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The structural framework of the Peloponnese continental margin from Zakynthos to Pylos from seismic reflection and morpho-bathymetric data

N. Wardell[1], L. Camera[2], J. Mascle[2], R. Nicolich[3], M. Marchi[1] and E. Barison[3]

[1] *Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Sgonico (TS), Italy*
[2] *Geo-Azur, Quai de la Darse, Villefranche-sur-Mer, France*
[3] *Dept. of Civil and Environment Engineering, University of Trieste, Italy*

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ABSTRACT One of the objectives of the European project SEAHELLARC (SEismic and tsunami risk Assessment and mitigation scenarios in the western HELLenic ARC) was to identify the key elements controlling the geological structure of the Peloponnese continental margin in order to better understand the distribution of earthquakes in the area. Vintage multichannel seismic lines were reprocessed, interpreted and integrated with detailed morpho-bathymetric data and high-resolution single channel seismic data. According to the interpretation, most of the upper continental margin has been created within the former Alpine Gavrovo, Ionian and *Apulian* thrust units, including their Miocene to Quaternary cover and their Triassic salt-bearing formations. The Ionian thrust complex seems to have been continuously overthrusting the *Apulian* Ridge, itself characterised by strongly fractured acoustic basement features. Ductile and mobile Triassic evaporitic sequences are present in most of the major Ionian zone morpho-structures. The westward directed thrusts of the Ionian zone reached their final positions in Lower Pliocene and were followed by uplift of the ridges that is continuing in the present time. Previous compressional structures are being reactivated as normal faults with associated diapirism in the Triassic evaporites. NNE-SSW shear displacements related to trans-extensional motion may have activated "pull apart" basins with ENE-WSW normal faulting at their heads. This NNE-SSW dextral strike-slip motion agrees with the present anticlockwise rotation of the Peloponnese. The focal mechanism and the NNE-SSW distribution of aftershocks of a major earthquake in June 2008 along the Andravida fault define a major lineament that can be followed past the Katakolo Peninsula to the diapiric morpho-structures defining the eastern boundary of the Strophades basin.

Key words: multichannel seismic data, External Hellenides, the Peloponnese continental margin, tectonics, SEAHELLARC.

1. Introduction

The area offshore western Peloponnese (Fig. 1) constitutes the westernmost segment of the active Hellenic continental margin (Angelier *et al.*, 1982) that had been strongly deformed during the Alpine orogeny (Aubouin, 1965). This active margin is the result of a long-term convergence between the two major African and European plates and, more recently, the Anatolia-Aegean microplate (Jolivet and Brun, 2010). This situation has led to the subduction, and locally to the collision, of parts of the African continental and oceanic lithospheres. As a consequence the western Peloponnese margin is characterised by significant seismic activity that has episodically caused destruction and loss of life in Peloponnese and the neighbouring Ionian islands.

Risks derived from earthquakes, and potentially related tsunamis, were the main reasons for the EEC Sixth Framework Program to support the "SEismic and tsunami risk Assessment and mitigation scenarios in western HELLenic ARC" project (SEAHELLARC). One of the objectives of this cooperative project (Papoulia *et al.*, 2014), was to provide reliable data to better define the geological structural framework of the Peloponnese continental margin. The majority of earthquakes are thought to be caused by ruptures occurring several kilometres below the Peloponnese continental slope. Their cumulated effects have generated, through geological time, particular structural features, which shape and affect the margin basement and its sedimentary cover. These features may represent key areas to better evaluate the geodynamic framework and hence to better understand the distribution of the earthquakes.

For this synthesis, vintage MultiChannel Seismic (MCS) lines recorded between the Island of Zakynthos to the north, the Gulf of Messinia and the North Matapan Trench (NMT) to the south were used. These data consisted of regional seismic lines acquired in the seventies by Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS) and more recent lines recorded in the Kyparissiakos Gulf in the 1980s that were made available to the project by the Hellenic National Oil Company (Fig. 2). Both sets of data were reprocessed using modern processing techniques to time migration and utilised in the interpretation of the tectonic setting. However, since the areal coverage was limited, high-resolution single-channel airgun lines recorded by the Hellenic Centre for Marine Research (HCMR) and the swath bathymetric coverage of the area that had been recorded during the project were integrated into the study.

Note: The term *Apulian* in this work is used in the same context as Aubouin (1965) who proposed the name Apulian Ridge and the associated margin of the Apulian Ridge. The Apulia platform outcrops in Puglia in southern Italy and is characterised by a long submerged 'nose' with basinal and shelf sequences extending south-eastwards and virtually making contact with the Cephalonia fault. This contact closes and separates the Ionian basin from the northern Leukas - Otranto - southern Adriatic pelagic basins.

The Apulia platform and continental margin in Puglia is part of the Mesozoic Adria carbonatic margin, but was separated from the Dinaric and Hellenic segmentations. The structure outcropping in Zakynthos and Cephalonia constitutes an isolated ridge resulting from the rifting and breaking of the original Adria. The ridge has a margin as Aubouin (1965) suggested, but this is not the margin of the "Puglia" Apulia platform. The term *Apulian* (in italics) therefore differentiates it from the definitions of other authors who apparently consider that the Apulia platform extends from Italy to Zakynthos with its margin reaching Greece.

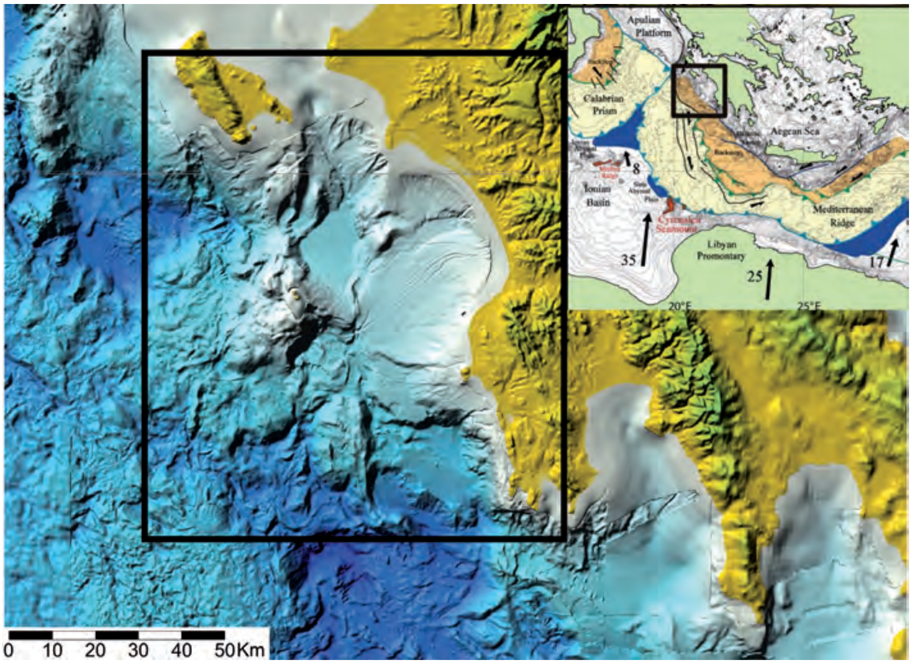

Fig. 1 - General morphology of the Peloponnese continental margin from the Island of Zakynthos to the northern Matapan trough and the Mediterranean Ridge inner basins; within the black frame the SEAHELLARC area surveyed in detail during the project. The map is a compilation of three distinct sets of swath bathymetric data: (a) data collected in 2006 by OGS RV "Explora" in the target area (Camera *et al*., 2014); (b) swath data collected by the HCMR RV "Aegaeo" in 2006 and (c) swath data collected in 1995 by IFREMER RV "L'Atalante" (Chamot-Rooke *et al*., 2005). The data have been merged to produce a DTM at 100 m, supplemented, in areas not covered by swath bathymetry, by the Gebco_08 grid. Insert: a geodynamic sketch of the Hellenic Arc showing the SEAHELLARC area lying at the boundary between the still-active subduction from southern Peloponnese to eastern Crete and the strike-slip motion occurring just west of Cephalonia Island with the collision between the Hellenic border and the "Puglia" continental nose (after Chamot-Rooke *et al*., 2005).

2. Onshore/offshore geological structural framework

Western Peloponnese displays outcrops of four major tectono-stratigraphic units successively emplaced as thrust sheets between the Oligocene and the Upper Pliocene (Underhill, 1989). This foreland fold and thrust belt is the result of the collision of the Adria microplate with the Eurasian continent. The northward subduction of the African plate below the southern margin of Eurasia is hypothesised (Jolivet and Brun, 2010) to be continuous from the Late Cretaceous suture of the Tethys ocean to the present-day situation (Fig. 1). The Adria margin, with Mesozoic carbonates occupying a wide zone from the Adriatic Sea to the area of eastern Crete, was broken by rifting since Late Lias with the formation of structural highs and depressions. The extended domains were later filled by shallow water carbonates on the ridges and by pelagic carbonates, cherty limestones and radiolarites in the basins. The four tectono-stratigraphic zones are, from east to west (Fig. 3): the Pindos furrow, the Gavrovo Ridge with shelf carbonates of African - Adria affinities, the Ionian furrow, and the Apulian Ridge (Aubouin, 1965; Underhill, 1989; Van Hinsbergen *et al*., 2006).

The Pindos oceanic realm was the first to be involved in the shortening process with ophiolitic obduction onto the eastern Adria margin. This zone is characterised by the presence of

