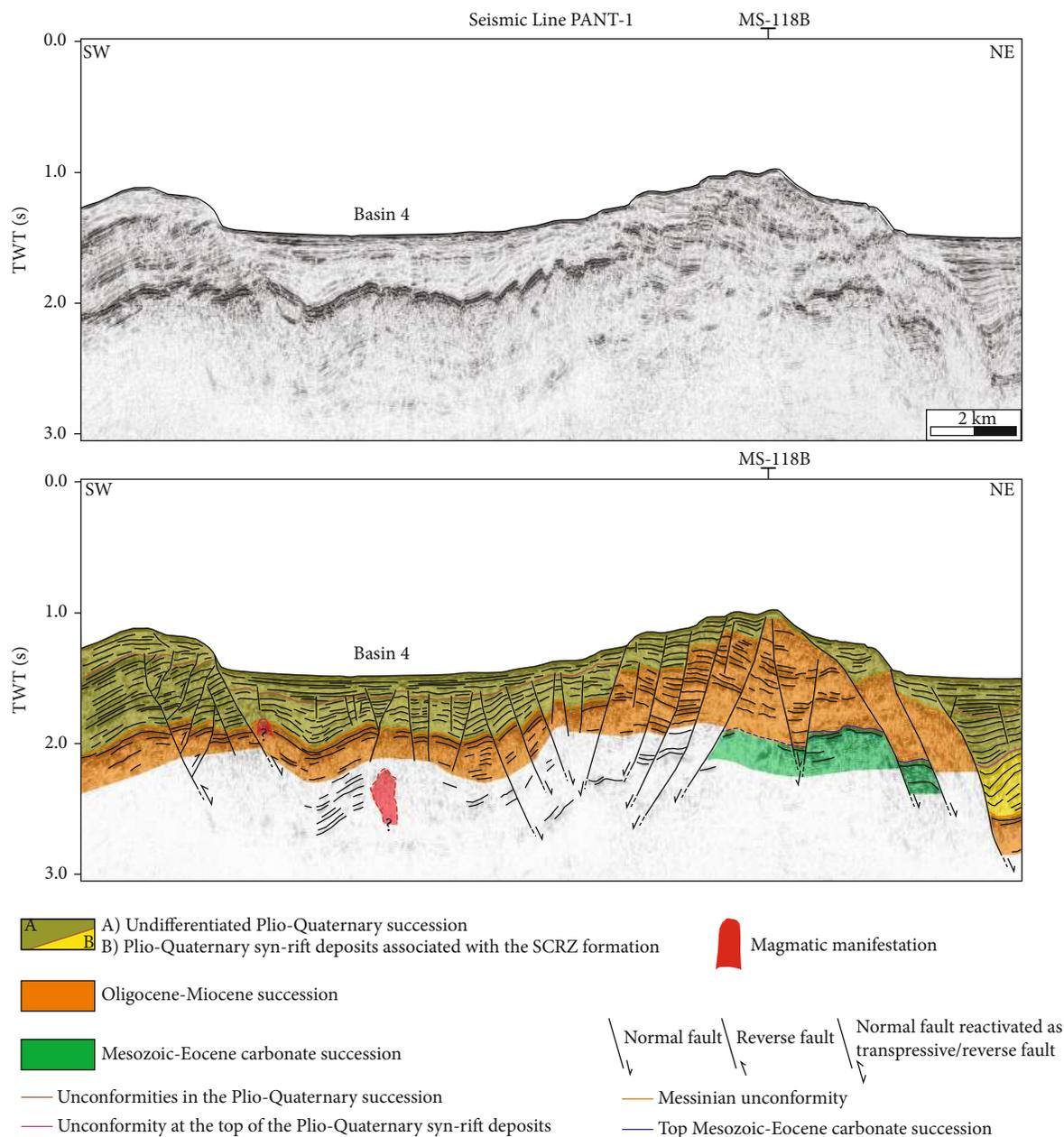


FIGURE 9: Part of the multichannel seismic reflection profile PANT-1 and interpreted line drawing (location in Figure 2). Vertical exaggeration about 4.5X.

anticline might be the result of the reactivation in compression/transpression of the normal fault located at the base of the northern margin of the MG. The sedimentary fill of the northern sector of the MG seems to be affected, as well as that of the LG, by two main tectonic stages: (1) a rifting stage starting from the Early Pliocene that led to the opening of the MG and (2) a second stage of basin inversion characterized by the development of a wide anticline and inversion of normal faults.

4.3.5. "Southern Sector of the Malta Graben." The southern sector of the MG has a southern steep margin tectonically controlled by a NW-trending and NE-dipping master fault, and a gently inclined northern margin affected by several

NW-oriented and SW-dipping normal faults (Figures 4 and 8). The maximum thickness of the Plio-Quaternary sedimentary fill is about 1500 m (about 1.3 s TWT) as seen along the seismic line MS-19 (Figure 8). The graben imaged in this line is over 20 km wide with a seafloor gently inclined towards the SW margin (Figure 8). A Plio-Quaternary sedimentary body with a wedge-shaped geometry characterized by an increasing thickness and divergent fanning strata toward the NE has been recognized; it has been interpreted as a syn-rift deposit. The latter is up to about 1100 m thick (ca. 0.9 s TWT) and is affected by several SW-dipping normal faults with vertical throws rapidly decreasing upwards (Figure 8). The unconformity at the top of the syn-rift deposits (U1 in Figure 8) is covered by a slightly deformed post-rift

