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A new seismogenic model for the Kyparissiakos Gulf and western Peloponnese (SW Hellenic Arc)

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ABSTRACT In order to define seismic hazard with sufficient accuracy required for engineering applications, we initiated a multidisciplinary geoscientific study offshore western Peloponnese, focusing on the Kyparissiakos Gulf. Multibeam swath bathymetry localised unstable coastal slopes, which were later investigated by high resolution seismic profiles. Sediments and crustal structures were studied by multi-channel seismic recordings and active large-offsets seismic profiling. We established an onshore/offshore local seismic array that recorded 3500 micro-earthquakes in two months, and combined the results with historical and digital seismicity data in order to understand the active crustal deformation. These findings were further combined with geological mapping and tectonic observations from onshore Peloponnese and available offshore data. All this geologic and tectonic information was coupled with evidence from the analysis of historical and recent seismicity with the aim of identifying the seismogenic sources. We have defined nine seismogenic zones in western Peloponnese that are significantly different from those published in the literature. The new zonation addresses more accurately the deformation of the crust and sediments, and is the basis for a reliable seismic hazard analysis and seismic risk assessment. We identified a large area of the northern Peloponnese and the Ionian islands of Lefkas, Cephalonia, Zakynthos and Strophades, to be involved in a SW-ward oriented crustal extrusion, dominated by two major dextral deforming strike slip faults: Cephalonia and Andravida with their offshore prolongation. Some changes with respect to the Greek zonation in the literature have been introduced in the region surrounding the new nine seismogenic zones to reach a homogeneous cover of the whole Peloponnese.

Key words: tectonics, seismicity, seismogenesis, seismic hazard, Peloponnese, SEAHELLARC.

Fig. 1 – Index map of the study region. Green triangles represent the OBS network; yellow triangles show the seismological stations recording on land.

1. Introduction

The western Hellenides are being deformed by thrusting, normal and wrench faulting, and westward movement of the Hellenic nappes due to crustal shortening. This is expressed by high seismicity and intense tectonic deformation of the upper crust and sediments (e.g., Aubouin *et al.*, 1976; Makris, 1978; McKenzie, 1978; Le Pichon and Angelier, 1979; Jacobshagen, 1986; Ambraseys, 2009; Makris and Papoulia, 2009; Papoulia and Makris, 2010).

The Hellenic nappes, according to geological reconstruction, have accomplished major horizontal movements to the SW and SE and are currently moving in this direction with a velocity of ca. 3.5 cm/a, as revealed by GPS observations (Kahle *et al.*, 1998; McClusky *et al.*, 2000; Reilinger *et al.*, 2010). Shaw and Jackson (2010) have stressed the complexity of the ongoing tectonic deformation in this area by re-evaluating focal mechanisms of selected events from western Greece. They showed that the subducting oceanic Ionian lithosphere is decoupled from the overlying continental Aegean, due to thick sediments involved in the subduction process.

The aim of this paper, in the framework of the SEAHELLARC project (Papoulia *et al.*, 2014a), is to demonstrate how the complexity of the tectonic processes can be precisely described and used in delineating local seismogenic zonation by multidisciplinary studies for the seismic hazard assessment of the Pylos region. The region under investigation is the broader Kyparissiakos Gulf area of western Peloponnese continental margin (Fig. 1). To derive the seismogenic model (see also SEAHELLARC Working Group, 2010), we combined Deep Seismic Soundings (DSS) of Wide Aperture Reflection Refraction Profiling (WARRP), multichannel reflection seismics (MCS), high resolution seismics, microseismicity observations with local "amphibious" seismic arrays, high resolution bathymetry, regional historical and digitally recorded seismicity, considering also tectonic and geological information from the literature for the surrounding onshore areas.

2. Geological and tectonic setting

The subduction of the oceanic domain of the African lithosphere below the southern margin of Eurasia is believed to be a continuous process initiated in Late Cretaceous (closing of the Tethys Ocean) and is still active to the present day (Jolivet and Brun, 2010). In western Peloponnese the various tectono-stratigraphic units resulting from this so-called Alpine evolution are emplaced as successive thrust sheets between Oligocene and Late Pliocene, and are known, from east to west, as the Pindos trough, the Gavrovo-Tripolitza Ridge (mainly made of shelf carbonates of African-Adria affinities), the Ionian trough, and the Apulian Ridge (Aubouin, 1965; Underhill, 1988; Van Hinsbergen *et al.*, 2006). The Pindos oceanic realm has been the first to be involved in the shortening process, which finally lead to ophiolite obduction over the eastern trough margin.