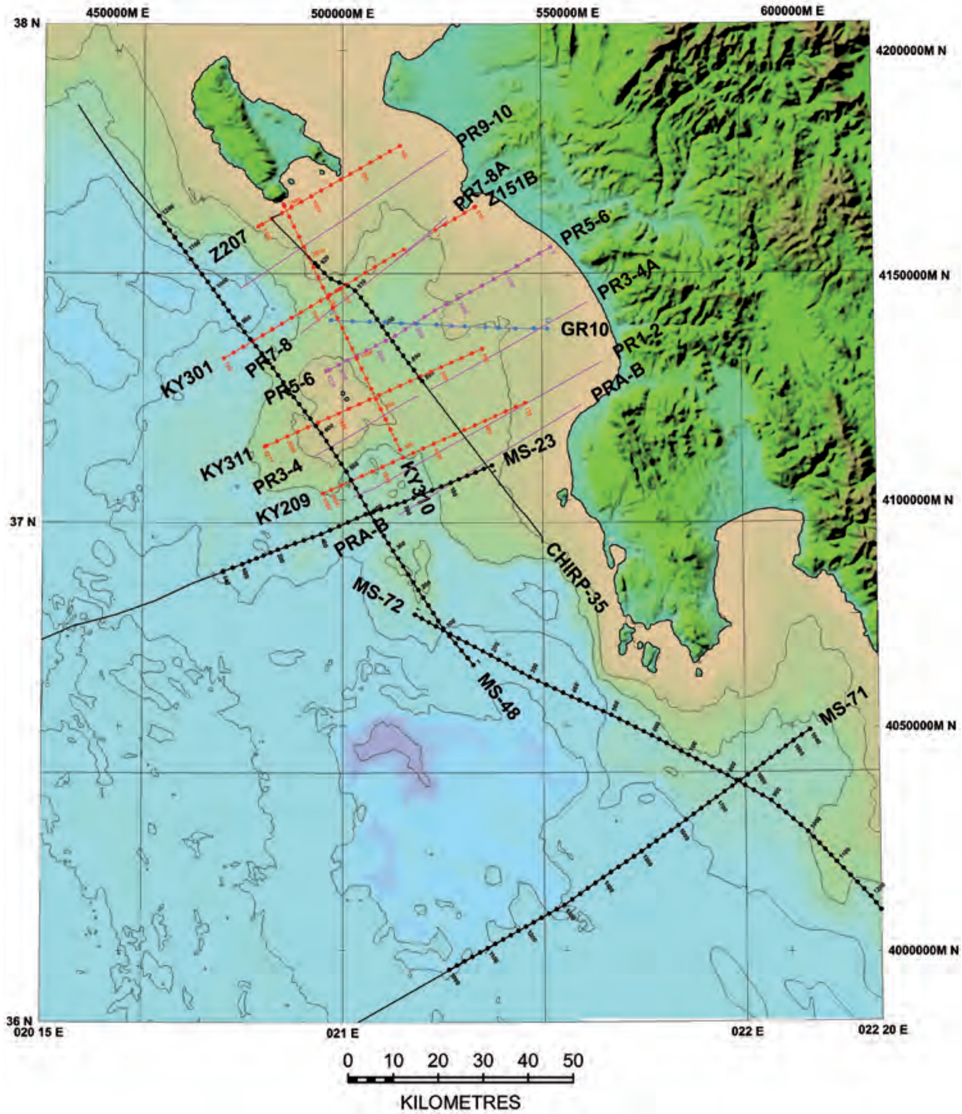

Fig. 2 - Simplified bathymetry showing the seismic lines used in this study. In red: MCS data from the Hellenic National Oil Company; in black: MCS data from OGS, Trieste; in purple: high resolution airgun profiles (from PRA-B to PR 9-10) from HCMR. Shotpoints are annotated on the parts of lines that are referred to or displayed in the text. The position of the CHIRP-35 profile (black) (Fig. 10), and the GR10 profile (blue) (from Auroux *et al.*, 1984) are also displayed.

pelagic Triassic to Cretaceous sediments with Eocene-Aquitanian flysch representing the final stage of the Pindos ocean closure. The metamorphic units outcropping in the Mani Peninsula, however, composed of marbles and Phillite-Quarzite units of the Arna formation, are thought to be relatively autochthonous basement and to correlate with the un-metamorphosed carbonates of the Ionian zone (Papanikolaou and Royden, 2007).

Shallow water strong and rigid carbonate sequences followed by late Eocene-Early Oligocene synorogenic flysch denote the Gavrovo zone, a present day antiform resembling a peripheral bulge induced by bending at the front of the Pindos obduction. Its western limit, as

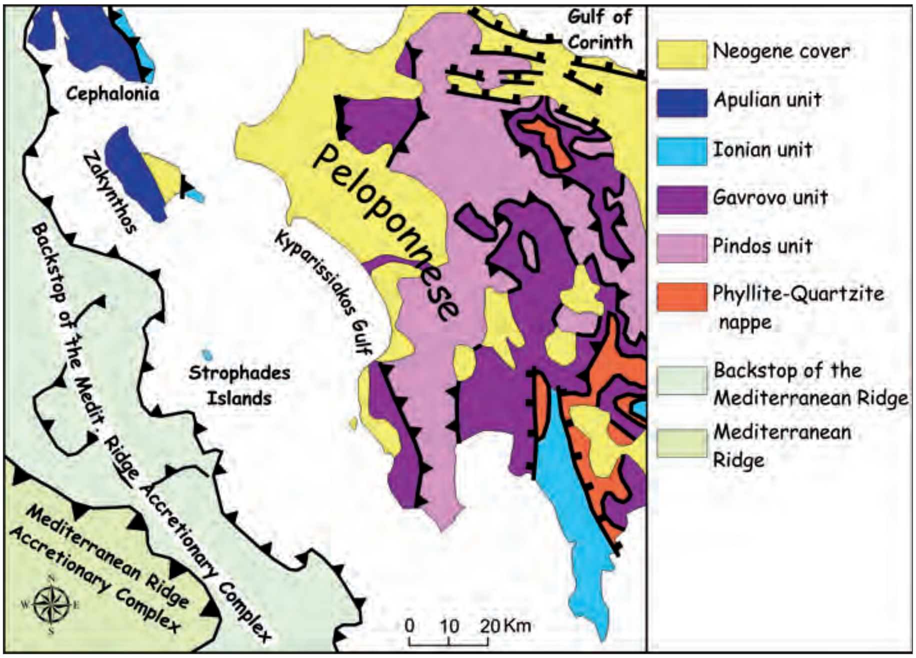

Fig. 3 - Simplified geological sketch of the main Alpine geological units outcropping onshore Peloponnesus, modified from Underhill (1989), Fountoulis and Moraiti (1994), Zelilidis *et al*. (1998) and the main offshore structural trends simplified from Chamot-Rooke *et al*. (2005).

revealed by seismic profiling in NW Peloponnese (Kamberis *et al*., 2000b), corresponds to the late Cenozoic front and is proposed to continue south-westward offshore. The Gavrovo thrust over the Ionian was developed on a detachment horizon at the top of the flysch supplied by the erosion of the Pindos formations. In the flexural subsidence thick synorogenic clastics were accommodated. The marine seismic profiles reveal the presence in the Kyparissiakos Gulf of a huge amount of Cenozoic continental deposits, followed by Pleistocene to Holocene lacustrine and marine deposits (sands, marls and calcarenites). E-W trending extensional active faults are occupying the onshore area along the Peloponnese coasts (Fountoulis and Moraiti, 1994).

The Ionian zone sequences are represented by Triassic to Eocene pelagic carbonates and by Late Eocene-Oligocene flysch. The region is considered as being deformed by an array of thrusts that propagate westwards, with each newly formed thrust being developed according to a piggy-back thrust propagation model. Overloading due to the deposition of the Gavrovo on the Ionian zone caused a lithosphere flexure and gave rise to halokinetic movements of the Triassic evaporites from east to west (Underhill, 1988). The diapiric movements continue to the present day in the Ionian zone as revealed by the sea floor antiforms in the seismic lines [Monopolis and Bruneton (1982) and this work].

The main lithologies of the *Apulian* Ridge are represented by shelf carbonates outcropping in the Ionian islands of Cephalonia and Zakynthos. The zone was dominated by shortening during Pliocene times, with the emplacement of the Ionian thrusts over the *Apulian* Ridge margin (the pre-Apulian zone, *auctorum*). Compressive structures have been evidenced by the Streamer ION-7 profile acquired between the two islands indicating shortening continuing in the Quaternary with westward propagation of the thrust system (Hirn *et al*., 1996; Kokinou *et* *al.*, 2006). The thrusts were activated on pre-existing high-angle normal faults, west dipping and related to regional extension during sedimentation.

Outcrops of the Ionian, Gavrovo and Pindos units are known (Fountoulis and Moraiti, 1994). The Ionian zone can be seen directly on the south-eastern part of the Island of Zakynthos, where it is expressed by outcrops of blocks of Triassic evaporites intruding Plio-Pleistocene sediments (Zelilidis *et al.*, 1998). Elsewhere, the *Apulian* Ridge massive limestone constitutes most of the western half of the island (Underhill, 1989) with recent Neogene deposits infilling the Alikanas basin in the centre (Zelilidis *et al.*, 1998). Triassic evaporites (mainly anhydrites) of the Ionian zone were drilled at Killini and on the Katakolo Peninsula during exploration for hydrocarbons (Kamberis *et al.*, 2000a; Mavromatidis *et al.*, 2004; Etiope *et al.*, 2006).

On the Strophades Islands, south of Zakynthos (Fig. 3), salt-rich evaporites have also been described (Lyberis and Bizon, 1981) as tectonically emplaced diapiric bodies within Pliocene marls; however, these were tentatively attributed to Messinian deposits.

The progressive westward migration of the deformation front was described by Clément *et al.* (2000). Their hypothesis was that a dipping interface, detected at a depth of around 13 km between the islands of Cephalonia and Zakynthos, and also to the SW of Zakynthos, may indicate the inter-plate subduction boundary. This seismic boundary shows a stratified domain that was interpreted as the probable presence, at depth, of former Mesozoic sediments of the Ionian basin.

The geological structures of the shallow first few kilometres of this continental margin segment are not well known. Few results have been published (Lyberis and Bizon, 1981; Monopolis and Bruneton, 1982; Auroux *et al.*, 1984; Kamberis *et al.*, 2000a), and, more recently, Papanikolaou and Royden (2007). Monopolis and Bruneton (1982) propose that the Ionian thrust zone lies beneath most of the upper continental slope. They also suspected the role of Triassic salt injections in shaping the structural fabric of the upper to middle continental margin. This was later confirmed (Kamberis *et al.*, 2000a; Etiope *et al.*, 2006) in the area around Zakynthos, and the Killini and Katakolo peninsulas.

Lyberis and Bizon (1981) emphasised the importance of a probable Pleistocene uplift of the Strophades swell, which they tentatively correlate to the presence of a WSW-ENE directed shallow discontinuity detected across the margin sedimentary cover. Finally, Papanikolaou *et al.* (2007) described variable rates of subsidence, with paleo-geographic changes during Pleistocene to Holocene times, on the continental shelf area. The authors also identified a coastal fault zone all along the Kyparissiakos Gulf. However, this would seem to be more the result of interpretation with an excessive vertical exaggeration of the single-channel reflection profiles and the features should probably be reconsidered as gravitational slides on the steep shelf edge.

3. Seismic reflection data

3.1. Multichannel seismic data

Multichannel seismic reflection data recorded in the study area by OGS in the 1970s were reprocessed during the SEAHELLARC project. Other lines acquired in the 1980s and made available by the Hellenic National Oil Company augmented this data set (Fig. 2). The reprocessing was performed at the OGS processing centre in Trieste using the FOCUS processing package from

Table 1 - The acquisition parameters of the reprocessed MCS lines.

Hellenic Petroleum Lines	Date Shot	Source	Cable Length	No. Channels	Fold	Data length
KY-209	1980	Maxipulse	2400 m	96	4800%	9 s
KY-301	1982	Airgun	2400 m	96	4800%	7 - 9 s
KY-310	1982	Airgun	2400 m	96	4800%	7 - 9 s
KY-311	1982	Airgun	2400 m	96	4800%	7 - 9 s
Z-151A	1988	Vaporchoc	2400 m	48	4800%	6 s
Z-151B	1988	Vaporchoc	2400 m	48	4800%	6 s
Z-207	1979	Maxipulse	2400 m	96	4800%	9 s
OGS MS lines						
MS-23	1971	Flexotir	2400 m	24	600%	6 - 10 s
MS-48	1973	Flexotir	2400 m	24	1200%	6 - 10 s
MS-71	1975	Flexotir	2400 m	48	1200%	6 - 10 s
MS-72	1975	Flexotir	2400 m	48	1200%	6 - 10 s

Paradigm Geophysical. It was directed, not only at improving the original sections, but also, to homogenise the data to compensate for the various different acquisition parameters (Table 1). Some lines, originally recorded using a Maxipulse source, required specific "debubbling" processing on the field data. This removed the bubble oscillations and corrected the data to time zero by match filtering with the recorded gun signature. This homogenisation of the data helped to facilitate comparison between and among the lines and assist the interpretation. The reprocessing of the lines all followed a similar sequence as described in Table 2. Velocity analysis was performed before and after the F/K filtering of the multiple energy. The first pass was to define the velocity trend of the multiples to overcorrect them, and the second to pick the stacking velocity functions with the multiples attenuated. The field data was not available for line MS-72 and it was necessary to work from the scanned and reconstructed originally processed stack data. This limited the processing that was possible to migration, filtering and trace equalisation. The seismic sections were finalised in filtered stack and migrated versions at a horizontal scale of 1:50,000 and a vertical scale of 5 cm/s.