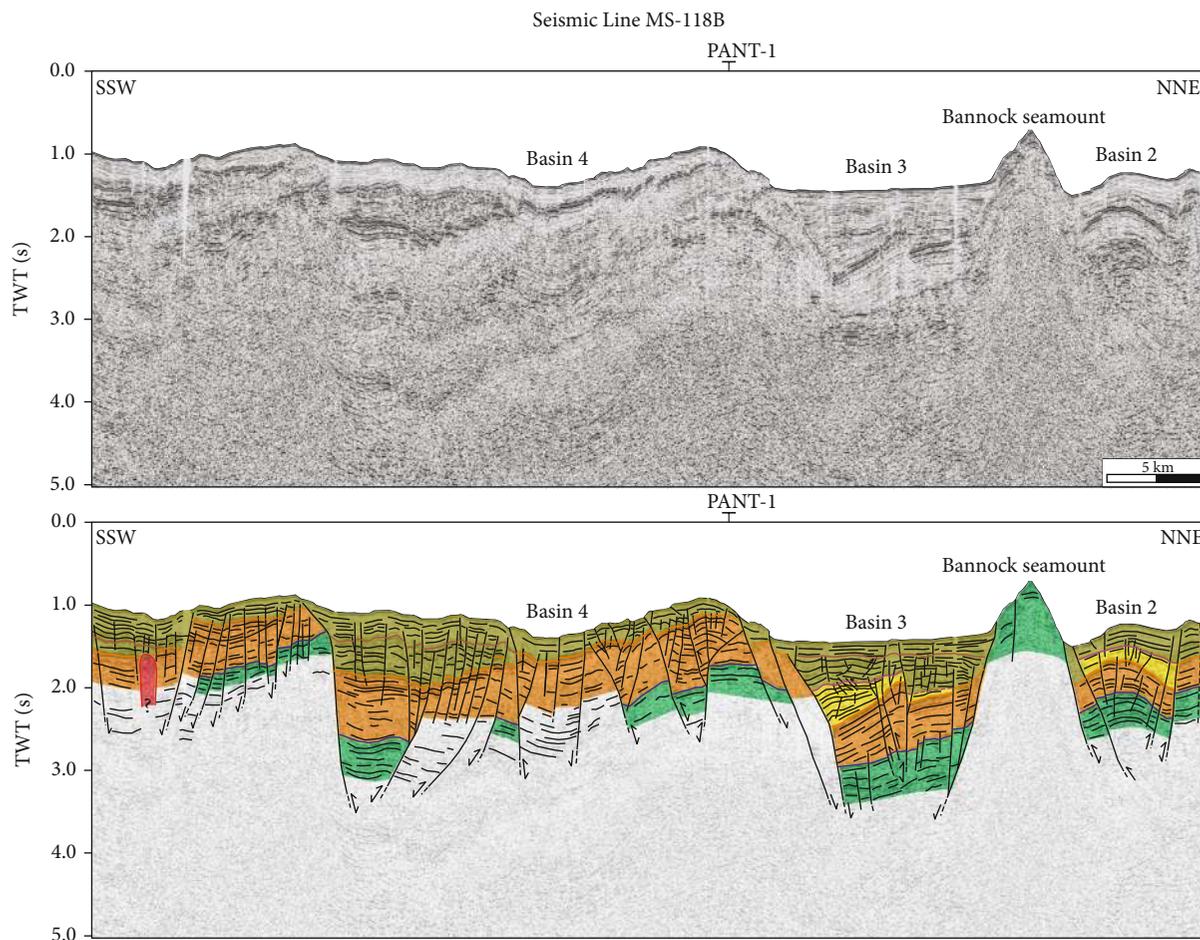


FIGURE 10: Part of the multichannel seismic reflection profile MS-118B and interpreted line drawing (location in Figure 2). For the legend, see Figure 9. Vertical exaggeration about 3.5X.

succession that thins toward the SW (Figure 8). The SW side of the graben is characterized by a series of half-grabens bounded by generally SW-dipping, high-angle normal faults (Figure 8). The lower part of the Plio-Quaternary fill of the half-grabens, which is characterized by a growth wedge-shaped geometry associated with thickening and divergent fanning reflectors down the dip slope of the tilted fault blocks, is interpreted as a syn-rift deposit. A different structural setting characterizes the NE margin of the MG, where evidences of positive tectonic inversion, consisting of high-angle and NE-dipping normal faults reactivated as reverse/transpressive faults, are recognizable (Figure 8). In particular, some faults maintain normal throws at depth changing to reverse offsets up-dip, generating a mild bending. Moreover, most of the inverted faults deform the seafloor.

4.4. Structural Setting of the “Separation Belt.” From south to north, the following seismic lines have been chosen to describe the structural setting of this area: MS-116, PANT-1, and MS-118B (Figure 2).

The seismic line MS-116 (Figure 5) shows the structural setting of the Basin 5 (B5 in Figures 2–4), bounded to the NW by a master fault that juxtaposes two sectors characterized by successions with significant differences both in thick-

ness and seismic facies. Moreover, this tectonic structure separates areas characterized by a different structural setting (Figure 5): (1) the PG to the west exhibits an extensional deformation and (2) the area located to the east of the master fault, that is the Basin 5, is mainly affected by a transpressive deformation. These structural evidences suggest that this master fault might be NNE-oriented and a strike-slip component of motion might be occurred along it (Figures 3 and 4). Seismic data suggest that this fault and the associated Basin 5 suffered a polyphase tectonic evolution (Figure 5). (1) It is probable that the Basin 5 developed during a first phase dominated by extensional deformation started from Early Pliocene. In fact, its Plio-Quaternary sedimentary fill consists of a lower part, interpreted as a syn-rift succession, characterized by a growth wedge-shaped geometry associated with a thickening down the south boundary fault (Figure 5). (2) A second stage characterized by the tectonic inversion of the preexisting basin produced by transpressive reactivation of the previous normal faults. The depocentre migrated from the southern margin of the Basin 5 towards its central part (Figure 5).

