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The Pantelleria graben (Sicily Channel, Central Mediterranean): An example of intraplate ‘passive’ rift

D. Civile [a], E. Lodolo [a,*], D. Accettella [a], R. Geletti [a], Z. Ben-Avraham [b], M. Deponte [a], L. Facchin [a], R. Ramella [a], R. Romeo [a]

[a] Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS) — Trieste, Italy
[b] Dept. of Geophysics and Planetary Sciences, University of Tel Aviv, Israel

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ABSTRACT

We present new high-resolution swath bathymetric data and multichannel seismic profiles acquired in the Pantelleria graben, one of the three main tectonic depressions forming the Sicily Channel Rift Zone. This region experienced a Late Miocene–Early Pliocene continental extension with the development of NW-trending, fault-bounded troughs, later accompanied by widespread volcanic manifestations. Data support the interpretation that the Pantelleria graben evolution was dominated by two tectonic phases: A lithospheric-scale continental rifting (Early Pliocene), in which the whole graben was formed, and a successive phase (Late Pliocene–Pleistocene) characterized by a magma-assisted extensional mechanism. Ascending magmas within the graben floor seem to migrate from the S–E sector of the depression toward the N–W sector, which is almost entirely floored by igneous material, and where the volcanic edifice of the Pantelleria Island is emerged. The volcanic activity is presently concentrated north of the Pantelleria Island. The tectonic evolution of the Pantelleria graben, characterized by the chronological sequence of events: rifting-doming-volcanism, can be referred to as a ‘passive’ rifting model. Crustal stretching, and subsequent fault development and rifting within the Pelagian block, may have been controlled by slab-pull forces of the northward-subducting African slab.

1. Introduction

Continental rifts are zones of strong crustal extension, which overlie on thinned lithosphere, accompanied by vertical movements, presence of diffuse volcanic activity, and thermal subsidence. There are two extreme views of the driving mechanism of lithospheric extension referred to as ‘active’ and ‘passive’ rifting models on the basis of the relative timing of rifting and volcanism (Baker and Morgan, 1981; Turcotte and Emerman, 1983; Keen, 1985; Ruppel, 1995). In the ‘active’ rifting, the extension is produced by rising of a thermal asthenospheric mantle plume. This plume is responsible for doming and cracking of the lithosphere, and the observed tectono-magmatic sequence should be: doming-volcanism-rifting. The alternative model hypothesizes that the ‘passive’ rifting is produced by tensional stresses in the continental lithosphere, allowing hot mantle rocks to penetrate locally the lithosphere. In this case, the rifting is a passive response to a regional stress field and the chronological sequence would be: rifting-doming-volcanism.

In the central Mediterranean Sea, a rift zone (Sicily Channel Rift Zone, Fig. 1) developed between Sicily and Tunisia. It lies within the continental African plate in the foreland of the Apennine–Maghrebian thrust-and-fold belt, and is constituted by three principal tectonic troughs (Pantelleria, Malta and Linosa graben).

The presence of a rift environment in a foreland area in front of a collisional belt is not a common tectonic scenario. This explains why the rifting mechanism remains still uncertain, as well as its age and tectono-magmatic evolution. In addition, the sparse coverage of geophysical data in the Sicily Channel has impeded a detailed morphostructural mapping of the region.

In this paper, we present a detailed structural map of the western tectonic depression of the Sicily Channel Rift Zone – the Pantelleria graben – and constrain its opening time. This interpretation is based on the analysis of the available seismic profiles, integrated with new data (swath bathymetric mapping and three multichannel seismic reflection profiles). A possible tectono-magmatic reconstruction of the events that led to the formation and successive development of the Pantelleria graben within the general scenario of the central Mediterranean geodynamic evolution, is also proposed.

2. General tectonic framework of the Sicily Channel

The Sicily Channel is located in the northern part of the African continental plate called the Pelagian block (Burollet et al., 1978). It is filled with a 6–7 km thick Meso-Cenozoic shallow-water to basinal carbonate succession with intercalated volcanic rocks. The age and nature of the crystalline basement are poorly known although on

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* Corresponding author.
E-mail address: elodolo@ogs.trieste.it (E. Lodolo).

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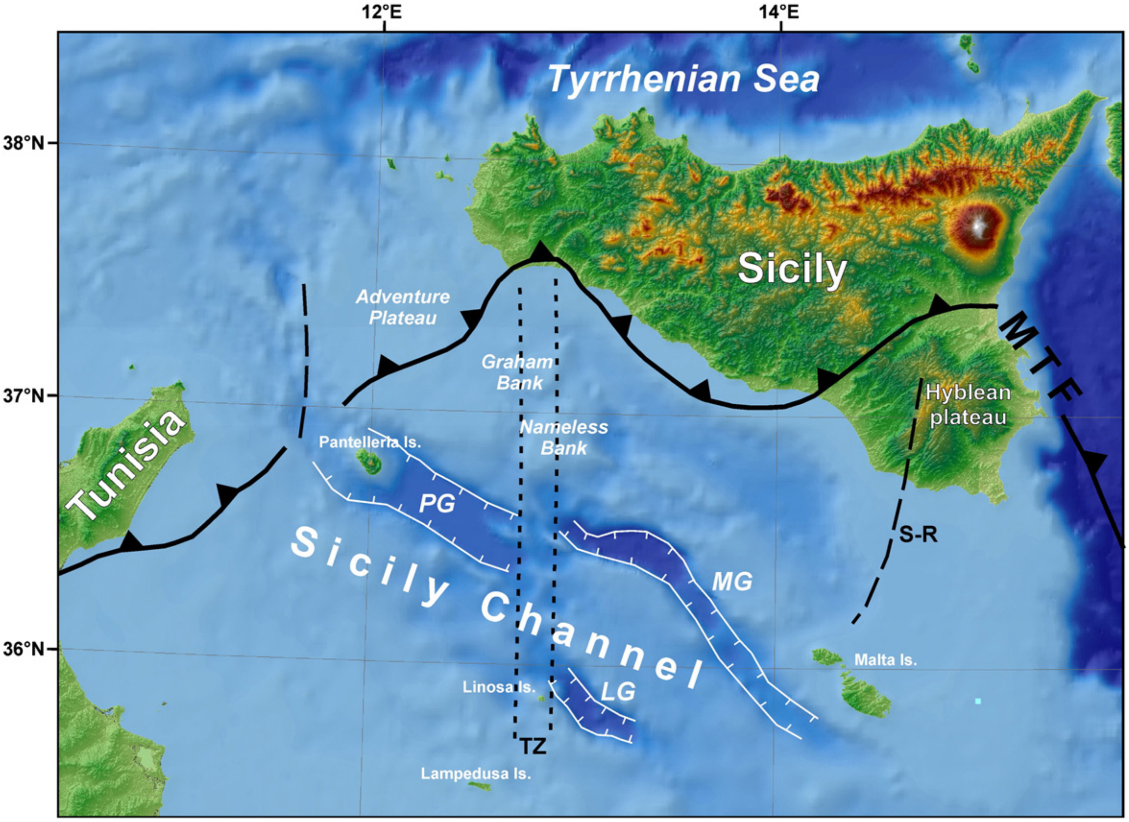

Fig. 1. Morphological map of the Sicily Channel and surrounding regions. Bathymetry from satellite-derived data (Smith and Sandwell, 1997), whereas topographic elevations are taken from the Shuttle Radar Topography Mission (SRTM) (http://www2.jpl.nasa.gov/srtm). The Pantelleria graben (PG), the Malta graben (MG), and the Linosa graben (LG) are the principal tectonic depressions of the Sicily Channel. The external deformation front of the Maghrebides–southern Apennines (MTF) has been taken from Argnani (2009). TZ indicates the broadly N-trending transfer zone discussed in the text, and S–R indicates the Scicli–Ragusa fault system.

mainland Tunisia, Precambrian granites and metamorphic rocks have been drilled (Burollet, 1991). Water depths of the Sicily Channel are in general less than 400 m, except in the three NW-trending depressions of Pantelleria, Linosa and Malta. These troughs, where water depths range from 1300 to more than 1700 m, are filled by Lower Pliocene–Pleistocene turbidites characterized by thicknesses of about 1000 m, 2000 m, and 1500 m in the Pantelleria, Linosa, and Malta graben, respectively, whereas on the continental platform the Pliocene–Pleistocene sediments consist of neritic deposits that do not exceed a thickness of 500 m (Maldonado and Stanley, 1977).