3.2. Single channel seismic data

Complementary, less penetrating, high-resolution single channel seismic data were recorded with an airgun source in 2006 by HCMR (Fig. 2). Due to problems with the digital recording, these data were not initially used in this study. However, the lack of coverage between the Zakynthos-Strophades Ridge and the coast necessitated that these lines be included to assist in a better understanding of the tectonic setting of the Strophades basin and the continental slope. They were therefore reconstructed from on-board screenshots and digitally combined together into continuous profiles (e.g., Fig. 9).

3.3. Morpho-bathymetric data

An almost 100% swath bathymetric coverage of the study area together with sub-bottom CHIRP profiles had already provided an interpretation of the shallow (up to 100 m penetration)

Table 2 - The processing sequence applied during the reprocessing of the MCS lines.

Processing Sequence	
Reformat	From SEGY to Focus internal Format
Quality control	Monitor Display of raw records with shot and trace editing
Debubble	Source Signature Deconvolution (Maxipulse Lines)
Amplitude recovery	Using a T^2V synthetic gain function
Geometry	Field geometry assignment
Deconvolution	320 ms operator, 12 ms prediction distance and 1% white noise
Multiple Attenuation	F/K Filtering of multiple energy after overcorrection of primaries
Velocity analysis	Semblance plots, velocity stacks and common distance gathers
NMO Correction	Application of NMO corrections
Far Trace Mute	Derived from common distance gathers and mute scans
Stack	CDP Stack
Migration	Finite difference time migration
Filter	Time variant bandpass filter application
Equalisation	Trace equalisation
Plotting Scales	Horizontal = 1:50000; Vertical = 5 cm/s

sedimentary features (Camera *et al.*, 2014). These data were integrated with the MCS data in the interpretation package Kingdom, provided by Seismic Micro-Technology, to visualise the complex geology in 3-dimensions and identify the main structural elements in a full 3D sense.

4. The interpreted sections

The E-W profiles are generally characterised by thick sedimentary cover (locally up to 5 s TWT) to the east across the upper/middle continental slope. In the centre, a deep slope basin domain is observed where tectonic deformations have strongly imprinted the sedimentary cover. Finally, to the west, the Zakynthos-Strophades Ridge gives way to the western slope area where most of the seismic data shows a highly fractured acoustic basement.

To correlate the seismic facies between the different lines, a litho-acoustic log (Fig. 4) was interpreted on Line KY209. This line traverses the middle/upper continental slope (Fig. 2) and can therefore be considered typical for most of the upper margin domain. Based on this log, the main contrasted acoustic units have been identified; these are, from top to bottom:

- Unit 1, about 1 s thick that, based on its acoustic facies, is made of alternatively strong and weak, but well-layered, reflectors showing rather good lateral continuity. This unit is probably chiefly made of turbidites and hemipelagites directly derived from the erosion of the nearby land outcrops. This unit would correlate to the Pleistocene and Pliocene sedimentary cover;
- Unit 2, up to 0.8 s thick in this area, and includes two sub-units: (a) an upper unit locally topped by an irregular and chaotic surface whilst its base appears to be conformable; (b) a well-layered lower unit showing significant thickness variations. These two sub-units are tentatively interpreted as indicating Messinian clastics resting on Upper Miocene turbidites. They may be

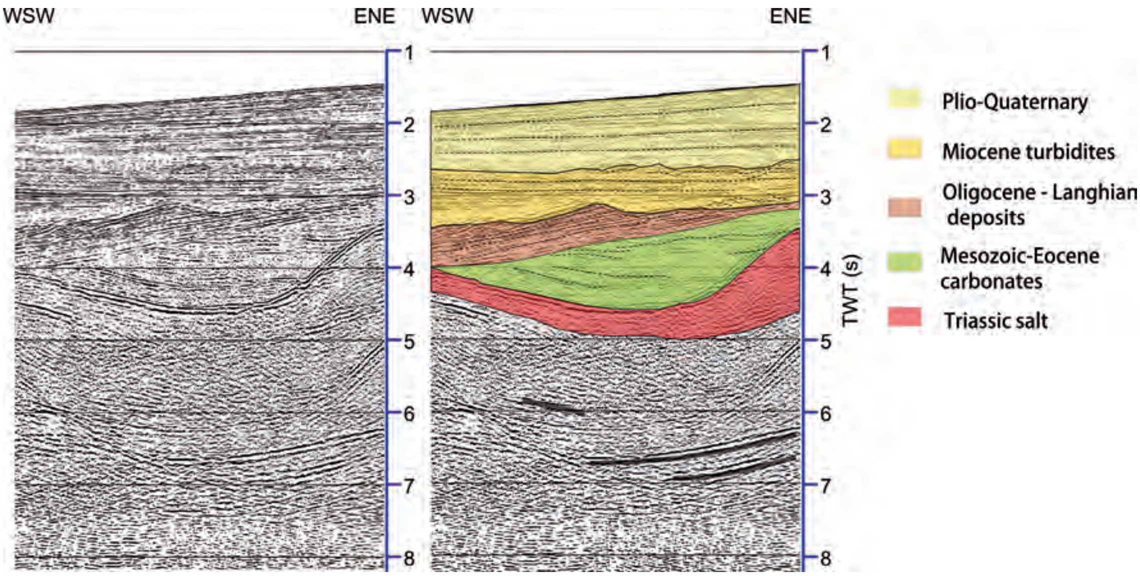

Fig. 4 - Litho-acoustic log, selected from MCS profile KY209 (Fig. 10, location in Fig. 2), depicting the main litho-acoustic units observed over most of the area (see text for explanation). The colour coding for these units is used on the subsequent interpreted sections.

coeval with the last "Alpine" tectonic events, starting from Late Miocene, which led to the final westward thrusting of the Ionian units over the *Apulian* Ridge (Underhill, 1989);

- Unit 3 consists of relatively strong but discontinuous reflecting events, and is separated from the one above by an angular unconformity that suggests an important erosional phase. This unit may represents Oligocene-Langhian deposits;
- Unit 4 shows highly variable thickness (from 0.3 to 1.6 s) and includes poorly continuous, but strong reflecting events in a package of irregular and weaker reflectors. This unit, which is also bounded at its top by an unconformity, is attributed to Mesozoic to Eocene limestone of the Ionian zone;
- Unit 5 displays an almost acoustically transparent facies and appears to be bounded at its top, as well as at its base by fairly strong reflectors. This unit shows evidence of deformation typical of salt tectonics; as a consequence, this unit is interpreted as probably made of deformed Triassic salt-rich sediments in agreement with the hypotheses of other authors (Monopolis and Bruneton, 1982);
- Finally at a depth of more than 5 s TWT, a few discontinuous, but strong, reflectors can be detected; these seismic events are tentatively attributed either to Early Mesozoic deposits or to intra-basement layers.

All the MCS seismic sections presented in this paper (Figs. 5 to 8 and 12 to 14) have been interpreted using the colour coding from Fig. 4 to indicate the main formations constituting the External Hellenide thrusts. On these figures, the Ionian Thrust is labelled IT and the other main faults in the map of Fig. 17 are shown with thick lines.

The interpretation of the shallow sedimentary features based on morpho-bathymetry and CHIRP data (Camera *et al.*, 2014) has already shown that the Peloponnese margin can be divided into several morpho-structural provinces: (a) an upper continental slope with thick Cenozoic

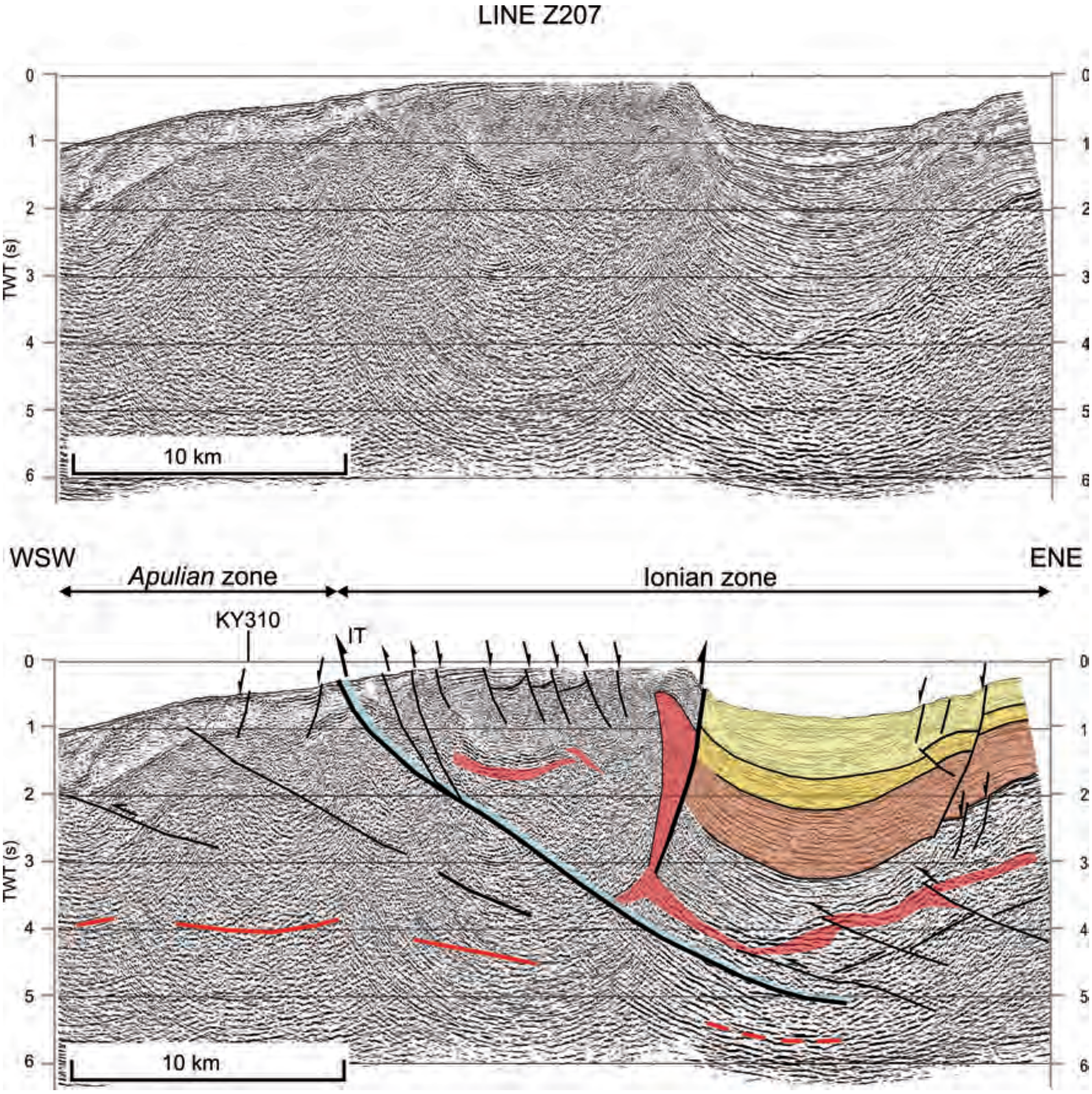

Fig. 5 - Migrated section (top) and interpreted section (bottom) of MCS profile Z207 south of Zakynthos Island. The profile shows the Ionian thrust zone bounded, on its eastern side, by inferred Triassic salt injections (in red); the line also illustrates the Ionian thrust system flexure and the sedimentary fill of the Zakynthos basin.

sediments, where various active sedimentary by-passing mechanisms are operating; (b) a series of mid-slope and sub-linear morpho-tectonic depressions bounded westwards by (c) massive carbonates ridges and, finally (d) a highly fractured lower continental slope, with only thin recent sediments, facing the deep Ionian basin. Similar morpho-structural provinces relative to three main margin segments as seen on the MCS data are described and discussed below.