The NE-oriented seismic line PANT-1 (Figure 9) crosses the NW-SE-trending, relatively flat Basin 4 (B4 in Figures 2–4), located at the southeastern termination of the PG. The

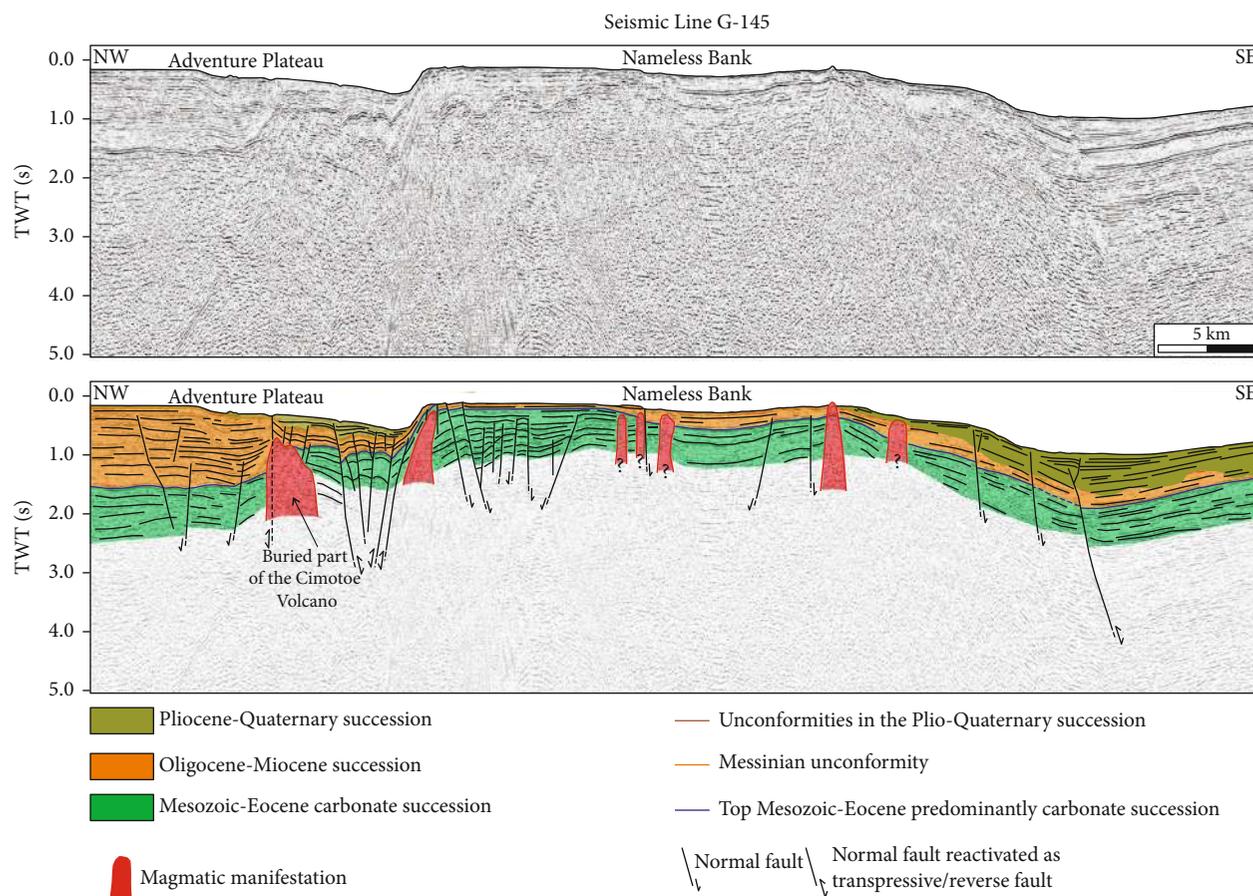


FIGURE 11: Part of the multichannel seismic reflection profile G-145 and interpreted line drawing (location in Figure 2). Vertical exaggeration about 2.5X.

southern margin of this basin is delimited by a structural high topped by a 0.78 s (TWT) thick Plio-Quaternary succession, which is thicker than that of the basin (Figure 9). The considerable thickness of Plio-Quaternary deposits visible in the southern margin of the Basin 4 allows to hypothesize that the original extension of this basin was wider than at the present day, and that the succession composing the southern margin was later uplifted. The Plio-Quaternary sedimentary fill of the Basin 4 consists of less deformed upper part, about 0.25 s (TWT) thick, unconformably lying on a lower deformed part that is 0.32 s thick (TWT) (Figure 9). The deformation is mainly generated by extensional faulting. The gentle folding visible in the central part of the basin might be related to the presence of an inferred buried magmatic intrusion. The position of the Messinian unconformity between the Basin 4 and its southern margin shows that the basin was probably uplifted by a tectonic inversion occurred along the WNW-oriented, NNE-dipping fault that bounds the Basin 4 to SW (Figures 4 and 9). Moreover, the different features of the seismic facies of the Plio-Quaternary succession between the Basin 4 and its southern margin allow to suppose that this boundary fault may have been reactivated as transpressive fault (Figure 9). The northern margin of the Basin 4 is a NW-trending structural high affected by nor-

mal faults with the same orientation and variable dip (Figures 4 and 9).