The Sicily Channel has been affected during Neogene–Quaternary (Finetti, 1984; Dart et al., 1993) by a process of continental rifting which produced several geologic features: (a) the Pantelleria, Malta and Linosa tectonic depressions, controlled by NW-directed sub-vertical normal faults clearly observable in seismic lines (Finetti, 1984; Torelli et al., 1991; Finetti and Del Ben, 2005); (b) two volcanic islands (Pantelleria and Linosa) and a series of submarine magmatic manifestations located substantially in the Adventure Plateau, Graham and Nameless banks (Peccerillo, 2005; Rotolo et al., 2006); (c) a thinning of the crust beneath the troughs up to about 17 km along the Pantelleria graben axis (Civile et al., 2008); (d) positive Bouguer anomalies ranging between +40 and +80 mGals (Morelli et al., 1975; Civile et al., 2008). The erupted volcanic products of the Sicily Channel have an alkaline to peralkaline affinity, and consist mainly of alkali basalts and hawaiites (Corti et al., 2006; Rotolo et al., 2006). The general petrologic features of the volcanism of the Sicily Channel point to an anorogenic magmatism similar to that found in continental rift areas (Corti et al., 2003). The volcanic activity occurred substantially during the Plio-Pleistocene (Calanchi et al., 1989; Rotolo et al., 2006), but historical submarine eruptions have been documented in Graham Bank (1831), when a submarine volcano was giving rise to an ephemeral island (Ferdinandea), and off the northwestern coast of Pantelleria Island (Washington, 1909).

Pantelleria Island, with its 83 km^2 of surface area, represents the largest extent of a composite emerged volcano of the Sicily Channel. The island is composed by volcanic products, erupted from about 300 to 3 kyr B.P. (Mahood and Hildreth, 1986), dominantly acidic, mainly peralkaline trachytes and peralkaline rhyolites (pantellerites) (Civetta et al., 1988; Orsi et al., 1991). Recent high-resolution mapping of the Pantelleria submarine area (Bosman et al., 2008) has revealed a complex sea-floor morphology characterized by the presence of several small volcanic cones principally concentrated to the N-W of the island. The seismic activity of the Sicily Channel is characterized by shallow events (depths generally less than 25 km), and low magnitude (usually from Mw 2 to 4). Most of the foci are located along a broad N–S oriented belt extending from Lampedusa Island in the south to the Graham Bank in the north. The seismicity seems to be absent along the Pantelleria graben (Civile et al., 2008).

The Sicily Channel Rift Zone has been interpreted in different ways. Some authors consider the tectonic depressions as large and discrete pull-apart basins involving deep crustal levels, developed along a major dextral wrench zone (Jongsma et al., 1985; Reuther and Eisbacher, 1985; Ben-Avraham et al., 1987; Boccaletti et al., 1987; Cello, 1987; Finetti, 1984; Catalano et al., 2009). Others interpret the rifting as due to mantle convections developed during the roll-back of the African lithosphere slab beneath the Tyrrhenian basin (e.g., Argnani, 1990). Lateral crustal density variations are invoked for explaining the remarkable segmentation along the central Mediterranean collision zone, which may lead to the formation of transform faults, as in the case of the Sicily Channel Rift Zone (Reuther et al., 1993). A mechanism of intraplate rift, related to NE-directed displacement of Sicily away from the African continent, has been also proposed (Illies, 1981; Winnock, 1981; Beccaluva et al., 1983; Finetti, 1984). Analogue modeling has shown that independent tectonic processes, i.e., the Maghrebian–southern Apennine accretionary prism and the Sicily Channel rift, may coexist and overlap each other, suggesting that plate boundaries are passive features rather than the driving mechanisms of plate tectonics (Corti et al., 2006).

3. Data acquisition

The original data presented in this paper were acquired in May 2009 by the *R/V OGS-Explora* in the Pantelleria graben, and in the western sector of the Malta graben. These data comprise: (1) High-resolution swath bathymetry collected with two keel-mounted Reson Multibeam Echosounders (*Reson Seabat 8111* for <400 m water depths, and *Reson Seabat 8150* for full ocean depths); the resulting multibeam map covers an area of 4455 km^2; (2) Three multichannel seismic reflection profiles for a total length of 170 km. Seismic equipment consisted of a 1600 m long, 96 channels *Sercel* digital marine streamer. Acoustic energy source was provided by two arrays of eight sleeve guns each, for a total volume of 39.4 l. Shot interval was 25 m, and sampling rate was 2 ms. A standard processing procedure was adopted to produce the final seismic profiles. These profiles have been integrated with Ministerial lines and MS and CROP profiles (Finetti, 1984; Finetti and Del Ben, 2005) (Fig. 2) to produce the structural map in Fig. 8.

4. Morphological setting of the Pantelleria graben and surrounding areas

Three main morphological domains can be recognized in the high-resolution swath bathymetric map of Fig. 3: The Pantelleria graben, the northwestern part of the Malta graben, and the separation zone between the two tectonic depressions, characterized by the Bannock seamount.

The Pantelleria graben is a large depression, with a broadly rectangular shape, about 90 km long and 30 km wide in the central and southern sectors; it broadens to about 40 km in correspondence of the Pantelleria Island. In the northern and southern sectors, the depression is divided into two sub-basins by fault-bounded morphological highs which are roughly elongated NW-SE. The northern morphological elevation is represented by the Pantelleria volcanic edifice. The Pantelleria depression shows linear NW-trending flanks controlled by faults with the same orientation, and a remarkable flat bottom which deepens gently from 1280 m at the base of the Pantelleria Island to 1330 in the S–E area (see Fig. 3). The plateau north of the Pantelleria graben gently inclines toward the trough, and is bounded by a steep slope up to 700 m high. Several circular craters in the sea-floor, possibly resulting from gas releases (pockmarks), and aligned with structural lineaments which parallel the Pantelleria graben axis, have been identified on the plateau (see blow-up of Fig. 3). The south-western flank of the plateau is morphologically more complex, with the presence of at least three distinct main structural highs that present an articulated morphology. The map does not cover entirely this southern sector of the Pantelleria graben, and for this reason its detailed morphostructural setting may be only inferred. The north-western part of the Malta graben is much narrower (about 15–20 km) than the Pantelleria graben. It is bounded by very steep faults that controlled the geometry of both flanks. The northern flank is morphologically more complex, and is segmented by a system of normal faults with different orientations: N–W in the western sector and broadly E–W in the eastern part. The sea-floor is generally flat and deepens gradually toward the S–E from 1400 m to 1730 m. The swath bathymetry map shows the presence of a 10–15 km wide and roughly N-trending zone separating the Pantelleria graben from the Malta graben. This zone is characterized by shallow basins of