4.1. The continental margin south and east of Zakynthos Island

MCS Lines Z207 and the composite line KY301, Z151A and Z151B (positions in Fig. 2) provide regional cross-sections from the Zakynthos basement ridge in the west to the Peloponnese upper

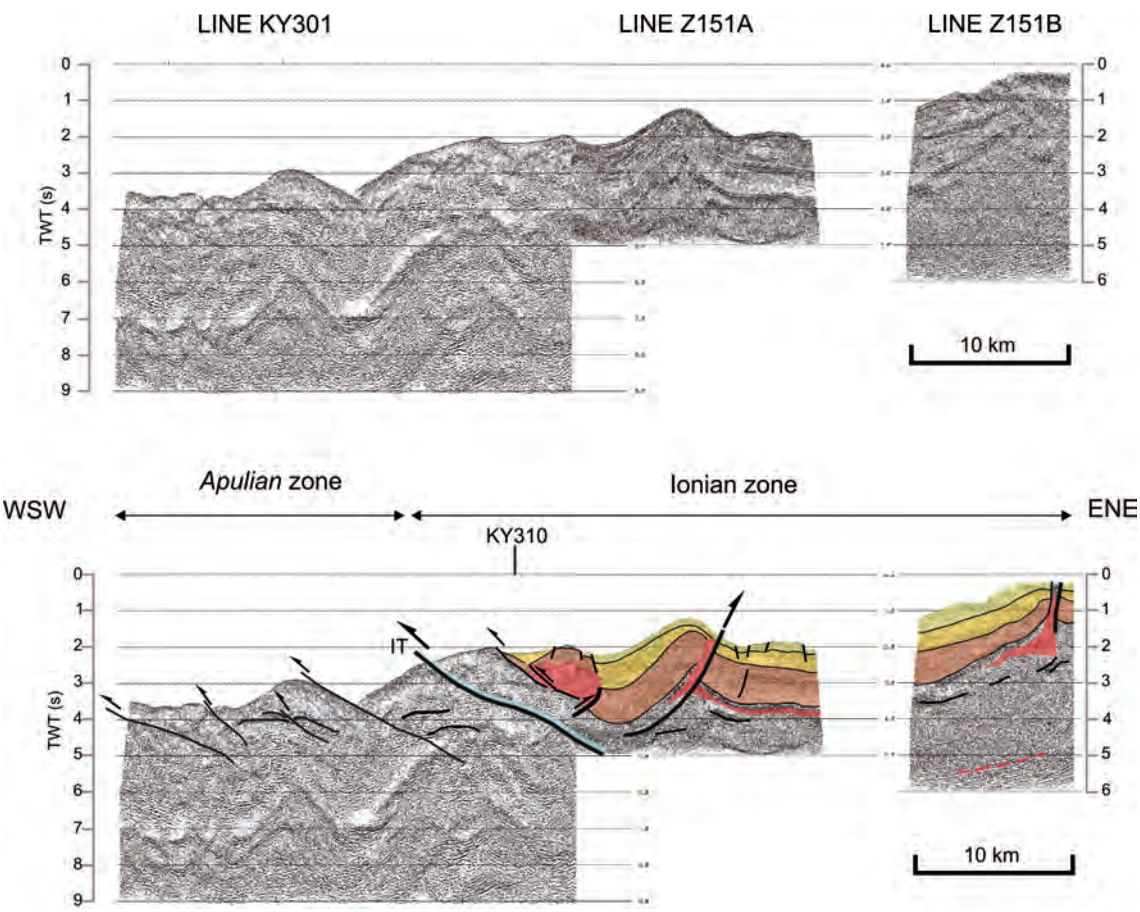

Fig. 6 - Composite section, with interpretation, of the profiles KY301, Z151A, Z151B located midway between Zakynthos and Strophades from the *Apulian* slope in the west, to the upper continental slope near the Katakolo Peninsula.

continental slope to the east and show the main litho-acoustic and structural characteristics of this region. The western end of profile Z207 (Fig. 5) demonstrates that the domain, which extends just south of Zakynthos, consists of an almost reflection-free but fractured acoustic basement. This is bounded to the east by a flat, strongly tectonized sector that is interpreted as the frontal thrust of the Ionian zone over the margin of the *Apulian* Ridge limestone (the pre-Apulian zone, *auctorum*). Towards the east the submerged prolongation of Zakynthos is bordered by a N-S directed fault zone in which near-vertical Triassic salt-injected bodies have been detected. As already indicated, both the *Apulian* Ridge limestone and the Ionian thrust (including its Triassic salt component) outcrop on Zakynthos even though a large part of the island is covered by Miocene to Quaternary deposits (Karakitsios, 1995; Zelilidis *et al.*, 1998). East of this area, the same profile shows a syncline-like basin that is referred to as the Zakynthos basin. The infill of this basin (more than 3 s TWT) comprises of a series of acoustically well-layered sequences, interpreted to be Quaternary to Early Tertiary in age, resting on strong horizons that are tentatively correlated with limestone and probable Triassic salt-bearing formations. This basin can still be detected beneath parts of the mid-slope, which is itself cut by a series of syn-sedimentary faults that may be driven by deeper tectonic lineaments. The compressional tectonics and the recent uplift of the Zakynthos Island are

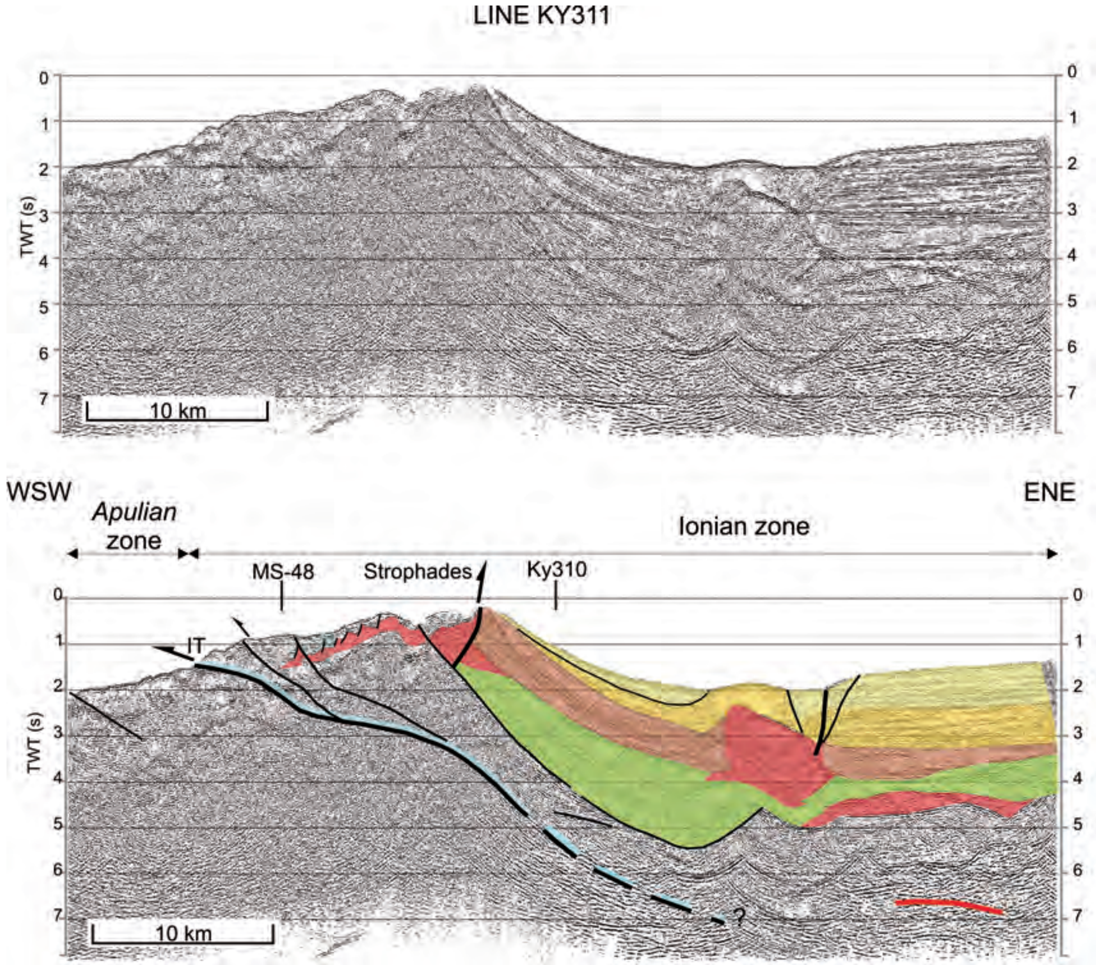

Fig. 7 - Section and interpretation of the profile KY311 across the Strophades Ridge to the border of the eastern Peloponnesus continental upper slope; most of the Strophades Ridge is interpreted as an uplifted part of the Ionian frontal thrust, including several Triassic salt bodies (in red). Triassic salt-rich intrusions have contributed to the deformation of the bordering margin basin and salt layers are also detected beneath the upper slope sedimentary cover (see text for explanation).

well represented by the main reverse fault and the geometry of the depositional sequences of Late Pliocene and Pleistocene sediments.