The NNE-oriented MS-118B (Figures 2 and 10) crosses, in its northern part, the Basin 2 (B2 in Figures 2–4) located to the north of the Bannock seamount. This basin is affected by a transpressional deformation that generated a positive flower structure, which deformed the entire Meso-Cenozoic succession and the seafloor, following the tectonic inversion of previous normal faults (Figure 10). The extensional phase that produced the Basin 2 is documented by the presence of a wedge-shaped body (syn-rift deposit) in the lower part of the Plio-Quaternary succession, which reaches a maximum thickness towards the NNE (Figure 10). The wide Basin 3 (B3 in Figures 2–4), located south of the Bannock seamount, hosts a deformed thick Plio-Quaternary succession (Figure 10). This basin is bounded by normal faults with considerable vertical throws, which seem to have been active for most of the Plio-Quaternary times as testified by the presence of drag folding along the fault planes (Figure 10). This extensional deformation is sealed by the uppermost unconformity recognized in the basin on which a less deformed succession rests (Figure 10). The lower part of the Plio-Quaternary succession of the Basin 3 shows a growing wedge-shaped geometry with an increase in thickness up to over 0.45 s (TWT)

and divergent fanning strata towards the northern boundary fault (Figure 10). This succession is interpreted as the syn-rift deposit associated with the opening of the basin. The syn-rift and postrift successions below the uppermost unconformity appear to be affected by transpressional deformation in the central part of the basin, where a set of high-angle faults arranged to form a positive flower structure that affects the seafloor is located (Figure 10). The main fault of this system exhibits a normal throw at the Messinian unconformity and at the top of the syn-rift deposits, and it seems to juxtapose parts of the basin characterized both by different thickness of the sedimentary succession and tectonic deformation (Figure 10).

The northern margin of the structural high that bounds the Basin 3 to the south is controlled by high-angle, NNE-dipping normal faults (Figure 10), which are imaged also by the seismic line PANT-1 (Figure 9). A different structural setting compared with the line PANT-1 is visible at the structural high located at the intersection between the lines PANT-1 and MS-118B (Figures 2 and 4). Evidence of extensional tectonics has been recognized along the line PANT-1 (Figure 9), while a transpressional deformation associated with the development of positive flower structures is visible along the seismic profile MS-118B (Figure 10). The juxtaposition of two zones characterized by a different tectonic deformation suggests the presence, in the SE part of the Basin 4, of a possible NE-trending strike-slip structure between them (Figure 4). Southward, the seismic line MS-118B crosses the southeastern termination of the Basin 4 (Figure 2), which is bounded by a WNW-trending, NNE-dipping, high-angle inverted normal fault (Figures 4 and 10). Also this fault juxtaposes Plio-Quaternary successions characterized by a significant difference in thickness and tectonic deformation suggesting, as already mentioned for the line PANT-1, that the Basin 4 was probably wider than at the present day. The zone located south of this fault exhibits an unconformity that separates the Plio-Quaternary succession in a poorly deformed upper part from a more deformed lower part, which disappears northward and consisting of folded discontinuous and chaotic reflectors (Figure 10). This deformation is produced by SSW-dipping inverted normal faults (Figure 10). This sector is interrupted by another EW-trending, NNE-dipping, high-angle normal fault (Figures 4 and 10) that juxtaposes Oligocene-Quaternary successions characterized by difference in thickness and tectonic deformation, suggesting also in this case a possible transpressional reactivation.

4.5. Structural Setting of the Area including the Eastern Margin of the Adventure Plateau and the Nameless Bank. The NW-oriented ministerial seismic line G-145 (Figures 2 and 11) was chosen to describe the structural setting of this sector. Based on literature information [7] and well data (Figure 2), the easternmost part of the Adventure Plateau consists of a thick siliciclastic succession (up to over 2000 m thick) associated with the deformed foredeep deposits of the Late Miocene Terravecchia Fm. Along the seismic line G-145, this succession is over 1.38 s (TWT) thick (Figure 11). The considerable thickness of the Terravecchia

Fm. might be partly due to the presence of internal thrusting, which however is not visible in the seismic profile. A remarkable thickness reduction of the Terravecchia Fm. is visible from the NW side to the SE side of the subvertical fault that cut the buried part of the Cimotoe Volcano (Figure 11) and bounds the SE margin of the Adventure Plateau (Figure 4). The formation of the Cimotoe Volcano might be related to the rising of magma through the identified fault. This fault, which produced a basin inversion, might be the southern prosecution of the CGFS. In fact, a similar tectonic structure was identified to the north by Civile et al. [7] in the area of the Graham Bank (Figure 4), where it produced a tectonic inversion related to the Early Pliocene transpressional reactivation of a NNE-trending Late Miocene normal fault. The NNE-oriented tectonic depression located between the Adventure Plateau and Nameless Bank (Figure 4) is filled by a thin Plio-Quaternary succession (0.28 s TWT) (Figure 11). This depression is probably a preexisting down-dropped area generated by Late Miocene normal faults, and connected to the Nameless Bank by a slope (Figure 11). The architecture of the reflectors in the eastern part of this depression suggests a possible positive tectonic inversion (Figure 11). The carbonate succession of the Nameless Bank is affected by normal faults and covered by a thin Cenozoic siliciclastic succession that thickens toward the SE (Figure 11). The Plio-Quaternary deposits are present only along the SE margin of the bank, where they show onlap terminations on the Miocene unconformity (Figure 11). A possible positive tectonic inversion is inferred for the NNW-trending normal fault located at the SE termination of the bank on the basis of the reflector configuration (Figures 4 and 11). The Nameless Bank probably represents an inherited carbonate structural high that was part of the foreland area adjacent to the Adventure foredeep.

The area including the eastern margin of the Adventure Plateau and the Nameless Bank is affected by diffuse magmatism at the Nameless Bank and in the tectonic depression that separates these two shallow shoals (Figure 4). The most impressive manifestations are the Cimotoe Volcano, positioned along the eastern margin of the Adventure Plateau, and the magmatic body, about 10 km long, located along the western side of the Nameless Bank.