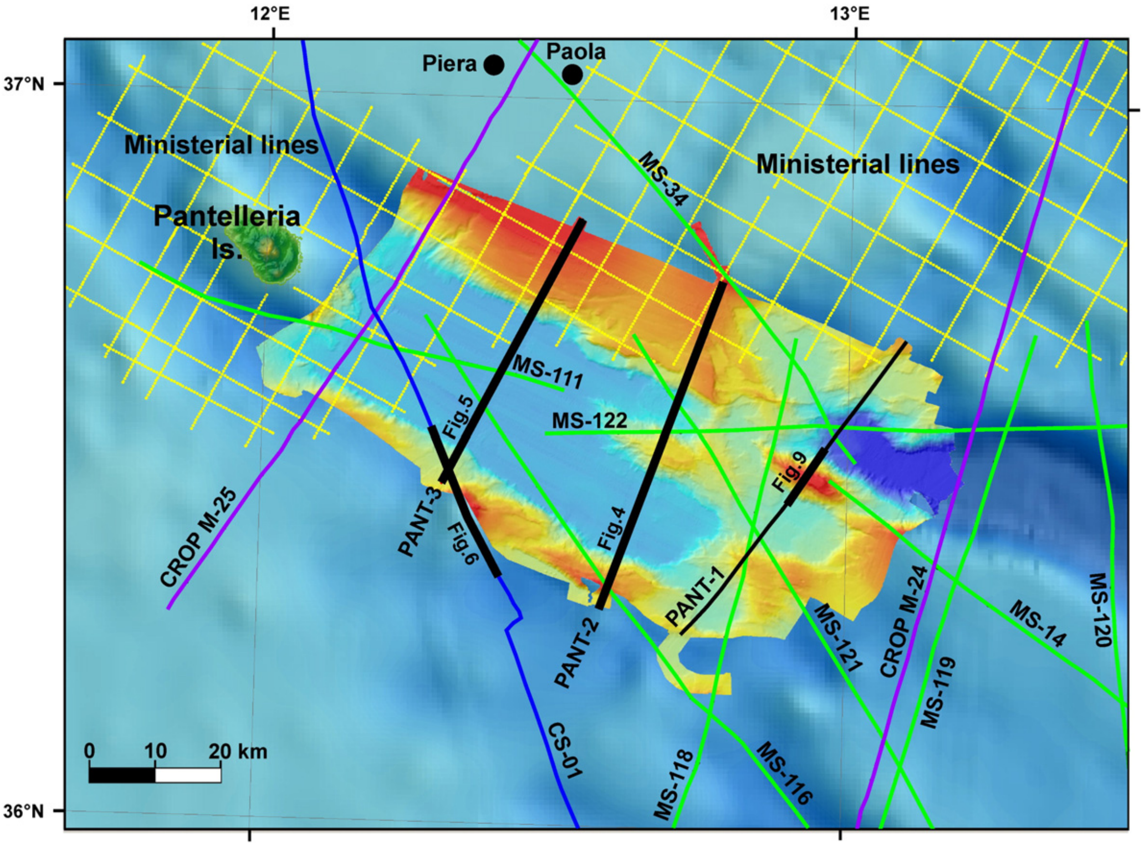

Fig. 2. Map of the multichannel seismic reflection profiles used in this study (with the corresponding figures), and location of the stratigraphic wells used for the seismostratigraphic correlations. Superposed is the swath bathymetric map obtained during the *OGS-Explora* cruise.

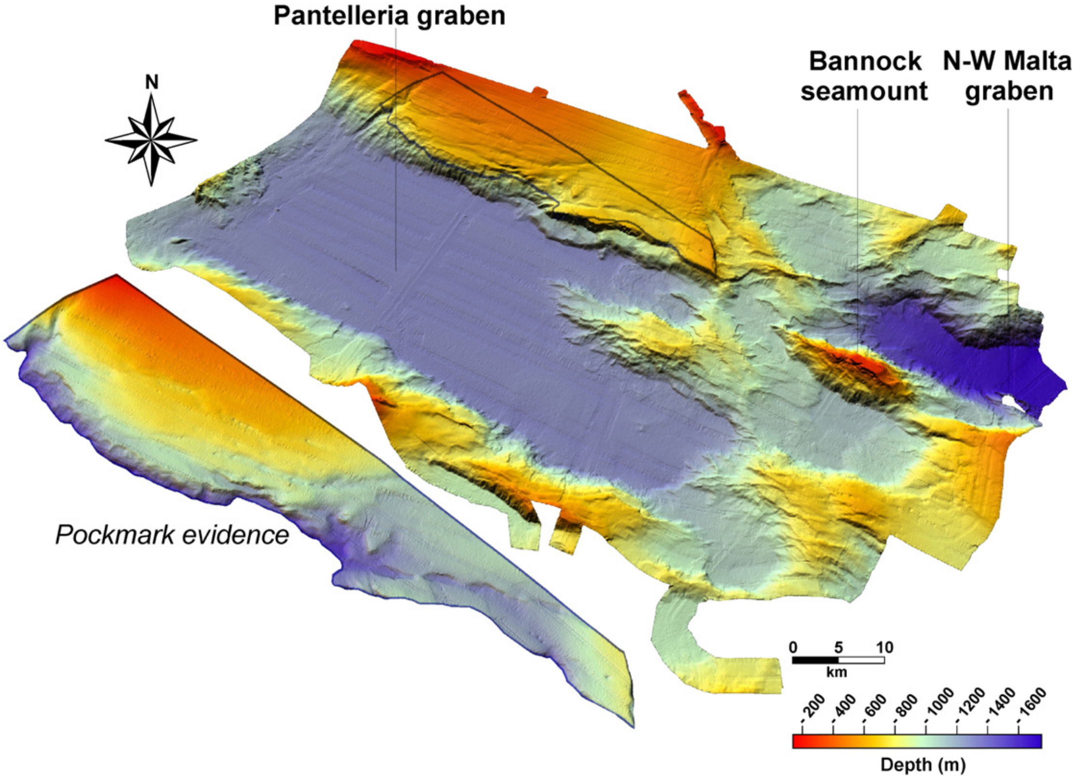

Fig. 3. High-resolution 3-D swath bathymetric image of the Pantelleria graben and surrounding areas. The thick black segment on the map indicates the perimeter of the pockmark area enlarged at the bottom of the figure.

different shapes and extensions, and NW- or roughly N-trending relieves. The main topographic relief is the Bannock seamount, situated close to the western edge of the Malta graben. The seamount is the largest subsurface feature of the Sicily Channel. It is about 800 m high, nearly 18 km long and 7 km wide, and its major axis is oriented NW-SE, like the axis of the Pantelleria graben. The flanks of the seamount are steep and symmetric, while the summit shows a nearly flat morphology with a maximum width of 1000 m and a maximum length of 3200 m.

5. Stratigraphy of the Pantelleria graben and surrounding areas

The stratigraphic interpretation of the seismic profiles was done integrating available wells (Piera and Paola, see Fig. 2 for location), all located some tens of kilometers to the north of the study area within the Pelagian plateau, and constrained by data from the literature (Finetti and Morelli, 1972; Dart et al., 1993; Corti et al., 2006). Exploratory wells within the Pantelleria graben are absent. The cores available for this area reach a maximum length of just over 31 m, and therefore provide a high-resolution record of the uppermost part of the succession only (Reeder et al., 2002). This analysis provided a schematic stratigraphic column for the Pantelleria area (see column in Fig. 7), and dates for the principal and most continuous horizons identified in the grid of seismic profiles.