Towards the south, the Zakynthos Ridge divides in two distinct structural domains as seen on the composite section of profiles KY301, Z151A, Z151B (Fig. 6). A western one with a series of imbricate thrusts that are believed to consist of massive limestone sheets and Tertiary units emplaced along the contact between the *Apulian* Ridge margin and the Ionian zone. A central structural domain corresponds to an uplifted and back-thrusted portion of the Zakynthos sedimentary basin intruded in place by massive salt bodies associated with the major faults. This basin can be identified beneath the upper continental slope up to the Katakolo Peninsula, where deep salt-bearing Triassic sequences have penetrated the carbonate series through diapiric movements related to the westward propagation of the thrust system. Offshore Katakolo, oil and gas have been discovered in Jurassic-Eocene carbonates underlying cap rocks of Pliocene clastics

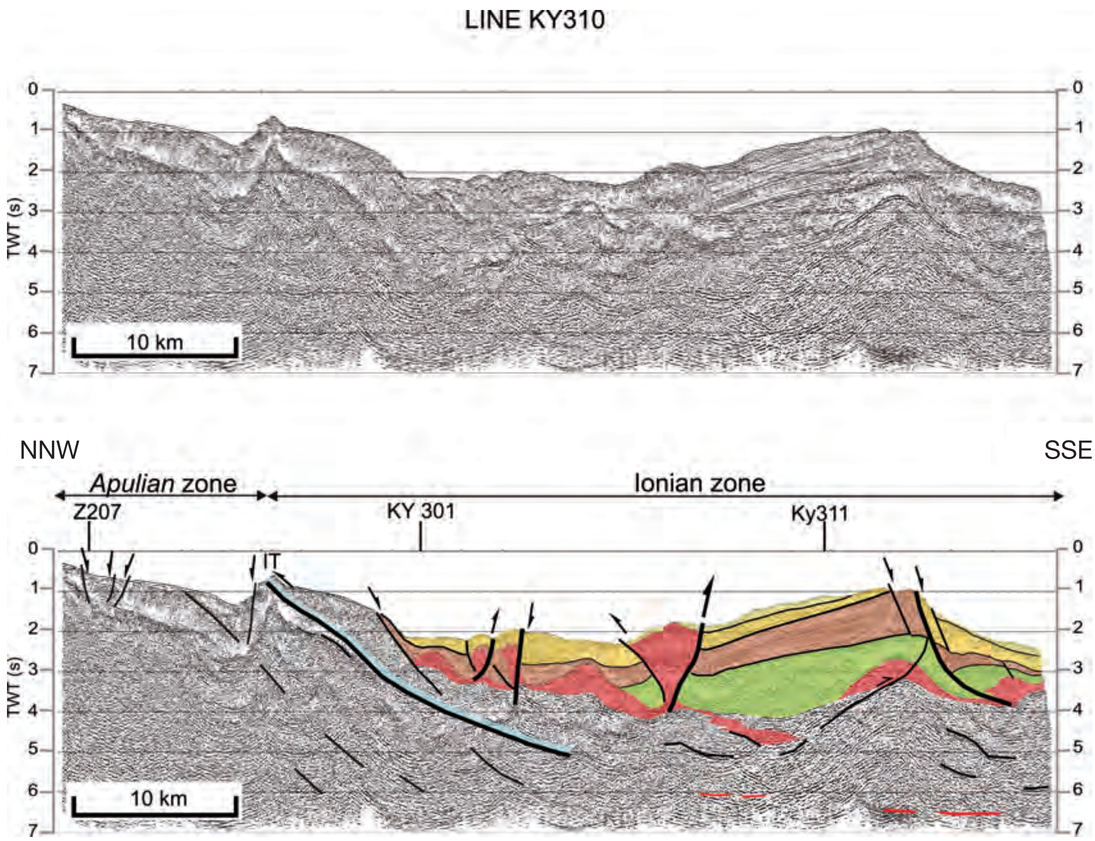

Fig. 8 - Section and interpretation of profile KY310, a seismic line through the structures of the Zakynthos - Strophades Ridge. The southern part of the section shows the re-activation of previous thrusts as normal faults.

and intruded Triassic evaporites (Kokinou *et al.*, 2005; Etiope *et al.*, 2006). Even though the Triassic salt and anhydrites were drilled by oil companies, no well has reached the pre-evaporitic formations (Mavromatidis *et al.*, 2004) at more than 3 s TWT (more than 5 km in depth).

4.2. The Strophades Ridge, basin and continental slope

The main structural characteristics of the region around the Strophades Islands, and of the nearby upper continental slope, are displayed on MCS profiles KY311, KY310, KY209 and MS-23, MS-48.

Profile KY311 (Fig. 7) shows that, like the Zakynthos Ridge, the Strophades swell can be interpreted as made of acoustic basement thrust units injected by Triassic salt bodies. Similar to the northern region, these thrusts are underlining tectonic contacts between the Ionian zone and the *Apulian* Ridge margin. While evaporites, attributed to Messinian age, have been reported to occur on Strophades (Lyberis and Bizon, 1981), the island is attributed to tectonically emplaced Triassic salt-bearing sediments. The uplift continues to the present day as evidenced by geodetic measurements from the 1997 Strophades earthquake (Stiros, 2005).

This continued uplift of Strophades is clearly seen in the sediments of the continental slope where the western part is severely tilted upwards towards Strophades. In the centre, the slope seems to be ruptured, probably as a result of this uplift and of the downloading in the mid-slope

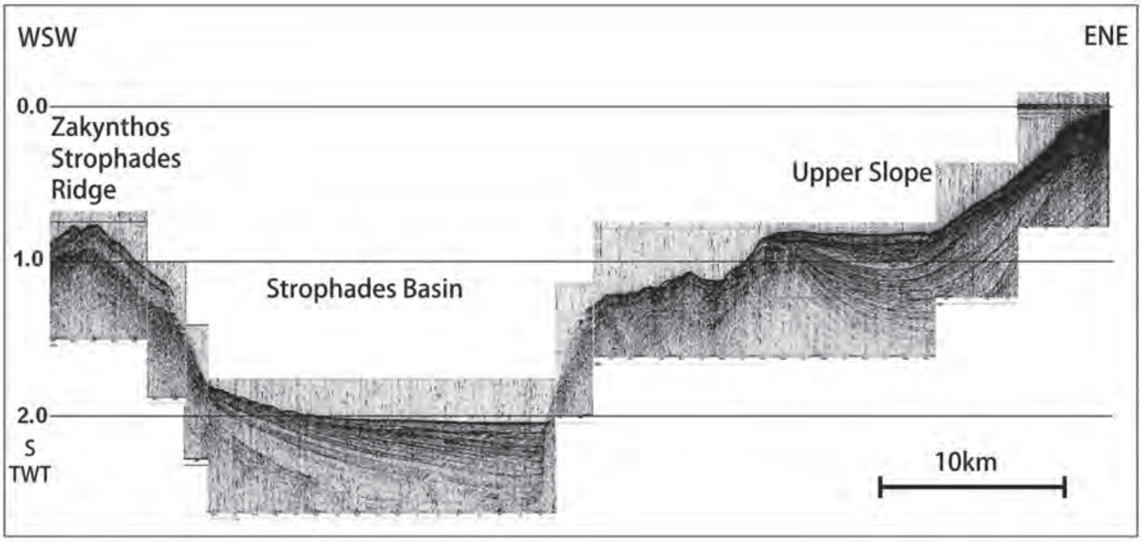

Fig. 9 - The shallow penetrating seismic profile PR5-6 crossing the deep slope basin NE of Strophades Ridge (location, in Fig. 2). The sedimentary deformation at the foot of the ridge may indicate instabilities leading to sedimentary slides. The seabed is slightly tilted towards the east against a salt dominated structure. A flexural basin south of Katakolo Peninsula, hidden by the prograding recent sedimentary blanket and slides of the upper slope, is seen in the east. The vertical exaggeration is approximately 1:10.

area by recent sedimentation, with associated faulting and intrusions of massive Triassic salt bodies.

The profile KY310 (Fig. 12) is a longitudinal section in a N-S direction intersecting the lines Z207, KY301, and KY311 and almost KY209. It runs along the eastern flank of the Zakynthos-Strophades Ridge. The thick sedimentary sequence of the continental slope is tilted by the uplift of Strophades and dips to the north. The Ionian thrust zone cuts the line at an angle near the intersection with line KY 301 where the role of the Triassic salt and the re-activation of thrusts as normal faults can be seen.

Between these two lines and bordered to the north by lines Z151A and Z151B lies the Strophades basin, a deep bordering depression at the foot of the middle continental slope, NE of Strophades. This has previously been interpreted by Monopolis and Bruneton (1982) as the scar of the Ionian frontal thrusts. However, from the detailed morpho-bathymetric data, this basin would seem to be a much more significant structure. It was already seen in an image of a high-resolution seismic (W-E) profile acquired in 1974, indicated as GR10 on the position map (Fig. 2), and presented by Auroux *et al.* (1984). It was described as one of a number of small basins orientated NW-SE structurally controlled by diapiric evaporites, of probable Triassic age, with associated inverse faulting, and infilled with a Plio-Quarternary sedimentary cover. This figure (Fig. 9 in Auroux *et al.*, 1984) also revealed the presence to the east of an upper slope flexural basin covered by recent westward prograding deposits.

The shallow penetrating air-gun seismic profile, PR5-6 (Fig. 9), was acquired by HCMR over the depression from the Strophades Ridge to the upper continental slope (from WSW to ENE, location in Fig. 2). The sedimentary deformation at the foot of the Strophades Ridge may denote slope instabilities due to the uplifting of the ridge, leading to sedimentary slides. The sediments in the basin are tilted down towards the ENE indicating recent basin filling and subsidence at the

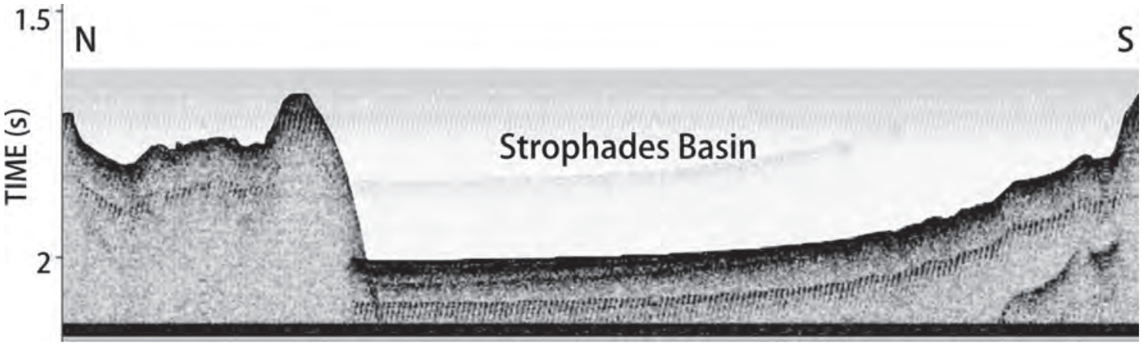

Fig. 10 - The N-S CHIRP-35 profile crossing the Strophades basin (location, in Fig. 2) showing the basin tilting to the north, sedimentary instabilities to the south and the normal fault at its northern boundary.

eastern boundary. The steep side of the basin is interpreted as a continuation of the tectonically emplaced salt structures along the line of a currently active fault system. Further to the east, the upper slope flexure, due to the thrusting and subsequent diapirism, seen on the line GR10 (Auroux *et al.*, 1984), is represented in the synclinal feature. Recent sediments filling the syncline have however hidden any imprint on the seafloor morphology.

The CHIRP-35 profile presented in Fig. 10 with an approximate N-S direction also illustrates the tilting of the basin, the sedimentary instabilities to the south and a normal fault at its northern boundary. From the available data, it is estimated that this fault could have a displacement of the Miocene-Oligocene sediments of up to 1000 m, and it is still active.