Shallow water and rigid carbonate sequences, covered by Late Eocene-Early Oligocene syn-orogenic flysch-type sediments, mainly characterize the Gavrovo-Tripolitza zone, a present day antiform induced by bulging and bending at the front of the Pindos obduction. Its western limit correlates on land to the Late Cenozoic frontal thrust revealed by seismic data in NW Peloponnese (Kamberis *et al.*, 2000b) and suspected to continue offshore SW-wards.

Triassic to Eocene pelagic carbonates and Late Eocene-Oligocene flysch characterize the Ionian zone; this domain is deformed by an array of thrust-sheets that propagate westwards. Overloading, due to the tectonic transport and subsequent deposition of the Gavrovo piles on the Ionian zone, induced a lithosphere flexure and may have been the origin of important halokinetic mobilisation of Triassic evaporites from east to west (Underhill, 1988). In the Ionian zone such diapiric deformation seems to continue to the present day as revealed by seismic reflection data (Monopolis and Bruneton, 1982). In the flexural subsiding area of the Ionian zone thick syn-orogenic clastics were deposited. These sequences are observed on seismic reflection profiles across the Kyparissiakos Gulf where they appear as thick Cenozoic continental deposits covered by Pleistocene to Holocene lacustrine and marine deposits.

The Apulian Ridge is made of massive shelf carbonates outcropping in the Ionian islands of Cephalonia and Zakynthos. The Apulia zone was affected by shortening during Pliocene times expressed by the tectonic emplacement of Ionian thrusts over its eastern margin (the so-called pre-Apulian zone). Compressive deformations, active until Quaternary times, have been evidenced by a seismic line recorded during the Streamer Project survey between the two islands and indicating crustal shortening (Hirn *et al.*, 1996; Kokinou *et al.*, 2006).

While in eastern Peloponnese metamorphic units from the Mani peninsula are believed to represent a more or less autochthonous basement, outcrops of the Ionian, Gavrovo and Pindos units are widespread elsewhere (Fountoulis and Moraiti, 1994). The Ionian units outcrop on the south-eastern half of the Island of Zakynthos, where they are expressed by blocks of Triassic evaporites intruding Pliocene-Pleistocene sediments (Zelilidis *et al*., 1998), while the massive limestones of the Apulian zone constitute most of the western half of the island (Underhill, 1989). Triassic evaporites (mainly anhydrites) were reached by drilling at Killini and at the nearby Katakolo Peninsula during hydrocarbon exploration (Kamberis *et al*., 2000a; Mavromatidis *et al*., 2004; Etiope *et al*., 2006). The Strophades Island is on the top of a wide submarine swell continuously uplifting to the present day (Stiros, 2005) and it is made up of thrust units injected by salt bodies, which are probably of Triassic origin.

Clement *et al*. (2000) proposed a progressive westward migration of the Alpine deformation through time on top of an east-dipping interface, detected at a depth of about 12 km SW of Zakynthos Island, representing the inter-plate subduction channel. This seismic boundary zone shows a stratified interval, interpreted as the presence, at depth, of the former Mesozoic sedimentary cover of the Ionian Basin (Laigle *et al*., 2002).

The geological structures of the shallow section of the western Peloponnese continental margin (first few kilometres) have been illustrated and discussed by Lyberis and Bizon (1981), Monopolis and Bruneton (1982), Auroux *et al*. (1984), Kamberis *et al*. (2000a), Papanikolaou *et al*. (2007). Monopolis and Bruneton (1982) propose that the Ionian thrusted units are extending beneath most of the upper continental slope and, that Triassic salt injections significantly contribute to the structural fabric of the upper to middle continental margin in the area around Zakynthos Island and the Killini and Katakolo peninsulas, a hypothesis also proposed by Kamberis *et al*. (2000a) and by Etiope *et al*. (2006). Along the Peloponnese coasts, the onshore area is itself mainly cut by E-W trending active strike-slip extensional faults and N-S directed extensional basins (Fountoulis and Moraiti, 1994). Various units known in the Peloponnese Hellenic thrusts are exposed in Kythira and Antikythira islands and can partly be extended to Crete (Kokinou and Kamberis, 2009). Recent extensional tectonics, a consequence of a general SW-ward anticlockwise displacement of the whole area along main dextral strike-slip faults, are progressively inverting, from east to west, the various thrusts as normal or extensional detachment faults; N-S directed extensional basins cross and disrupt the thrust belt of the Hellenic Arc (Papanikolaou *et al*., 2007).