The upper part of the stratigraphic succession is constituted by a Plio-Quaternary sequence, characterized by an interval velocity ranging from 1800 to 2500 m/s, with a variable thickness from 0 m, on some structural highs, to about 1100–1200 m within the Pantelleria graben. Seismic data show that the maximum thickness of the sedimentary fill remains constant within the Pantelleria graben. The lower part of the Plio-Quaternary sequence is composed of marls and carbonate mudstones that can be correlated with similar Early Pliocene deposits in Sicily (the Trubi Formation). This sequence, up to 250–300 m thick, is generally well recognized on seismic lines due to its characteristic semi-transparent facies. The remaining Plio-Quaternary succession is constituted by thin hemipelagic and turbiditic alternations of sands and muds with a seismic facies generally characterized by high-amplitude and continuous reflectors. The base of the Plio-Quaternary (top of Messinian) represents the main marker surface for the study area because it is generally well recognized in seismic profiles due to its high reflectivity. Siliciclastic deposits, upper Tortonian–Messinian in age (Terravecchia Formation), are present below the Plio-Quaternary succession. These deposits, with variable thicknesses from 1000 m to 1600 m, are constituted by sands, clay, and conglomerates in shelf and littoral facies. The Terravecchia Formation deposits lie over the Triassic–Miocene (Serravallian) succession of the Pelagian block, which is at least 5 km thick. This sequence is composed of Triassic dolomites followed up by Cretaceous–Miocene limestones, marls, and clay of a shallow-water to basinal environment. Jurassic deposits are generally absent or with a negligible thickness up to about 20 m. The Terravecchia Formation and the Pelagian block successions show discontinuous reflectors with mid- to high-amplitude in seismic profiles and an interval sound velocity ranging from 3000 to 5500 m/s. Several magmatic bodies, mostly intruded in the sedimentary sequences described above, have been recognized on the basis of the following observations: (a) shape and geometry of the bodies; (b) seismic facies characterized by limited acoustic penetration, with discontinuous and chaotic reflectors and a reflective and high-amplitude top; (c) presence of acoustic velocity jumps; (d) tilting of the reflectors around the magmatic intrusions.

6. Seismic profiles interpretation

Two NNE-trending multichannel seismic reflection profiles acquired roughly perpendicular to the main structural trends of the Pantelleria graben, are here presented. These data, combined with published profiles, are used to derive the general structural framework of the depression, analyze its depositional architecture, and propose a possible evolutionary history.

6.1. Pant-2 seismic line

This profile crosses the southern part of the Pantelleria graben, where it is divided into two sub-basins separated by a very symmetric structural high (Fig. 4). The southern basin is wider and deeper than the northern one, and the sea-floor of the southern basin is particularly flat. The S–W margin of the graben is expressed as a NW-SE elongated structural elevation characterized by a relatively steep, down-faulted flank on its southern side, and a gently inclined flank on its northern side. This structural high is bounded by two main normal faults oriented parallel to the graben axis and is covered by a Plio-Quaternary succession, up to 600–700 m thick, tilted toward the basin. This sedimentary cover is affected by several sub-vertical normal faults, with modest throw, that offset the sea-floor. The N–E margin of the graben is controlled by two main normal faults that present a total throw of about 800 m. Toward the plateau, the Plio-Quaternary succession, about 300 m thick, is relatively undeformed, and characterized by continuous and parallel reflectors. The structural high that separates the two arms of the Pantelleria graben is bounded by sub-vertical normal faults with throws of 500 m along the S–W side and more than 900 m along the N–E side. This structural elevation shows a strong variability in the thickness of the Plio-Quaternary (from <100 m to about 500 m), due to the action of normal faults with throws of some hundreds of meters, affecting the sea-floor.

In the S–W basin of the Pantelleria graben, the pre-Pliocene and the Early Pliocene sequences, correlated to the Trubi Formation, are deformed by several faults with modest offset, while the upper part of the Plio-Quaternary succession is undisturbed. The maximum thickness of the Plio-Quaternary fill is 1100 m. Buried magmatic bodies are recognized in the basin, on the basis of their seismic response. In particular, the centre of the basin is occupied by a magmatic intrusion similar in shape to an oceanic ridge, with the top located at about 550 m from the sea-floor. The N–E basin is not affected by magmatic intrusions but by several sub-vertical normal faults dipping toward S–W and with throws of some hundreds of meters. These faults produced a staircase configuration of the top of the Miocene sequence and a strong variability of the thickness of the Plio-Quaternary succession (from 1100 m, along the S–W margin, to 400 m, along the N–E margin). An antiformal geometry is recognized in the central part of the basin fill, which could be caused by a tectonic reactivation as reverse fault.

6.2. Pant-3 seismic line

This profile crosses orthogonally the northern sector of the Pantelleria graben (Fig. 5) and shows the entire geometry of the rift flanks and the basin fill. The two margins of the Pantelleria graben have different structural settings. The S–W margin has a structural relief that shallows at about 250 m water depth, as imaged by the seismic profile CS-01 (Fig. 6). At the base of the northern margin, there is a V-shaped basin filled up by a thick (up to 1400–1500 m) Plio-Quaternary succession. This significant sedimentary thickness may be the product of a rapid erosion of the structural high, suggested by both the flat top of the structure, and the lack of Plio-Quaternary deposits at its top. This may be explained by a shallow-water or sub-aerial exposure for a relatively long period. Vertical tectonics associated with rifting is common along the flanks of a depression: similar structures within the Sicily Channel are represented by the Malta Islands, interpreted as the emerged part of a composite horst structure. The V-shaped basin was probably formed by a counter-clockwise rotation of a basement block