5. Discussion

The foreland area of the Sicilian Channel hosts three deep tectonic grabens generated by a continental rifting process (SCRZ) (Figure 4). The ca. 300 km long and 100 km wide SCRZ is divided into a western sector hosting the PG and in an eastern sector where other two tectonic depressions are present (i.e., MG and LG). These Plio-Quaternary tectonic depressions, bounded by NW-trending normal faults, show significant morphobathymetric and structural differences (Figures 3 and 4). In addition, data analysis has shown that the distribution of the identified magmatic manifestations in the study area (Figure 4) is uneven and localized in specific areas. A widespread magmatism, mostly Quaternary in age, seems to be present in the PG and LG, whereas in the MG, no magmatic manifestations have been identified. The PG is the tectonic depression where the presence of

magmatism seems to be more abundant. The magmatism of the LG mainly occurs along the margins of the tectonic depression. The presence of buried magmatism along the axis of the LG has been only supposed on the basis of the seismic facies, but its areal distribution remains uncertain. The lack of magmatism along the MG cannot be considered as a reliable evidence due to the very low coverage of seismic data; however, a localized magmatism may be supposed. The widespread magmatism visible inside the PG might be connected to a greater amount of crustal stretching with respect to the extension occurred in the MG and LG.

The average sedimentation rates in the three tectonic depressions for the last 5.33 Ma (Miocene-Pliocene boundary) were estimated considering the maximum thickness of the Plio-Quaternary fill of the PG, MG, and LG. The sedimentation rate is ca. 22.5 cm/ka for the PG, 37.5 cm/ka and 28.1 cm/ka for the northern and southern MG, respectively, and about 41 cm/ka for LG. These values have been compared with the only available literature data for the grabens of the Sicilian Channel reported in Reeder et al. [79], which were based on few tens of meters long cores penetrated on the uppermost part of the Plio-Quaternary succession. These authors estimated a sedimentation rate ranging between >16 and 30 cm/ka.

The lower part of the Plio-Quaternary sedimentary fill of the grabens has been interpreted as syn-rift deposits (Figures 5–7). The age of the unconformity recognized at the top of syn-rift deposits was indirectly determined by considering the maximum thickness of the syn-rift succession in the three grabens (880 m for the PG, 1300 m and 1100 m for the northern and southern MG, respectively, and 1550 for the LG), and the sedimentation rate was previously obtained. In particular, the sedimentary fill was deposited in about 3.9 Ma for the PG and southern MG, and in about 3.55–3.7 Ma for the northern MG and LG. As documented in the data description, the opening of the grabens of the SCRZ was synchronous, since Early Pliocene. The process of continental rifting ended around the Early Calabrian (1.4–1.7 Ma).

The recognition of syn-rift deposits in the lower part of the Plio-Quaternary succession of the basins 2, 3, and 5, located in the separation belt between the western and eastern sectors of the SCRZ (Figures 4, 5, and 10), allows to infer that at least during the first phases of opening of the SCRZ, the PG was in some ways connected with the MG to the north and with the LG to the south. Seismic data show that the post-rifting tectonic evolution of the western and eastern sectors of the SCRZ, including the LG and the northern MG, differs as follows: in the PG and in the southern part of the MG, the syn-rift deposits are covered by an undeformed post-rift succession (Figures 5 and 9), whereas in the LG and northern MG, the post-rift successions suffered a modest basin inversion developing anticlines and locally inverted normal faults (Figures 6 and 7). This positive tectonic inversion is sealed by an unconformity dated around the Latest Calabrian, considering the maximum thickness of the undeformed succession lying on this surface and the obtained sedimentation rate. In particular, the age ranges between about 0.7 and 0.96 Ma in the LG and northern MG, respectively. The kinematic decoupling between the western sector of the

SCRZ hosting the PG, and its eastern sector hosting LG and northern MG allows to infer the presence of a roughly NS-oriented regional lithospheric-scale discontinuity, as suggested by some authors [4, 10, 24], of which the separation belt represents the shallow manifestation. Another NE-oriented lithospheric-scale structure might separate the northern MG from the southern MG. This tectonic lineament, which is clearly visible along the southern termination of the Pelagian High and seems to form a morphological high between the two parts of the MG, may represent the southern extension of the Scicli-Ragusa Fault System (SRFS in Figures 1 and 4 and in the text) [80]. A right-lateral strike-slip motion was documented along this fault system for most of the Plio-Quaternary times, while a left-lateral motion was suggested for the last 0.85 Ma [81].

The separation belt extends from the Nameless Bank to the Linosa Island and shows an articulated morphobathymetry consisting of an alternation of basins and structural highs (Figure 3). On the basis of the age of the recognized syn-rift deposits, the opening of these basins was coeval and probably related to the opening of the grabens of the SCRZ. A tectonic inversion dominated by transpressional kinematics, which affected the former NW- to EW-oriented extensional structures, is clearly recognizable along the separation belt, except in its southernmost part (Figures 4 and 9–11). This tectonic stage produced positive flower structures that locally affect the seafloor. NNW- to NNE-oriented structural lineaments, with a probably prevailing strike-slip kinematics, have also been identified in the separation belt on the basis of morphobathymetric, tectonic, and seismic evidence (dashed lines in Figure 4). These faults separate zones affected by an extensional tectonics from zones dominated by transpressional structures. The current structural setting observed along the separation belt would be the result of the interaction between the NW-trending extensional structures produced during the rifting phase and the subsequent transpressional tectonics. This area is dominated by the presence of NW-trending tectonic structures, while few roughly NS-trending faults associated with a predominant strike-slip tectonics were identified by the available seismic data. The best evidence of the interaction consists in the inversion tectonics represented by NW-trending push-up structures.