At the foot of the margin, the deep (up to 5000 m water depth) North Matapan Trough is imprinted on the Inner Plateau of the Mediterranean Ridge, whose eastern and actively deforming accreted sedimentary pile rests on a continental crust-rooted backstop of variable width (Truffert *et al*., 1993; Le Pichon *et al*., 2002). This part of the Mediterranean Ridge was built up, from Oligocene to Miocene, by sedimentary thrust slices intermixed with Messinian evaporites, while, eastwards, thick Messinian salt layers were deposited and trapped in flexural basins, accommodated by piggy-back thrust propagation (Tay *et al*., 2002; Chamot-Rooke *et al*., 2005).

Using passive seismological data and wide-angle seismic investigations, Hirn *et al*. (1996) and Sachpazi *et al*. (2000) provided insights on the deep structure of the Cephalonia transform fault zone, while Clement *et al*. (2000) illustrated the structure of the intra-plate layers in areas around Cephalonia and Zakynthos islands and in the vicinity of the Kyparissiakos Gulf. They conclude that the Apulian and Ionian zones started to override the ocean-floored Ionian basin lower plate during Late Neogene. Recently, Gesret *et al*. (2010) confirmed the oceanic nature of the lower plate, the African slab, subducting beneath Peloponnese using high-resolution receiver functions modelling. Suckale *et al*. (2009) showed the basis of this subducting oceanic domain to be at about 35 km beneath the western Peloponnese coasts and reaching a depth of 150 km along the eastern coasts facing the Aegean Sea. As indicated by Makris (1978) and Makris *et al*. (2001, 2013), the Moho of the Hellenic upper plate is itself at about 30-35 km beneath central Greece and the western Aegean Sea.

3. New data on the tectonic evolution of Kyparissiakos – SW Peloponnese derived from active and passive experiments through the SEAHELLARC project

3.1. Morpho-bathymetric data

A precise mapping (DTM at 50 m) of the morphological characteristics of an area of approximately 12,000 km^2 (200 km by 60 km) was performed onboard the OGS R/V EXPLORA using multibeam sonar and swath mapping techniques. A final map (DTM at 100 m) resulted from a compilation of these data together with complementary multibeam data collected by the Hellenic Centre for Marine Research (HCMR) in 2006 and by IFREMER in 1995; the areas not yet covered by swath bathymetry have been added using the Gebco_08 grid. The shallow structure (up to 100 m penetration depending on the area) of the recent sedimentary cover was imaged using a high-resolution sub-bottom CHIRP system; these data have been used, concurrently with the detailed morphology, to better assess the various active geological processes, particularly slope by-passing and sedimentary failures, debris flows, and faulting, which characterize the area and are directly imprinted on the seabed and sub seafloor. The interpretation is given in Camera *et al*. (2014). One of the unexpected results from this analysis has been to draw attention to submarine failures and sedimentary destabilization particularly in the north-eastern zone of the study area. The observations prove a real potentiality of sedimentary collapse and therefore of local tsunamis, particularly along the shelf break nearby Cape Katakolo. In a recent past (Holocene) major submarine failures, well shown by large debris flow deposits detected in the sedimentary cover, have already clearly occurred in the area and have probably triggered significant tsunamis whose records may be potentially discovered along the coast.

3.2. Single channel and multi channel seismic data

In 2006, during the SEAHELLARC OBS deployment with the R/V AEGAEO, a few complementary, high-resolution seismic (HRS) reflection profiles were recorded, using a small airgun source. Through interpretation of these profiles, instabilities of sediments at steep escarpments were identified; they may cause landslides triggered by earthquakes and induce local tsunamis that pose a significant threat to the coastal zones of western Peloponnese (Fig. 2). Their interpretation was integrated with that of the MCS data using the package Kingdom (T.M. of Seismic Micro-Technology) to analyse, visualise and interpret the complex geological structures in 3D.

Industry multichannel seismic reflection lines, acquired in the 1980s, were made available by the Public Oil Corporation of Greece; a few MCS lines collected in the study area by OGS in the 1970s have complemented this data set. All seismic lines have been reprocessed at the