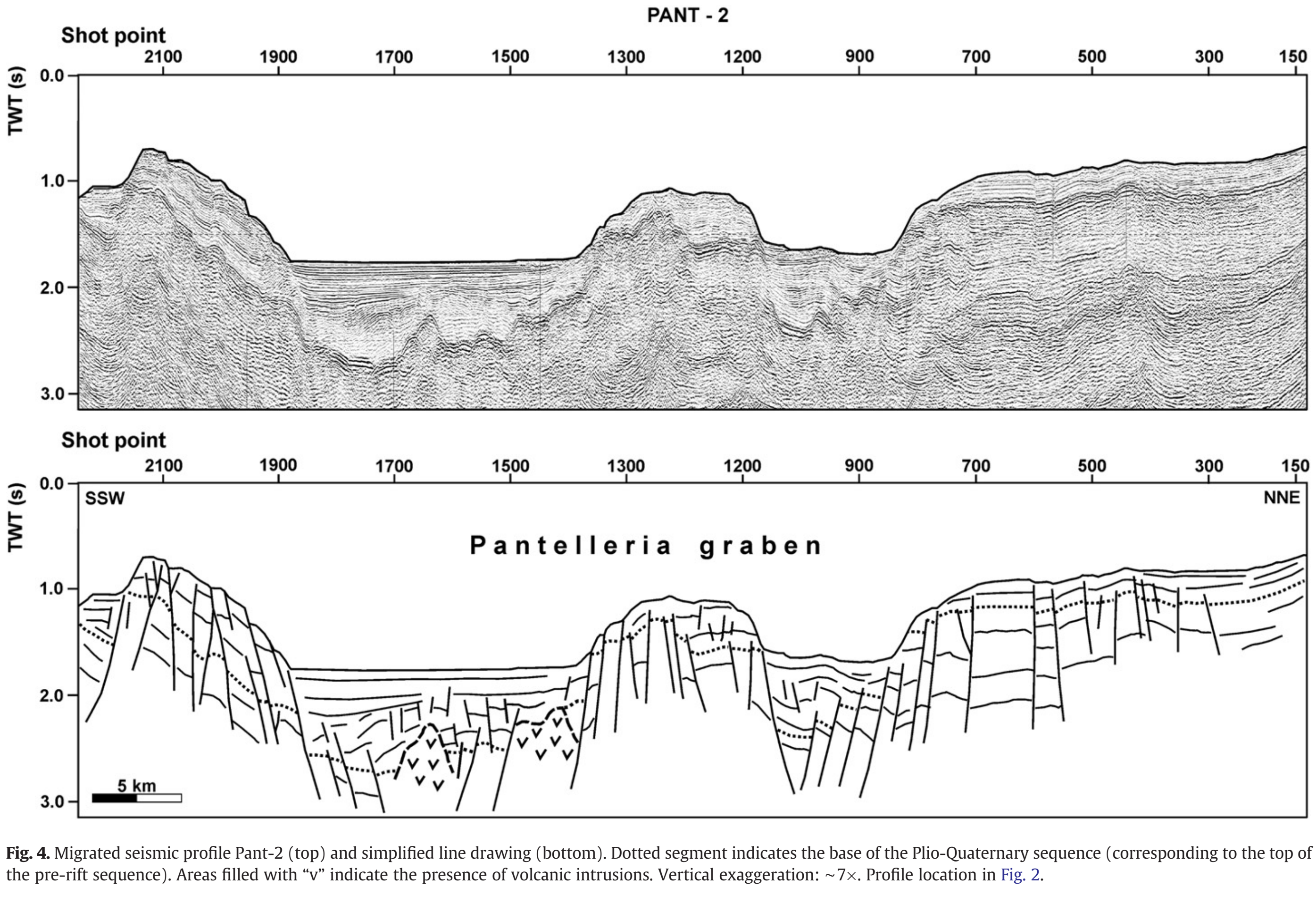

Fig. 4. Migrated seismic profile Pant-2 (top) and simplified line drawing (bottom). Dotted segment indicates the base of the Plio-Quaternary sequence (corresponding to the top of the pre-rift sequence). Areas filled with "v" indicate the presence of volcanic intrusions. Vertical exaggeration: ~7×. Profile location in Fig. 2.

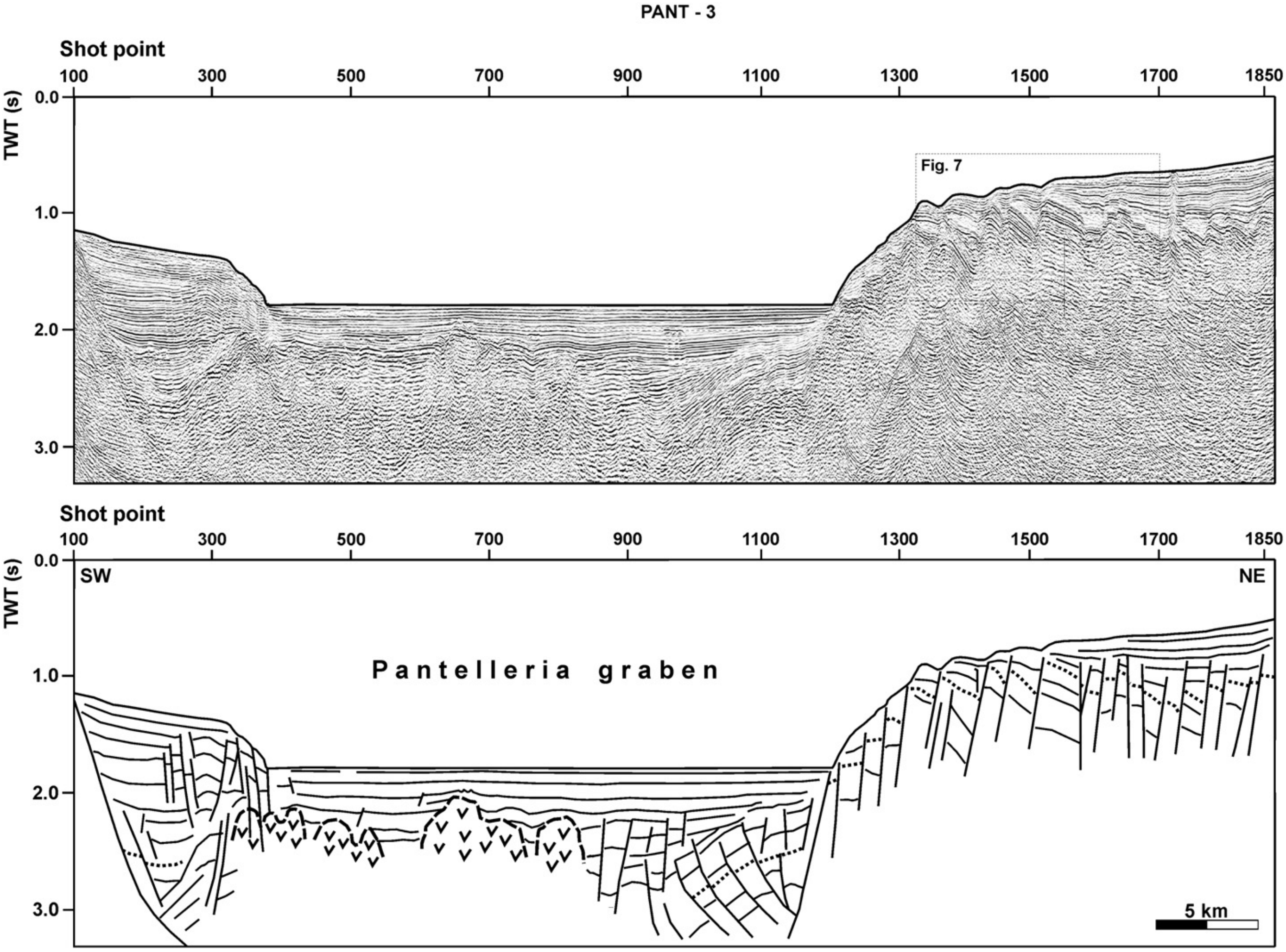

Fig. 5. Migrated seismic profile Pant-3 (top) and simplified line drawing (bottom). Dotted segment indicates the base of the Plio-Quaternary sequence (corresponding to the top of the pre-rift sequence). Vertical exaggeration: ~7×. Box indicates the blow-up presented in Fig. 7. Profile location in Fig. 2.

along a N–E dipping listric normal fault. Plio-Quaternary deposits that fill the basin are deformed by several faults with modest offsets, which affect the sea-floor in the frontal part of the relief where a gentle antiformal geometry is also recognized. This geometry could be the result of local reactivation of normal faults as reverse faults. The platform north of the N–E margin presents a relatively flat surface, gently inclined toward the depression. The Plio-Quaternary succession thins from 600–700 m to 100–200 m toward the Pantelleria graben. This margin, which is limited by a border fault with a throw of about 600–700 m, is structurally characterized by a domino-style configuration, with half- and full-grabens separated by an array of sub-vertical normal faults with offsets of a few hundred meters, and covered by a relatively undeformed Late Pliocene–Quaternary sequence (Fig. 7). Shallow and widespread magmatic bodies, covered by undeformed Plio-Quaternary deposits up to 250–350 m thick, mask the base of the Plio-Quaternary succession within the central and southern part of the graben. A Plio-Quaternary succession up to 1100–1200 m thick is recognized within the N–E part of the depression. Here, under about 500–600 m of mostly undeformed deposits, an array of inclined antithetic faults, involving the lower part of the Plio-Quaternary succession and pre-Pliocene deposits, has been recognized. The deformed succession shows a general tilting toward the centre of the graben.

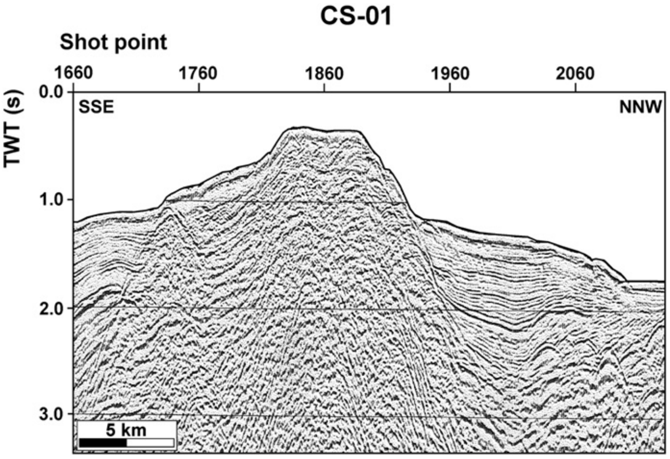

Fig. 6. Part of seismic line CS-01 (unmigrated seismic profile) showing the topographic high bounding to the southern part of the Pantelleria graben. Vertical exaggeration: ~7×. Profile location in Fig. 2.