The tilting of the Strophades basin is also shown in the 3D fence diagram (Fig. 11). This figure shows the intersections between the N-S line KY-310 and the E-W lines KY311 and KY-209 as viewed from the NE. The bathymetry derived from the multibeam swath sonar data is also shown, but it has been offset vertically by 2 s to allow the seismic sections to be visualised. This morpho-bathymetric surface shows the lower continental slope, visible on the seismic sections, dipping to the NNE into the Strophades basin. The northern and eastern boundaries to this basin are clearly imaged. Along the northern boundary the normal fault can be readily inferred whilst the intruded salt structures along the apparent rupture of the continental slope define the eastern boundary through line KY311 and extending to KY209.

The easternmost sectors of the profiles KY209 (Fig. 12) and MS-23 (Fig. 13) show a comparable overall margin structure involving, at depth, thick and deformed packages of presumed salt layers. The bordering depression south of Strophades is presently delimited by normal faults reactivating previous thrusts as can be seen at the junction of lines KY-310 and KY-209 (Fig. 12), and also in lines KY310 (Fig. 8) and MS-48 (Fig. 14). The depression is showing a definitive change in the tectonic style with prevailing extension in the southern domains towards the inner plateau and basins of the Mediterranean Ridge.

The lower continental slope, illustrated on the western part of the profile MS-23 (Fig. 13), exhibits a series of short wave-length acoustic basement reliefs draped by very thin recent sediments. These features may result from intense shortening exerted on the *Apulian* Ridge limestone. On the same section, at depth, one may observe a few scattered deep reflectors. They may either indicate stacked Alpine thrust units or, alternatively, the top of a thinned continental

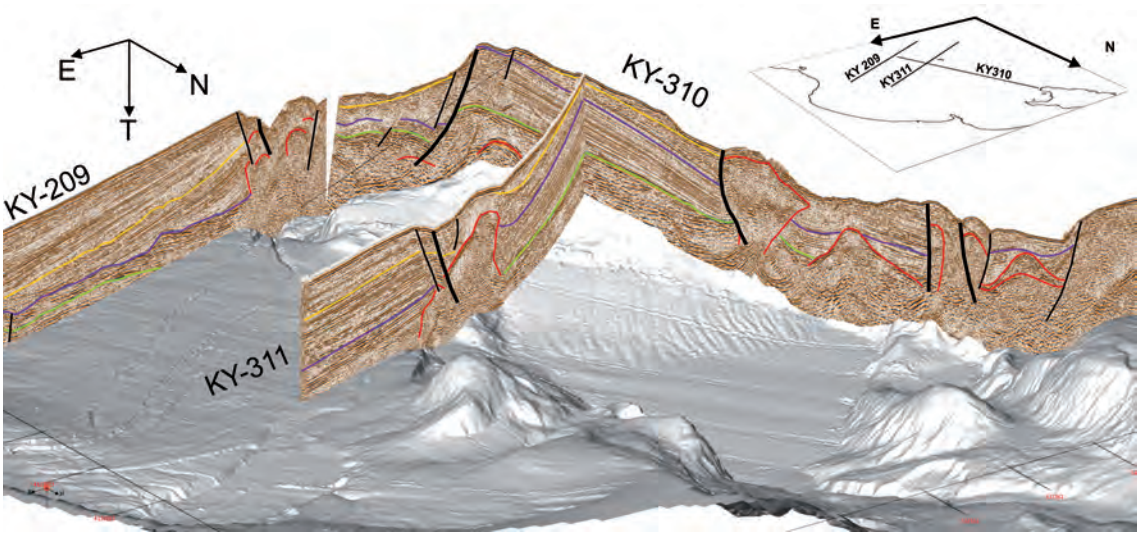

Fig. 11 - An interpreted 3D fence diagram of lines KY310, KY311 and KY209 together with the sea floor surface (50 m bathymetric grid from the multibeam survey offset by 2 s) showing the relationship between the seismic data and the morpho-bathymetry in the Strophades basin. The yellow horizon represents the base of the Plio-Quaternary deposits, the purple, the top of the Oligocene-Langhian sequences, the green, the top of the Mesozoic-Eocene carbonates and the red, the top of the Triassic salt.

crust, which presumably would constitute the backstop of the nearby Mediterranean Ridge (Chamot-Rooke *et al.*, 2005).

The NW-SE longitudinal section MS-48 running along the western flank of the ridge is presented in Fig. 14. The southern half again illustrates the Ionian/*Apulian* contact near the Strophades Islands. The extensional neotectonics have reactivated the old thrust fronts south of Strophades and now normal faults mark the transition to the deep northern Matapan trough.

4.3. The continental margin off the Gulf of Messinia and the NMT structures

Even though it is outside of the target area of the SEAHELLARC project, it is important to briefly discuss the geological structure of the continental margin west of the Gulf of Messinia that results from fairly recent extensional events in Plio-Quaternary times (Mariolakos *et al.*, 1994; Fountoulis and Mariolakos, 2008). An important difference between the two margin areas, well expressed in the morphology (Figs. 1 and 2), relates to the presence in this last region of bordering deep troughs (Mascle and Chaumillon, 1998). These deep structures, being up to 5100 m deep, are the deepest area in the Mediterranean Sea. They are currently interpreted as transcurrent fore-arc-type basins cutting across a thinned continental crust, which is itself acting as a backstop for the Mediterranean Ridge (Chamot-Rooke *et al.*, 2005). The ridge was built up by Oligocene to Miocene sediments implicated in south-western thrusts with Messinian evaporites and thick salt layers within flexural basins accommodated in a piggy-back thrust propagation (Tay *et al.*, 2002). The ridge was detached from its initial substratum along Messinian evaporites and deeper decollement horizons.

The interpreted tracing of the MCS profile MS-71 (position in Fig. 2) displayed in Fig. 15, shows the continental slope consisting of a series of stacked Alpine units, including, from east to west: the Gavrovo zone (acoustic basement of the upper continental slope) with the obducted

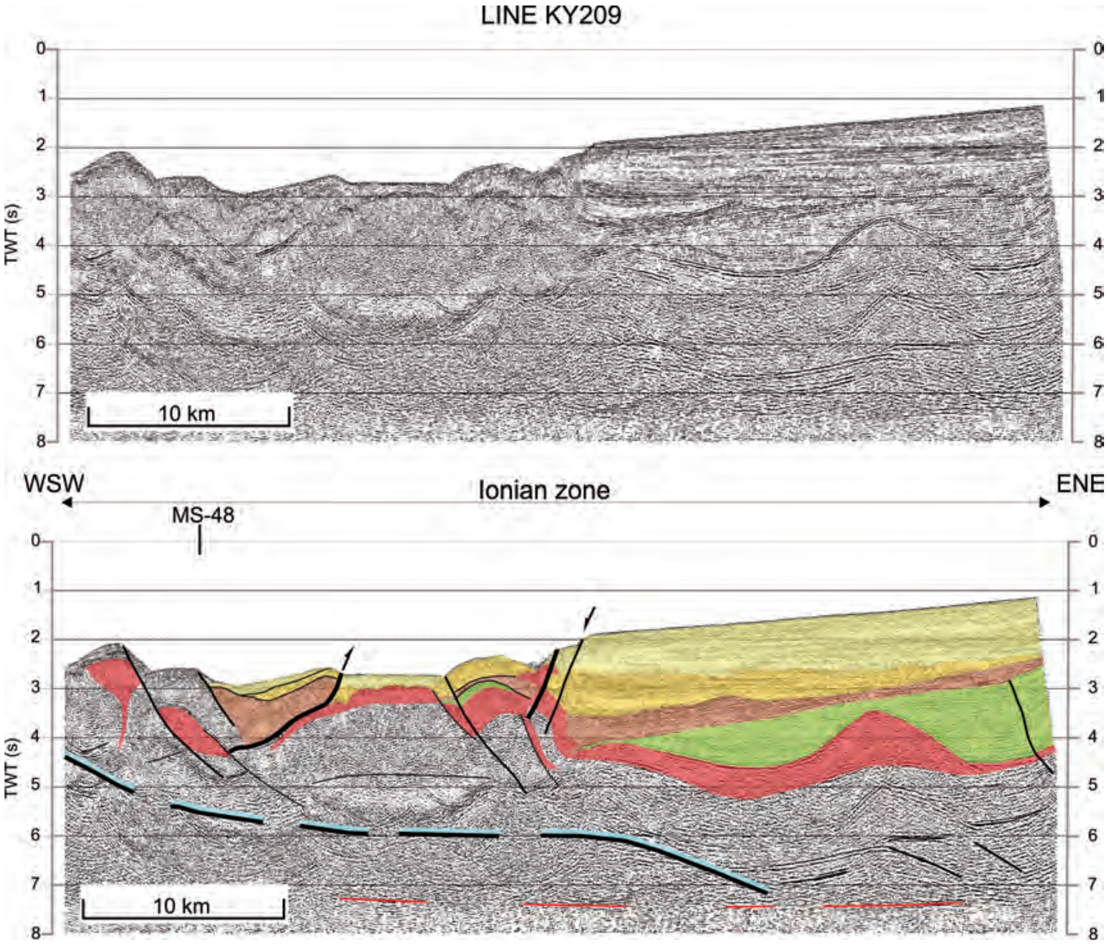

Fig. 12 - Section and interpretation of the line KY209 illustrating the geological structure of the upper to middle continental slope SE of Strophades. The area rests on the Ionian Unit, which includes, at depth, thick Triassic salt-bearing layers (in red). These layers have been involved in the various thrust sheets and locally show typical (diapir-like) salt deformations.

Pindos units; the Ionian thrust sheets (constituting most of the mid-slope, with Oligocene to Miocene flysch sequences and thin recent sediments draped on the top); and the *Apulian* Ridge domain. In the interpretation, the NMT appears as a piggy-back thrust propagating system shaped by a presently active extending half-graben. The westward emplacement of the Gavrovo-Pindo nappe complex is affected by a network of normal faults, particularly well marked on the upper continental slope and shelf where they have generated basement horst and sediment-filled graben features. The reactivation of the westernmost front of the Gavrovo thrust results in normal to listric faults indicating the present-day extension dominating the upper plate.