It suggested that, during the rifting phase, the lithospheric discontinuity conditioned the SCRZ configuration at a regional scale leading to the development of the PG in the western sector and of the LG and MG in the eastern one. It is likely that a structural control of the SCRZ configuration was also induced by pre-existing zones with different rheology. In particular, before the development of the SCRZ, some predominantly carbonate structural highs were already present, such as the Adventure Plateau, the Nameless Bank, and the Linosa Plateau (Figure 4). The lithospheric-scale discontinuity seems to end against the Nameless Bank (Figure 4). The NNE-oriented tectonic depression located between the Nameless Bank and the Adventure Plateau is bounded by inverted Miocene normal faults and hosts several magmatic manifestations (Figures 4 and 11). These evidences and the position of the tectonic depression allow to consider this zone as the direct prosecution to the south of the CGSFZ.

In turn, it is suggested that the separation belt represents the further southward extension of the CGSFZ. A left-stepping of the CGSFZ positioned at the Nameless Bank is visible between the northern (i.e., between the Sicily coast and the PG) and southern (i.e., between the Nameless Bank and Linosa Island) parts of this structure. The left-stepping is probably related to the presence of the pre-existing carbonate Nameless Bank that, on the basis both tectonic evidence (i.e., reactivation in transpression of the NS-oriented normal faults bounding the bank to the west and east) and for the presence of a widespread magmatism (Figures 4 and 11), is involved in the CGSFZ. The northern part of the CGSFZ is dominated, since Early Pliocene, by a transpressional tectonics, while its southern part is affected by an evident transpressional deformation only after the opening of the PG, LG, and MG.

In support of the presented interpretation, new evidences have recently been provided by Palano et al. [82]. The authors, using a dataset consisting of geodetic, seismological, and seismic reflection data (sparker profiles), proposed the presence of an approximately oriented NS lithospheric fault system, characterized by a left-lateral strike-slip deformation, active volcanism, and high heat flow, and extended from the Sicily coast of Sciacca to the Lampedusa Island. This structure is considered the most active tectonic domain of the Sicilian Channel, and its central part coincides with the separation belt between the two sectors of the SCRZ.

In short, the tectonic evolution of the study area can be summarized in three steps. (1) Continental rifting process started since Early Pliocene, generating the PG to the west, and the LG and MG to the east of the CGSFZ. During this phase, extensional tectonics dominates also along the southern part of the CGSFZ, forming a series of small basins (identified as B1-B6 in Figure 4) that connected the PG to the LG and MG. (2) The rifting process ends in the Early Calabrian with the complete formation of the SCRZ. (3) After the rifting phase, the western and eastern (including LG and northern MG) sectors of the SCRZ followed a different tectonic evolution. The syn-rift deposits of the PG and southern part of the MG, separated by the northern part of the MG by the SRFS, were sealed by an undeformed postrift succession. The LG and northern MG were affected by a modest basin inversion that ends around the Calabrian-Middle Pleistocene boundary.

The proposed tectonic evolution for the central part of the Sicilian Channel has been tentatively linked to the geodynamic evolution of the Central Mediterranean since 10 Ma, as reconstructed by literature information (Figure 12).

The geodynamic evolution of the Central Mediterranean is the product of two first-order coexisting processes: (1) the Africa-Eurasia oblique convergence and (2) the tear of the Tyrrhenian slab.

- (1) According to geological reconstructions [83, 84], the Africa-Eurasia relative motion has maintained relatively steady, between 5 and 7 mm/yr and with a NW-NNW direction, during the past 10 Ma (Figure 12)

- (2) In Northern Tunisia, a change of the geochemical signature of the magmatism between 10 and 8 Ma was interpreted as due to slab break-off and lateral tearing, producing mantle return flows around the ruptured slab [85]. Analogously, the (Na)-alkaline basalts of Ustica in the southwestern Tyrrhenian Sea probably mark a further episode of slab break off between 6 and 4 Ma [86, 87]. The present-day absence of a slab along the African margin from Tunisia to Calabria is also supported by seismic tomography models [88–90]

During the Late Miocene (10–8 Ma) (Figure 12(a)), the Sicilian Channel was a foreland area with respect to the Sicilian-Maghrebian thrust front [16], and it was characterized by the presence of several carbonate structural highs (e.g., Adventure Plateau, Nameless Bank, Linosa Plateau, Madrepora Bank, and Hyblean Plateau) (Figure 12(a)). At the same time, the opening of the Tyrrhenian back-arc basin began in its northern part [91]. Moreover, the opening of the Algero-Provençal Basin was accomplished, and the Sardinia-Corsica continental block reached its present-day position, in built with the Calabro-Peloritani continental block [92, 93].

During the Latest Miocene-Early Pliocene (8–4 Ma) (Figure 12(b)), the subduction of the African plate was deactivated in the Sicilian Channel and North of Sicily inducing a rapid retreat of the Southern Apennines and Ionian slabs, and the opening of the Vavilov Basin [94–96]. This event also produced a re-orientation of the stress field and a change in the boundary conditions for the Central Mediterranean area. Sicily and Sicilian Channel became a transitional area between the eastward opening of the Tyrrhenian Basin and the slow relative NW movement of the African plate. It is suggested that this differential motion was accommodated along the Sicilian Channel by the development of a NW-trending right-lateral transtensional mega-shear zone that produced the grabens of Pantelleria, Linosa, and Malta (SCRZ), and determined the contemporary fragmentation of the foreland by the development of two roughly NS-trending regional-scale shear zones: the left-lateral CGSFZ and the right-lateral SRFS (Figure 12(b)). During this stage, the southern part of the CGSFZ induced a kinematic decoupling along the SCRZ leading to the formation of a western sector formed by the PG and an eastern sector characterized by the presence of the LG and MG. At the same time, the southern part of the CGSFZ was dominated by an extensional tectonics. The area between the CGSFZ and the SCRZ behaved as a northward migrating indenter that produced a clockwise rotation of the stacked tectonic units in Sicily [97].