6.3. Rift-related deposits

A detailed seismostratigraphic analysis conducted along the N–E side of the Pantelleria graben (see seismic line Pant-3) allowed us to recognize (see Fig. 7): (a) an undifferentiated Miocene pre-rift

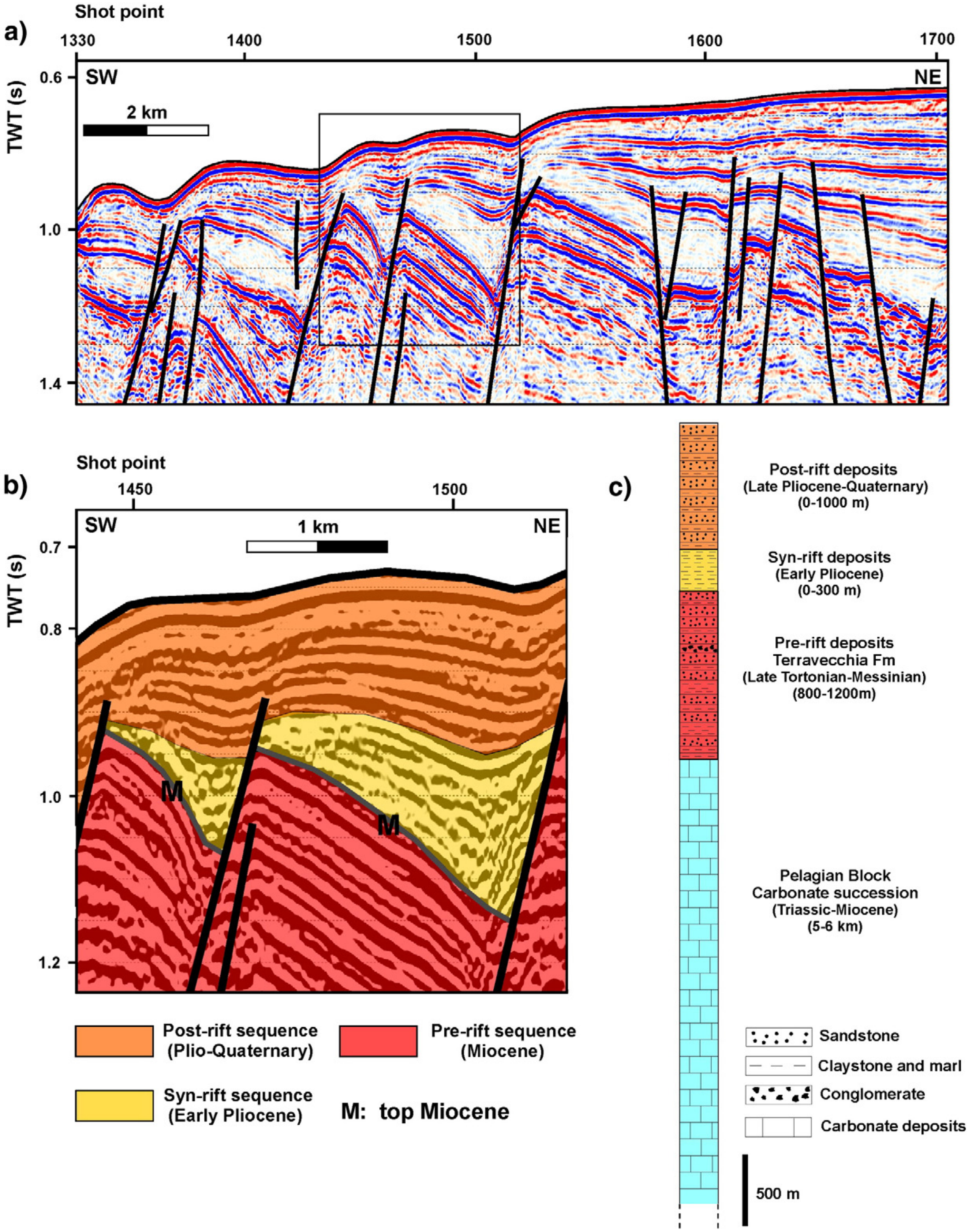

Fig. 7. (a) Example of the domino-style fault array structure characterizing the northern margin of the Pantelleria graben (see location in Fig. 5); (b) blow-up of the syn-tectonic sequences (see text for details); (c) simplified stratigraphic column of the Pelagian platform sedimentary sequences, derived combining the information from available exploratory wells.

succession, corresponding to the Terravecchia Formation, defined by sub-parallel reflectors that have been tilted by intervening normal faults. This succession does not show fault-related thickness changes; (b) a syn-rift sequence, mostly represented by the Early Pliocene deposits (Trubi Formation), which are only a small part of the half-graben fill. This sequence is acoustically semi-transparent and well recognizable along most of the seismic profiles. The syn-rift sequence shows a growth wedge-shaped geometry exhibiting an increasing thickness and divergent fanning strata down the dip slope of the tilted fault-blocks. This fanning geometry, along with thickening of syn-rift units toward the boundary fault, is produced by syn-depositional faulting. Similar characteristics of the syn-rift sequences have been described in several rifting settings (Mutter and Larsen, 1989; Prosser, 1993; Ravnås and Steel, 1998; Færseth and Lien, 2002); (c) a post-rift succession, probably Late Pliocene–Quaternary in age, characterized by sub-parallel reflectors that drape the morphology below.

7. Structural map

The analysis of the new seismic data, integrated with the available seismic profiles (Ministerial lines, CROP and MS seismic lines) has allowed us to derive a structural map of the Pantelleria graben and surrounding areas, and to map the occurrence of the magmatic manifestations (Fig. 8). The two flanks of the Pantelleria rift show a different structural setting. The S–W flank is controlled by a NW-trending rift-border fault and three principal elevations with different structural configurations (see the high-resolution bathymetric map and the Pant-2 and Pant-3 seismic profiles). The N–E flank is less complex and is structured by NW-SE rift-border faults presenting high and steep slopes. The northern part of the Pantelleria graben, where the Pantelleria Island is located, is wider (by about 40 km) than the central and southern parts (by about 30 km). North of the Pantelleria Island, the Pantelleria rift rapidly narrows to about 10 km and is bounded by relatively gentle slopes trending NNW-SSE.

The study area is dominated by a NW-trending fault system characterized by lineaments up to tens of kilometers long, bordering the Pantelleria graben, the Malta graben and the Bannock seamount, with maximum normal offset up to 1 km and sub-vertical planes. The northern flank of the Pantelleria graben is characterized by a domino-style configuration with half-grabens separated by modest NW-trending lineaments. This configuration, where the total offset is distributed in several faults, has been recognized along several seismic profiles. Along the southern flank of the Pantelleria graben, where the domino-style is less evident, the extensional offset is mostly concentrated along the rift-border faults. Some roughly N-trending faults have been mapped just to the S–E of Pantelleria Island and in the sector which separates the Pantelleria graben from the Malta graben. This represents a complex structural belt, roughly trending N–S. This belt is about 10–15 km wide, and is constituted by a series of *en-echelon* tectonic lineaments with different lengths. A significant component of extension possibly accompanies these structures, considering the presence of some depressions which lie parallel to the main trend of the lineaments. Sub-vertical reverse faults, characterized by S–E dipping planes, have been observed in this sector to the north and east of the Bannock seamount. This structural high is bounded by sub-vertical normal faults and is characterized by a limited signal penetration (Fig. 9). The structural map also shows the distribution of the magmatic intrusions. The analysis of the seismic facies suggests that the Pantelleria graben was intruded by magmatic bodies emplaced during the rifting processes. The map shows that the magmatic activity is progressively more diffuse moving from S–E to N–W up to Pantelleria Island. The emerged part of the island, with its submerged sector, constitutes a wide volcanic edifice covering an area of about 580 km^2 and almost occupying the entire graben. In the northern part of this edifice, several small cones have been detected (Bosman et al., 2008). The seismic analysis also shows that the magmatic bodies progressively shallow along the Pantelleria graben axis from S–E to N–W. The top of the magmatic manifestations range from 500 to 600 m below the sea-floor in the southern part of the Pantelleria graben, to 250–400 in the northern part, up to the emerged Pantelleria volcano.