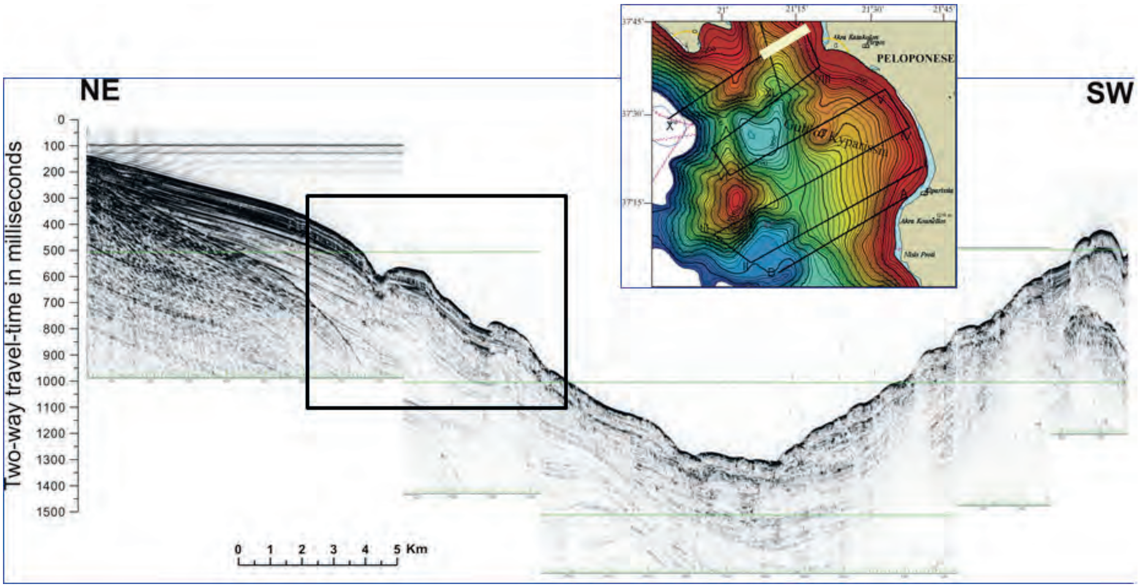

Fig. 2 - Example of a high resolution seismic profile located NW of Cape Katakolo, showing submarine landslides.

OGS processing centre in Trieste using FOCUS (Paradigm Geophysical) processing package. The final seismic sections were provided in filtered stack and migrated versions. Based on the interpretation of these reprocessed data a structural sketch of the study area, extrapolated using the available detailed bathymetry, has been constructed (Wardell *et al.*, 2014).

The Ionian and Apulian Ridge units constitute most of the acoustic basement of the continental margin. The Ionian thrusts, which may have been active until Early Pliocene, are still well expressed on the morpho-structure of the Strophades and Zakynthos uplifted areas, where the Ionian frontal thrust zone, from Zakynthos Island to the deeper area south of Strophades, shows a more or less continuous feature running approximately along a N-S trend.

A dense network of fractures cut across the lower margin, west of the Zakynthos and Strophades ridges. A similar pattern, but to a lesser extent, characterizes several areas of the upper continental margin where extension is prevailing; this is a consequence of the general E-W directed extension propagation, which has affected the western Aegean domain border since Late Pliocene. Localised transtensional morpho-structures appear to have been generated within the NNE-SSW-directed regional shear displacements, and in particular the deep, still deforming, rhombo-shaped Strophades basin extending to the NE and south of Strophades. This feature is interpreted as an active thrust-top pull-apart type basin.

A NNE-SSW dextral strike-slip motion is in good agreement with the focal mechanism obtained for the strong (M_W 6.4) earthquake that occurred in the area of Patras on June 8, 2008 (e.g., Feng *et al.*, 2010; Papadopoulos *et al.*, 2010). The aftershocks of this event line up well, supporting thus the presence, at depth, of a tectonic lineament, the Andravida fault zone, which passes through the Katakolo Peninsula, to the south, and correlates with a line of small reliefs deforming the sea floor and interpreted as probable salt domes.

The diapiric structures, associated to the underlying Ionian zone, may have intruded along the fault system, which represents the eastern boundary of the Strophades pull-apart basin; the

Zakynthos and Strophades ridges, where Triassic salt is intruded all along the frontal thrust of the Ionian zone, constitute the western border of this basin. Uplifting, backthrusting, tilting and faulting testify to the present day high tectonic activity of this area of the continental margin.

The important scarps, which shape the southern part of the study area, indicate borders of other extensional basins that are open towards the north Matapan Trough and the inner domain of the Mediterranean Ridge. Normal, possibly listric, faults underline the frontal thrust of the Gavrovo and of its underlying metamorphic basement detected all along the upper continental slope and shelf; trans-tensional tectonic affects most the Hellenic Arc in the area including the Gavrovo frontal thrust. Sub-horizontal reflecting horizons, detected around 8-s TWT, may indicate a detachment zone, lying at a depth of around 12-13 km, which separates the upper plate, the External Hellenides units, from the lower plate, that is the Ionian subducting oceanic crust and its sedimentary cover.