The profile MS-72 (Fig. 15) shows the seaward continuation of the sequences outcropping in the Peloponnese and extending along the Peloponnese-Crete Hellenic Arc Ridge (Kokinou and Kamberis, 2009). The increased thickness of the mechanically strong and rigid Gavrovo platform on the western side of this ridge marks the frontal accretion related to the westward migration of the External Hellenides. Reflecting horizons at 8 s TWT that are very clear in

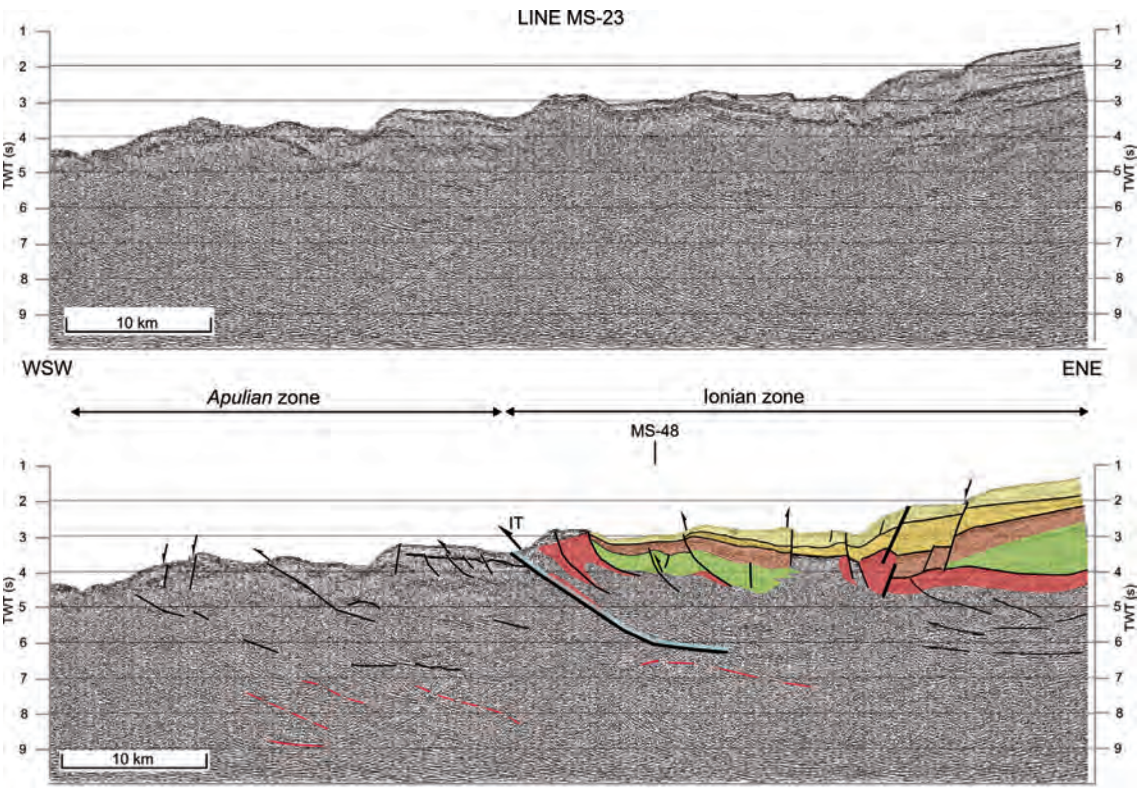

Fig. 13 - Line MS-23 with thick and deformed packages of presumed salt layers in the Ionian zone and short wavelength acoustic basement relief in the *Apulian* Ridge domain.

the NMT part of this profile, but also present on line MS-71, presumably indicate the top of a thinned continental crust. This stratified domain indicates the presence at depth of former Mesozoic sediments of the old and deep Ionian basin or fragments of the North-African continental lithosphere. The detachment interval at more than 12 km depth may separate the upper plate of the External Hellenides and the lower Ionian subducting plate.

5. Discussion

Most of the upper continental margin has been created within the former Alpine thrust units. The Zakynthos-Strophades massive ridges underline the thrust contacts between the Ionian and *Apulian* Ridge margin. This thrust was active during Miocene to Lower Pliocene, although the westward movements continued in the *Apulian* zone during the Quaternary.

Tracings of E-W trending MCS profiles across the continental margin are shown on Fig. 16, and illustrate the main domains of the Peloponnese margin. From Zakynthos to the latitude of the Messinia Peninsula, the Ionian thrust complex (in light blue on Fig. 16) seems to be continuously overthrusting the *Apulian* Ridge margin, that is itself characterised by strongly fractured acoustic basement features. The E-W halokinetic movement of the Triassic evaporites, that represent ductile and mobile sequences within the major morpho-structures, are expressed on the margin

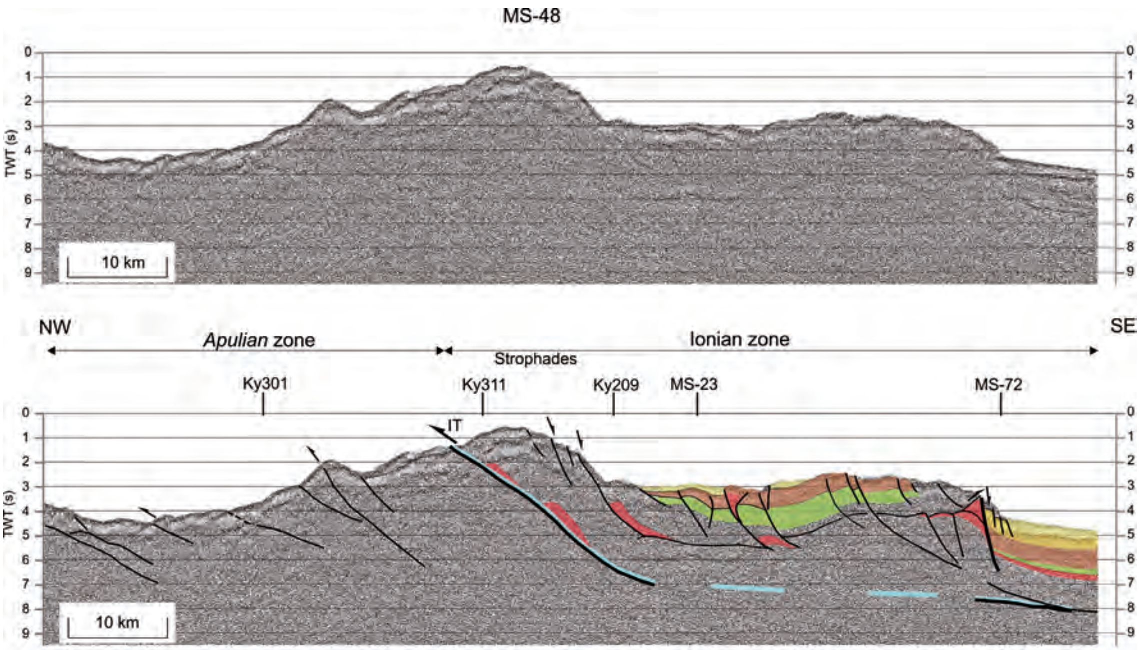

Fig. 14 - The seismic line MS-48 running almost parallel to the Strophades Ridge and the western slope. Normal faults characterise the southern sector of the section.

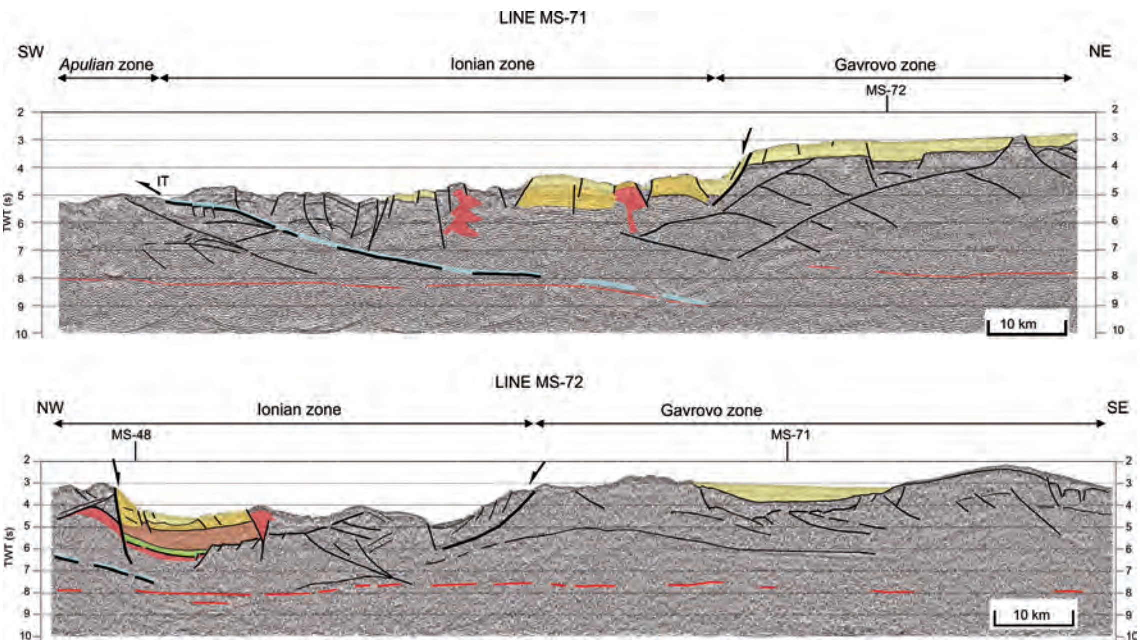

Fig. 15 - Profile MS-71 (above) crossing the Messinia Gulf and the NMT (see text for explanation) and profile MS-72 (below) parallel to the structure of the western front of the Hellenic Arc. Large wavelength deformations of the presumed Gavrovo shelf limestone with Pindos units and the metamorphic-crystalline basement can be seen. The Gabrovo frontal thrust has been reactivated as normal listric faults.

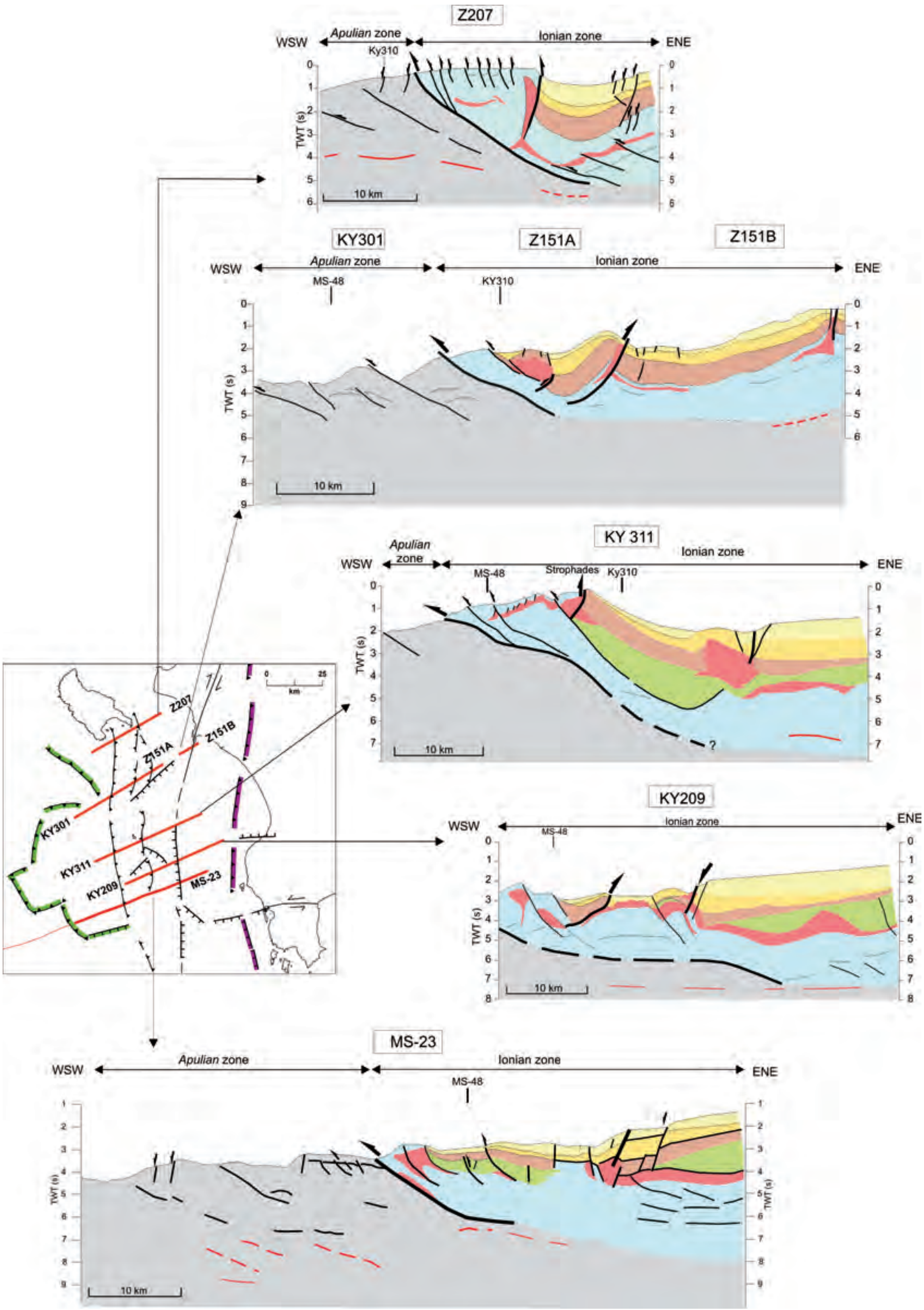

Fig. 16 - Simplified interpretations of the profiles crossing the continental margin in SW-NE direction from Zakynthos in the north to the Messinia Peninsula in the south. In light blue the Ionian zone limestone; in red probable Triassic salt bearing layers; in light grey the *Apulian* Ridge limestone units; and the post-Alpine sedimentation as per Fig. 4.