8. Model of the Pantelleria rift evolution

The data presented support the interpretation that continental rifting in the Pantelleria region evolved in two different phases (Fig. 10). The main temporal constraint is the Early Pliocene age of the syn-rift succession identified along the N–E flank of the graben: It indicates the beginning of the rifting process which caused fault-related collapse and block rotation.

During the first phase (Late Messinian–Early Pliocene in age), the Pantelleria graben reached a final shape and geometry similar to the present-day configuration. This is also suggested by the maximum filling thickness that is nearly constant along the graben axis. Before the lithospheric stretching, short *en-echelon* NW-trending fault segments, with modest normal offset, developed. Subsequently, during Early Pliocene, long and linear extensional faults trending NW-SE, with offset of hundreds of meters, formed as a result of along-strike linkage of initially smaller fault segments. This type of evolution is shown by analogue rifting models and natural examples (McClay et al., 2002; Morley, 2002). Lithospheric thinning and subsidence of the rift depression was possibly accompanied by very localized and punctuated magmatic intrusions.

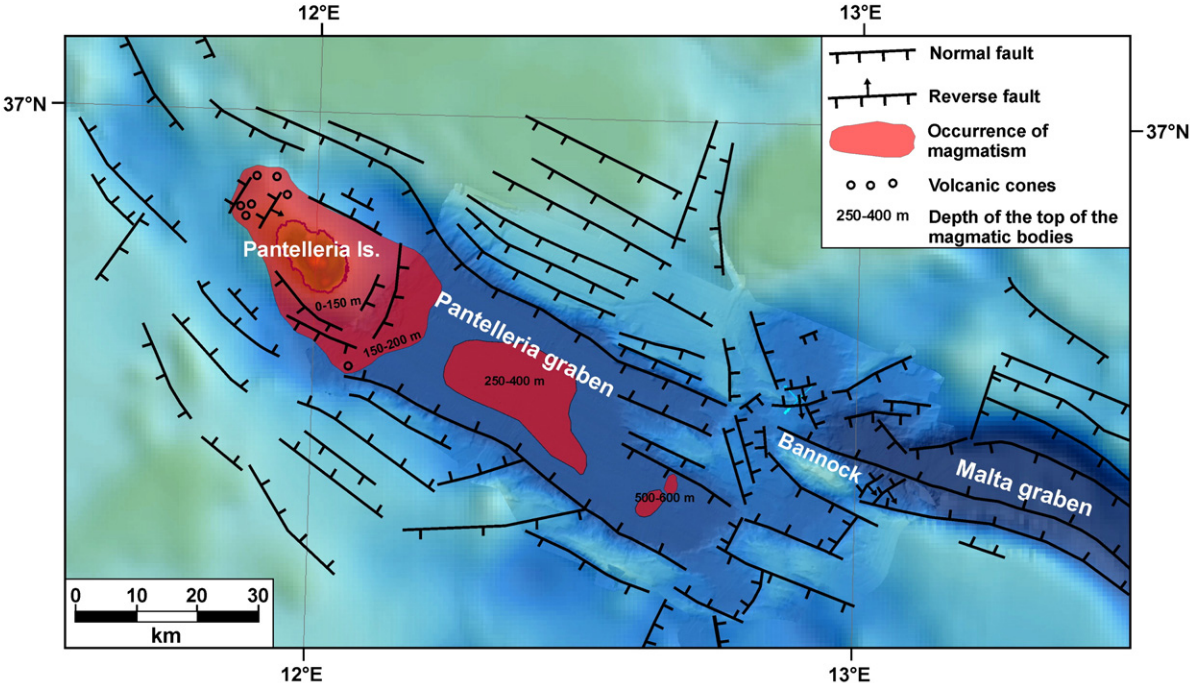

Fig. 8. Structural map of the Pantelleria graben and surrounding areas, and distribution of the magmatic bodies. The high-resolution swath bathymetric map is superposed to the satellite-derived data (Smith and Sandwell, 1997).

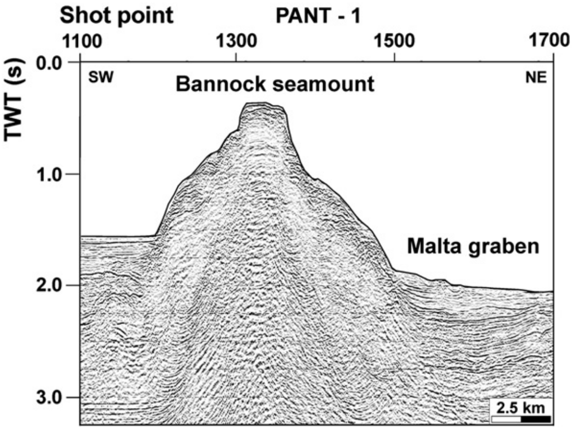

Fig. 9. Seismic image (migrated seismic profile) of the Bannock seamount, bounded by sub-vertical normal faults, and characterized by a very limited penetration. Profile location in Fig. 2.

In the second phase (Late Pliocene–Quaternary in age), the main boundary faults were deactivated, and magmatic processes became dominant. The data show in general that the sea-floor and the most recent deposits are not significantly offset by fault displacements, except in restricted zones along the southern margin of the Pantelleria graben, where modest superficial deformations seem to be present. The strong crustal stretching and the consequent decrease in the crustal load possibly generated a rapid Moho uplift along the Pantelleria rift axis, which reached a depth of 17–18 km beneath the southern part of Pantelleria Island (Civile et al., 2008). This activity triggered the abundant emplacement of magmas that progressively occupied a significant part the rift zone. Ascending magmas within the graben floor seem to migrate over time from the S–E sector toward the N–W sector, because seismic data show that the top of the volcanic intrusions shallows from S–E to N–W. The volcanic activity is presently concentrated only to the north of Pantelleria Island, where several small volcanic edifices have been observed (Bosman et al., 2008).

9. Discussion and conclusions

New data acquired across the Pantelleria graben and surrounding areas, integrated with the analysis of available seismic lines, have imaged the morphostructural setting of this sector of the Pelagian continental shelf, where a Late Miocene–Early Pliocene tectonic extension generated fault-bounded troughs, and favoured a widespread occurrence of Plio-Quaternary volcanism. Data analysis supports the interpretation that the Pantelleria graben developed from the Early Pliocene in two main tectonic phases. The time constraint for the rifting initiation has been inferred from the recognition of wedge-shaped syn-rift units within the northern flank of the trough, filled with deposits correlated to the Sicilian Trubi Formation.