In the Early Pleistocene (Figure 12(c)), the subduction in the Southern Apennines was inhibited by the entrance of the continental Apulian lithosphere at the trench. Consequently, the rifting of the Vavilov Basin ceased [96, 98]. The subduction process was only active in the Ionian domain with the retreat of the oceanic slab that induced the rapid SE migration of the Calabro-Peloritani continental block along two STEP faults [87]. This produced, in the Southern Tyrrhenian, the opening of the Marsili Basin [99]. Shortening in the Sicilian-Maghrebian chain ceased around the end of the Early

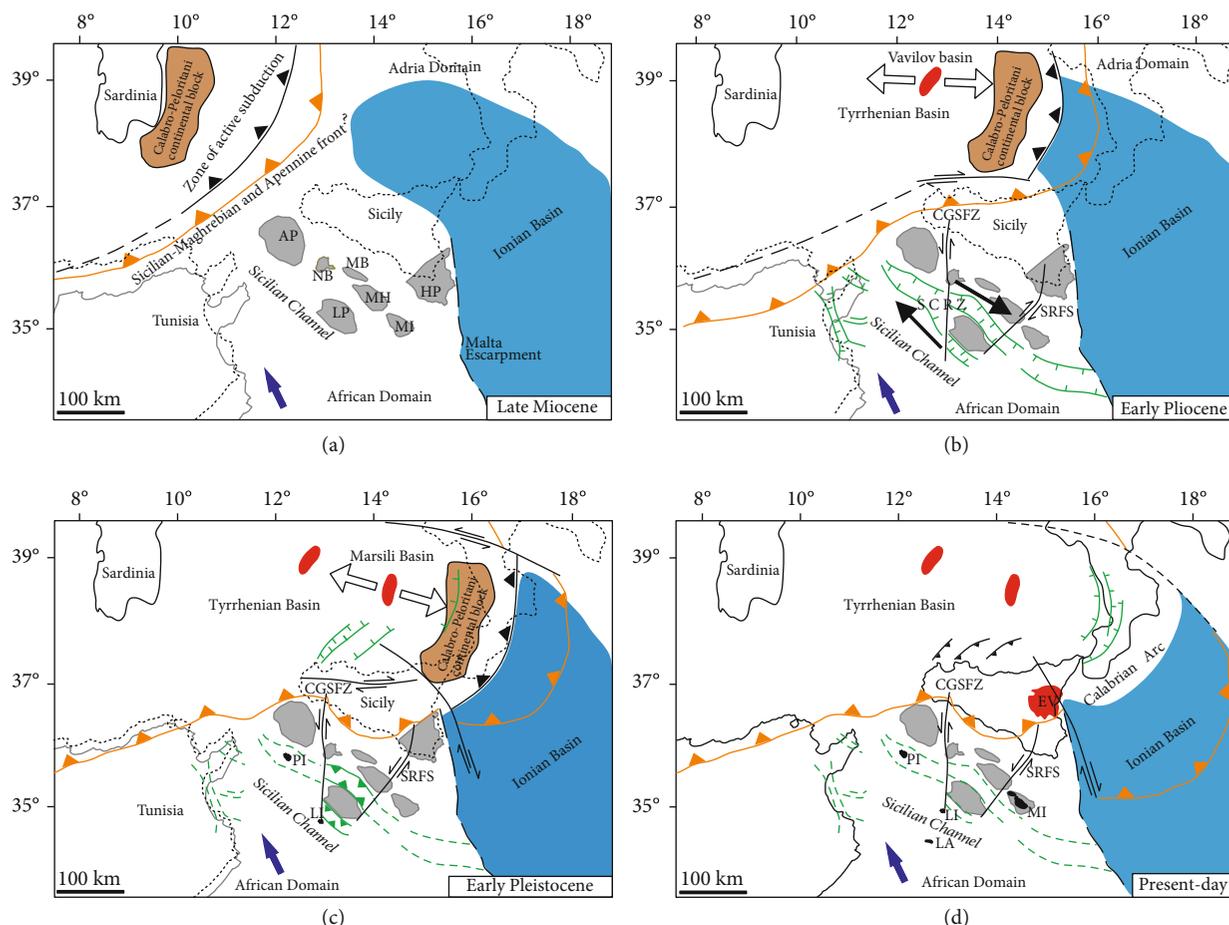


FIGURE 12: Simplified sketch of the tectonic evolution of the Sicilian Channel in the framework of the geodynamic evolution of the Central Mediterranean area since Late Miocene onwards: (a) Late Miocene: in this period, the Sicilian Channel was characterized by the presence of several predominantly carbonate structural highs (Adventure Plateau (AP), Nameless Bank (NB), Linosa Plateau (LP), Madrepora Bank (MB), Malta High (MH), Hyblean Plateau (HP), and Maltese Islands (MI)). Moreover, the Sicilian-Maghrebian thrust sheets were already emplaced. (b) Early Pliocene: the subduction zone between Tunisia and Sicily was deactivated, and this produced a reorientation of the stress field in the Central Mediterranean area that allowed a rapid retreat of the Ionian oceanic slab, with the opening of the Vavilov Basin, and the clockwise rotation of the Sicilian-Maghrebian thrust front. The Sicilian Channel became a transitional zone between the eastward opening of the Tyrrhenian Basin and the migration to NW of the African plate. This produced the development of a NW-trending right-lateral transensional mega-shear zone that generated the Sicilian Channel Rift Zone (SCRZ) affected by the left-lateral Capo Granitola-Sciacca Fault Zone (CGSFZ) and by the right-lateral Scicli-Ragusa Fault System (SRFS). (c) Early Pleistocene: the subduction along the Southern Apennines and the rifting of the Vavilov Basin ceased. The subduction process went on only in the Ionian Basin inducing the opening of the Marsili Basin. Shortening in the Sicilian-Maghrebian chain ceased around the end of the Early Pleistocene when the Gela Nappe reached its present-day position showing the inability of the Pelagian foreland to keep the underthrusting beneath the chain. The basin inversion in the central part of the SCRZ, located between the lithospheric discontinuities of the CGSFZ and SRFS, might be the result of the partial accommodation of the compressional regime produced by the NW relative motion of the Africa plate. (d) At the present day, the CGSFZ is still active, while the grabens of the SCRZ seem to be deactivated. EV: Etna Volcano; PI: Pantelleria Island; LA: Lampedusa Island; LI: Linosa Island. The large arrow indicated the orientation of the motion of Africa relative to Eurasia.