by the Zakynthos Ridge, the Strophades swell, and along important tectonic features. The diapiric movements continue in the present day in the Ionian zone as revealed by the sea floor antiforms on the seismic lines.

Backthrusts accompanied the final settling of the Ionian frontal thrust in Lower Pliocene. These are well imaged especially when accompanied by salt intrusions upsetting the Oligo-Miocene flysch and the subsequent Mio-Pliocene deposits filling the Ionian zone flexure (e.g., line Z151A in Fig. 6). The recent uplifts of the ridges are recognised by the tilting of the Pleistocene sediments (line Z207 in Fig. 5).

The westernmost domain of the lower continental slope, probably made up of outcropping *Apulian* Ridge limestone, is intensively cut by a network of NNW-SSE and SW-NE to E-W directed fractures. These are particularly numerous in the vicinity of Zakynthos and between Zakynthos and Strophades Islands. This domain was deformed during the Late Pliocene and Quaternary and is well imaged in the morphotectonic interpretation of Camera *et al*. (2014).

Based on the interpretation of the seismic reflection data, extrapolated using the detailed bathymetric morphology, a structural diagram of the studied area has been constructed (Fig. 17). The Ionian frontal thrust zone is a continuous feature running approximately along a N-S axis from the Island of Zakynthos to a deeper area, south of Strophades. Here, it can tentatively be detected on line MS-23 (Fig. 13), and even on MS-71 (see Fig. 15). Triassic salt intrusions appear closely associated with the Ionian zone and along the entire length of the frontal thrust zone. The Gabrovo frontal thrust is tentatively indicated in the map, but it has not been revealed by the MCS profiles and the high resolution lines do not penetrated to the depth of the thrust. It was recognised on land by Kamberis *et al*. (2000b) and continued offshore in the Kyparissiakos Gulf by other authors (Karakistios, 1995; Mavromatidis *et al*., 2004). West of the Messinia Peninsula it can be seen in unpublished lines of Auroux *et al*. (1984) and was prolonged southwards along the Hellenic Arc structures by Kokinou and Kamberis (2009), but the thrust appears in this area reactivated as normal or listric fault.

The recent tectonic evolution from the Alpine orogenic thrusting episodes to the more recent trans-extensional and NNE-SSW shear displacement events on the upper plate is due to the anticlockwise rotation of the Peloponnese continental margin (Reilinger *et al*., 2009). Within this framework the series of sedimentary basins running along the middle slope, including the rhombohedral Strophades basin NE of Strophades, could be interpreted as active thrust-top “pull apart” type basins. They could have been generated in response to this anticlockwise strike-slip regime affecting the Peloponnese, that is, itself, due to the ongoing collision between the Hellenic front and the “Puglia” nose in the Cephalonia sector. The NNE-SSW dextral strike-slip motion is in good agreement with the focal mechanism of a significant earthquake [the Andravida or Achaia-Elia earthquake of Feng *et al*. (2010)] which occurred in the area of Patras in June 2008. The aftershocks line up well, indicating the presence of a deep fault that would pass through the Katakolo Peninsula to the south and follow the line of salt domes that are deforming the sea floor (Fig. 11). These diapiric structures are intruded along a fracture in the continental slope that forms the eastern boundary of the Strophades basin (Figs. 16 and 17).

This basin was formed by the active uplift of Strophades in the SW, the tilting of the continental margin to the NE and the subsidence due to continued recent deposition along the ENE-WSW normal fault on its northern boundary. A fracture zone that appears to be a continuation of the Andravida fault defines its eastern boundary and the Zakynthos-Strophades Ridge its western

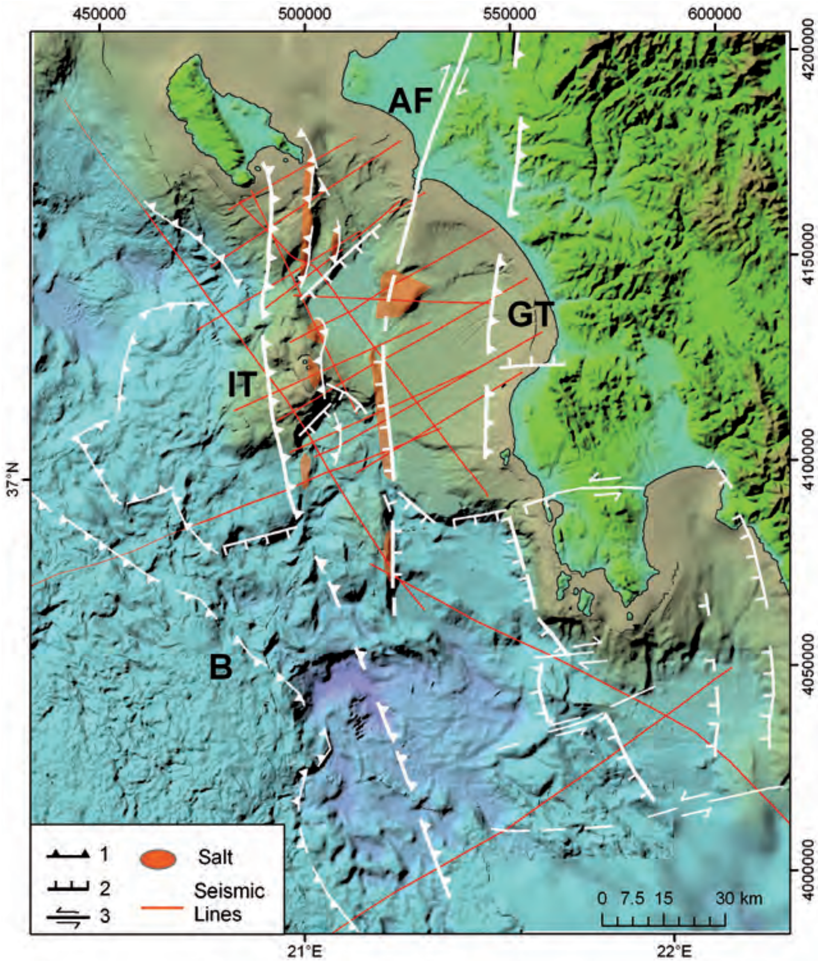

Fig. 17 - Structural sketch map of the Peloponnese continental margin within the SEAHELLARC area. All available MCS data have been integrated with the shallow penetrating seismic data and interpolated using the very detailed morphological control from the swath bathymetry: 1 - thrust faults; 2 - normal faults; 3 - strike-slip faults; AF - Andravida fault; GT - Gavrovo thrust; IT - Ionian thrust; B - Mediterranean Ridge backthrust, corresponding to the western extension of the Hellenic backstop.

boundary. In both these structures, the role of the Triassic salt and the re-activation of thrusts as normal faults can be seen, however there is little evidence of strike-slip motion. The ENE-WSW northern boundary is a normal fault, as is the parallel boundary of the basin to the south of Strophades; both these faults have a throw to the south of the order of 1000 m. The eastern boundary of this second basin could be the further continuation of Andravida fracture zone, but its western boundary is not well defined. Whereas the mechanism for these basins could be "pull-apart", further seismic data are needed to fully resolve the complexity of these structures.

Towards the east, the upper continental slope is the locus of recent thick sedimentation. Significant active tectonic features are detected along the southern margin of the Katakolo Peninsula and offshore the Messinia Peninsula, with the presence of faults that are known to be active onshore.

6. Conclusions

The overall structural fabric of the margin is clearly imprinted by the former Alpine structural heritage including the Ionian and *Apulian* Ridge thrust units, which constitute most of the acoustic basement of the margin. The Ionian thrust zones may have still been active until Early Pliocene and are well expressed on the morpho-structure of the margin, particularly at the level of the Strophades and Zakynthos uplifted ridges. This acoustic basement is however cut by N-S and E-W tectonic lineaments, which seem to originate from two distinct episodes:

- a dense fracture network affects the margin, particularly west of Zakynthos-Strophades ridges, and, to a lesser extent, on some areas of the upper continental margin. This, apparently still active, and chiefly extensional system, is a signature of the overall east-west directed extension, which affected the western Aegean domain border in Late Pliocene and Quaternary times (Angelier *et al.*, 1982; Papanikolaou and Royden, 2007);
- NNE-SSW shear displacements in the upper plate that appear to have generated more localised trans-extensional related morpho-structures including the two deep, still deforming slope basins NE and south of Strophades. The scarp observed on the southern part of the profile MS-48, and on the western end of MS-72, may represent the border margin of a further extensional basin that opens towards the north Matapan trough and the inner basin of the Mediterranean Ridge.

Normal listric faults mark the frontal thrust of the Gabrovo on the upper continental slope and shelf of the Hellenic Arc, while trans-extensional tectonics dominate the inner Mediterranean Ridge basin dissecting the Gabrovo front. Reflecting horizons at 8 s TWT indicate, in this area, the top of a stratified domain denoting the presence at depth of former sediments of the deep Ionian basin, a fragment of the North-African continental lithosphere. They may evidence the detachment interval at more than 12 km depth that separates the upper plate of the External Hellenides from the lower Ionian subducting plate.

The Peloponnese continental active margin may be considered as a transition between a more or less frontal subduction, still operating along the continental margin off the Messinia Peninsula to western Crete and the Cephalonia strike-slip fault zone, which highlights the in-progress collision between the "Puglia" continental nose and the extended Aegean plate, and the anticlockwise rotation of this margin.

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Corresponding author: Nigel Wardell
Istituto Nazionale di Oceanografia e di Geofisica Sperimentale,
Borgo Grotta Gigante 42c, 34010 Sgonico (TS), Italy
Phone: +39 040 2140228; fax: +39 040 327307; e-mail: nwardell@inogs.it