During the first phase (Late Messinian–Early Pliocene), crustal stretching generated the complete structuration of the graben with a geometry similar to the present-day configuration, due to the action of NW-trending normal faults. Along these faults, some strike-slip component of motion has also been recognized. Different structural settings characterize the northern and southern margins of the Pantelleria graben: The northern margin is characterized by a domino-style configuration with an extensional deformation generated by several NW-trending normal faults; along the southern margin, the extensional deformation is concentrated along rift-border faults. The fault-dominated rift morphology seems to have largely ceased at the end of the first phase because only few faults with modest offset affect the shallower deposits and the sea-

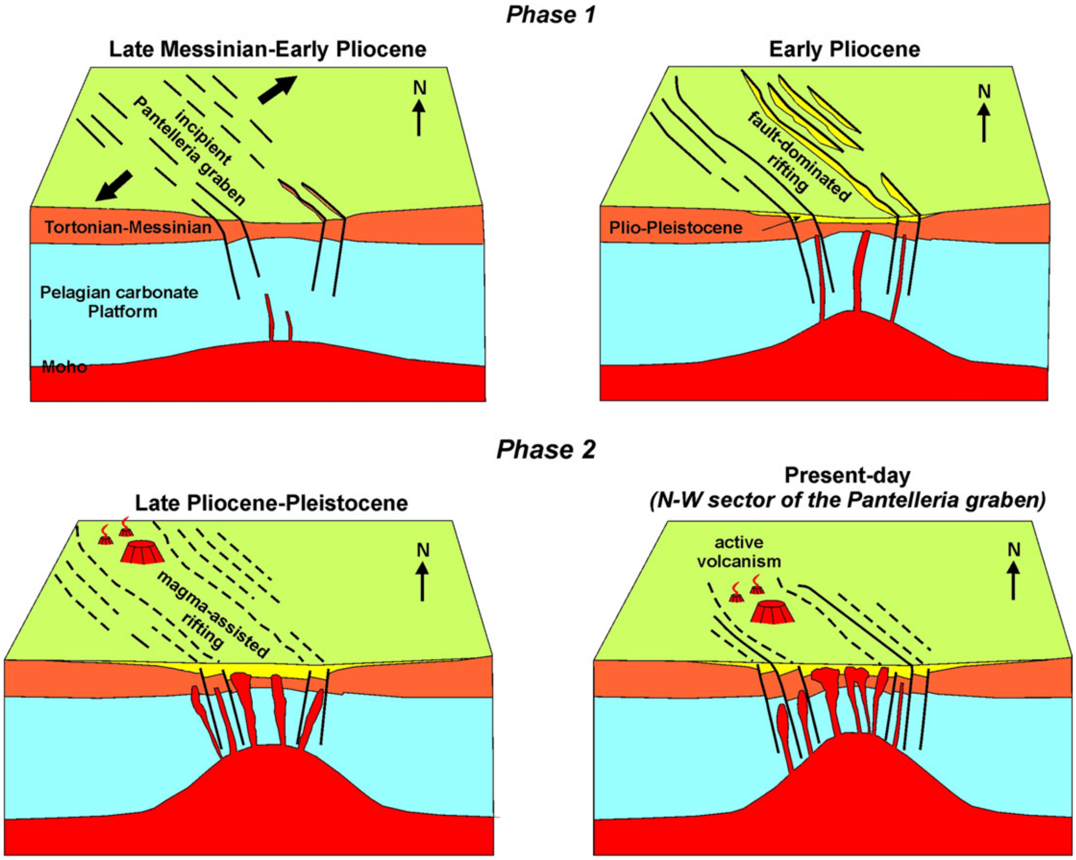

Fig. 10. Schematic model of the Pantelleria rift evolution showing the two principal phases that characterize the graben formation. See text for details.

floor. During the second phase, a significant and rapid uplift of the Moho was associated with a widespread volcanic emplacement within the graben, mostly concentrated in the northern sector of the trough where the extension was stronger. The magmatic activity seems to have migrated from S–E to N–W, as evidenced by: (a) the depth of the top of the magmatic manifestations along the Pantelleria graben, (b) the age of the volcanic products of the Pantelleria Island, and (c) the present-day volcanic activity located to the north of the island.

This evolutionary history as a whole documents a transition from fault-dominated rift morphology in the early extensional phase, toward a magma-assisted rifting during the final stage of continental break-up. This evolution, characterized by the chronological sequence: rifting-doming-volcanism, can be referred to as 'passive' rifting model, where the rifting process is a passive response to regional tensional stresses within the Pelagian continental lithosphere, allowing hot mantle rocks to rise. Several crustal and structure analogues may be found with the Main Ethiopian Rift, where a similar two-phase tectonic development has been proposed (Corti, 2009). This area is an ideal place to test break-up models because it formed in cratonic lithosphere with minor plate stresses (McClusky et al., 2003). Geophysical measurements, together with geological data, indicate a strong component of melt-induced anisotropy with only minor crustal stretching, supporting the magma-assisted rifting model in this region characterized by a thick, initially cold continental lithosphere (Kendall et al., 2005). Wide-angle seismic experiments across another continental extensional zone – the Baikal rift – have revealed the presence of a high-velocity zone beneath the axis of the rift, which can be associated with a magmatic layer intruded into the lower crust: this may explain the lack of Moho uplift across the Baikal rift (Nielsen and Thybo, 2009). In this case, the lithospheric thinning is compensated by magmatic emplacement during the main rifting phase, that has thickened the lower crust (Thybo and Nielsen, 2009).

The N-trending belt located in the central part of the Sicily Channel, interpreted as a lithospheric transfer zone (Argnani, 1990), may have acted as a boundary that constrained the location of the southern edge of the Pantelleria graben and its development within the Pelagian platform. It impeded the migration of rifting across this crustal discontinuity, possibly characterized by density/thickness crustal variations. A similar tectonic mechanism may be proposed for the other two depressions of Linosa and Malta, both structurally bounded at their western edges by the transfer zone, extending from Linosa Island in the south to the Graham Bank in the north. It is important to emphasize that most of the volcanic centres of the Sicily Channel (Linosa Island, Bannock seamount, Nameless Bank, Graham Bank) and earthquakes, are located within this belt (Argnani, 1990; Civile et al., 2008), where reverse faults have been also recognized from seismic data. The Bannock seamount is also located within this belt. The presence of roughly N-trending lineaments in the Sicily Channel has been observed by several authors (Reuther et al., 1993; Argnani, 2009): These structures probably conditioned the development and the evolution of the Sicily Channel tectonic depressions. At the north-western part of the Pantelleria Island, the Pantelleria graben narrows and it is limited by another N-trending, strike-slip tectonic feature (Gamberi and Argnani, 1995; Argnani, 2009). The Malta trough also appears to be affected by the NNE-trending Scicli–Ragusa strike-slip fault that continues northward in the Hyblean plateau (Gardiner et al., 1995).

The tectonic mechanisms that generated the initiation and subsequent evolution of the Sicily Channel Rift Zone are still unclear, especially because it is difficult to link them temporally with the geodynamic events occurring in the central sector of the Mediterranean from the Late Miocene. Argnani (2009) proposed that crustal stretching, and subsequent fault development and rifting within the Pelagian block, was controlled by slab-pull forces of the subducted slab, causing trench retreat and rolling back of the plate. Initially, slab-pull caused limited extension in the subducted plate, and ultimately led to the break-off of the slab (Argnani, 1990 and 2003). This author identifies two major episodes of slab tearing in the evolution of the sinking lithospheric plate.

If we link this event with results of plate kinematic reconstructions, important temporal discrepancies arise. Results derived by matching geological and geophysical information between adjacent sets of plates, show that the motion of Africa with respect to Europe changed to a clear NW-directed convergence from latest Upper Tortonian times onward (Mazzoli and Helman, 1994). Several Late Neogene tectonic features of the central Mediterranean region are compatible with this change of relative motion, such as the NW-directed subduction of the Ionian Sea beneath Calabria, the extension in the Tyrrhenian Sea, and dextral strike-slip across the North African margin. As for the Pantelleria graben, the temporal mismatch suggests that the creation of the Sicily Channel Rift Zone is not closely related to a change of the relative motion between the plates, but rather to a substantial change in the rheological behaviour of the northern African continental lithosphere.

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