Pleistocene when the Gela Nappe reached its present-day position [16, 18]. This event highlights the inability of the Pelagian foreland to keep the underthrusting beneath the Sicilian-Maghrebian chain, and therefore the possible partial accommodation of the compressional regime by basin inversion in the central part of the SCRZ located between the lithospheric discontinuities of the CGSFZ and SRFS (Figure 12(c)). In the meantime, the SRFS may have changed its sense of

motion from right-lateral to left-lateral strike-slip, while a transpressional tectonics was active along the entire CGSFZ.

At present (Figure 12(d)), the Ionian slab seems to be at a final stage of development, as indicated by the presence of lateral and vertical tears [100]. In the Sicilian Channel, there is no evidence of a significant tectonic activity along the grabens of the SCRZ, while a recent tectonics is documented along the CGSFZ [7, 10, 11, 82]. Moreover, geodetic and

seismological evidences suggest that at present day, the Africa-Eurasia convergence is accommodated in the Southern Tyrrhenian [14, 101].

6. Conclusions

The interpretation of a considerable number of multichannel seismic reflection profiles, integrated with the analysis of bathymetric data, allowed to produce a detailed structural map of the still poorly known central part of the Sicilian Channel and to identify the main magmatic manifestations, both outcropping and buried. Moreover, an original Plio-Quaternary tectonic evolution of the study area has been proposed in the framework of the geodynamic evolution of the Central Mediterranean.

Data have shown significant differences in the morphology and structural configuration between the grabens composing the Sicilian Channel Rift Zone (SCRZ), which consists in a western sector hosting the Pantelleria graben (PG), and an eastern sector occupied by the Linosa (LG) and Malta (MG) grabens. Seismic data have also shown differences in the geometry of the Plio-Quaternary sedimentary fill of the troughs connected to a different tectonic evolution. In turn, the MG can be divided into northern and southern parts, separated by a NE-oriented tectonic lineament that has been interpreted as the possible southern prosecution of the Scicli-Ragusa Fault System (SRFS). A separation belt, characterized by an alternation of basins and structural highs, is present between the western and eastern sectors of the SCRZ. It has been interpreted as the shallow manifestation of the southern part of the tectonically active lithospheric-scale discontinuity Capo Granitola-Sciacca Fault Zone (CGSFZ), which has been already documented to the north from the Sicily coast to the Graham and Terrible Banks. The presence of this NNE-oriented regional-scale structure developed from the coast of Sicily between Capo Granitola and Sciacca to Lampedusa Island, and crossing the SCRZ, has been confirmed by other authors also considering seismological, geodetic, and gravity data [10, 82].

The analysis of the Plio-Quaternary fill of the grabens has allowed to identify two main tectonic stages:

- (1) The presence of fan-shaped syn-rift deposits suggested that the opening of the grabens of the SCRZ was coeval, and started since Early Pliocene in the framework of a NW-oriented right-lateral transtensional mega-shear zone developed along the Sicilian Channel. The process of continental rifting ended around the Early Calabrian. During this phase, the extensional tectonics dominated also along the separation belt producing a series of small basins that connected the PG to those of LG and MG. During this rifting phase, the lithospheric-scale discontinuity conditioned the SCRZ configuration at regional-scale leading to the development of the PG in the western sector and of the LG and MG in the eastern one
- (2) Afterwards, the western and eastern sectors of the SCRZ follow a different tectonic evolution with respect to the central one. The syn-rift deposits of the PG and

southern MG were covered by a post-rift undeformed succession, while LG and northern MG suffered a modest basin inversion that ended around the Latest Calabrian time. The basin inversion was driven by the two lithospheric-scale discontinuities of CGSFZ and SRFS that induced a kinematic decoupling along the SCRZ. During this second stage, the CGSFZ was affected by a dominant transpressional tectonics that mainly produced positive flower structures. Shortening in the Sicilian-Maghrebic chain ceased around the end of the Early Pleistocene showing the inability of the Pelagian foreland to keep the underthrusting beneath the chain. The basin inversion in the central part of the SCRZ might be the result of the partial accommodation of the compressional regime produced by the NW relative motion of the Africa plate

At the present day, the grabens of the Sicilian Channel seem to be tectonically inactive, while the CGSFZ represent an active tectonic domain.

Data Availability

The seismic data used in the manuscript are available at the OGS –SNAP data management system (<https://snap.ogs.trieste.it>) doi:10.6092/SNAP.e94dbecc-6dc5-9e79-64ac-65dee0b11690.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Supplementary Materials

An image of the interactive velocity analysis and of the related velocity function performed in the Plio-Quaternary succession of the Pantelleria graben along the seismic line MS-116. An image of the seismic line MS-122 (prestack time migration version). An excel file containing the time vs. depth charts and the interval velocities computed for the Plio-Quaternary succession of the Malta and Linosa grabens; the values have been derived from the instantaneous interval velocity field obtained from grid tomography along the seismic line MS-119. (*Supplementary Materials*)

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