The tectonic deformation of the Strophades Island is also described by Stiros (2005) and is in agreement with the general deformation pattern derived by the present observations. As Shaw and Jackson (2010) showed, the subducting slab is decoupled from the crust above it. It is, therefore, soft deformable sediments that account for the decrease of frictional forces between the two interacting rigid lithospheric systems. Only densely spaced OBS stations and shorter shooting intervals could map the deeper interfaces with sufficient resolution needed to identify the sediments involved in the subduction and the velocity inversion they would cause.

3.3 Wide angle reflection/refraction seismic data - OBS profiles

Using large offset seismic data from OBS observations along five profiles, Makris and Papoulia (2014) delineated the velocity structure of the crust and upper mantle offshore western Peloponnese, between Zakynthos Island and the Gulf of Messinia. By applying a recently developed refraction migration procedure (Pilipenko and Makris, 1999), the fault systems at crustal depth were recognized. The results of active seismic observations were combined with microseismicity and high resolution swath mapping, to delineate the tectonic structures in the offshore area of western Peloponnese.

The Kyparissiakos basin appears to be strongly affected by the dextral strike slip faulting of the Andravida shear zone, which is displacing the geological formations SW-wards. As a consequence transtensional basins and transpressional uplifts have been formed. Examples are the rhombic basin NE of the Strophades Island and the Strophades uplifted block itself (Papoulia *et al.*, 2014b). Correlating the onshore geological units with those mapped offshore these authors have placed the limits of the Ionian to the pre-Apulia zones in the Kyparissiakos area, and the pre-Apulian, Ionian and Gavrovo zones south of Messinia. They propose that the Hellenic Alpine nappes do not extend beyond the pre-Apulian thrust, in the backstop area. This observation contradicts previous models (Aubouin *et al.* 1976 and Le Pichon *et al.* 2002) for the Ionian backstop, where the limit of western Hellenides is placed deep in the Ionian Sea, and extends it to the Mediterranean Ridge, stating that the backstop consists mainly of Alpine Hellenic nappes. The crustal and tectonic elements mapped by the active seismic experiment greatly helped to delineate the seismic zones offshore and onshore western Peloponnese and the Ionian islands.

In addition to the standard evaluation of the active seismic observations a special processing of four of the OBSs profiles as standard reflection seismic data based only on near vertical incidence arrivals was successfully performed (Barison *et al.*, 2014). A detailed velocity field, from first break tomographic inversion, was applied in a wave equation datuming procedure to relocate shots and receivers on the same datum plane. A standard processing sequence was further applied to the corrected data; this allowed a good image of the deep crustal interfaces to be obtained. The results revealed the geometry of the crustal structures, in particular, an upper continental and a lower oceanic plate separated by an inter-plate detachment. This reflecting zone is located at a depth varying between 10 to 20 km. The external Hellenides constitute most of the upper plate, which overrides the oceanic crust-floored Ionian deep basin, characterized by a crustal thickness of 9 to 10 km. On these sections, the Moho, globally gently dipping from north to south, deepens from the Ionian Sea towards the Peloponnese coasts where it quickly reaches depths in the order of 35 km.

3.4 Microseismicity recorded from an onshore/offshore seismic array

To better constrain the microseismic activity and associate it with local tectonics, an onshore/offshore seismic array was deployed in the Kyparissiakos Gulf, in the Zakynthos and Strophades islands, and in the surrounding coastal regions of western Peloponnese. More than 3500 micro-earthquakes were located (Papoulia *et al.*, 2014b) in a two-month period in the Kyparissiakos Gulf and its vicinity (Fig. 3). Most of the seismicity is concentrated along major thrust belts and the very active strike-slip fault systems. Sub-crustal events extending to 100 km depth were mapped in an area NE of the Strophades Island, defining the location of lithospheric fracturing of the Ionian slab being forced below a continental crust of laterally variable thickness. Location accuracy of the seismic foci was optimized by applying a 3D velocity model developed from 2D active seismic data and 3D gravity modelling (Makris *et al.*, 2013). The precise location of micro-earthquakes, mapped by local seismic arrays and ranging between 0.5 to 1 km, depending on depth, allows active faults within the crust and sediments to be delineated with the very high accuracy that is needed for optimizing seismic hazard engineering applications.

4. The seismological contribution

The area of interest is characterized by high seismicity confirmed from earthquake records covering a long time span extending from antiquity to the present day. The occurrence of large and moderate historical earthquakes is known from a large number of documentary sources compiled, evaluated and presented by several authors in the form of catalogues, either descriptive (e.g., Mallet, 1853, 1854, 1855; Schmidt, 1879; Sieberg, 1932a, 1932b; Guidoboni *et al.*, 1994) and/or parametric (e.g., Galanopoulos, 1953, 1960, 1961; Shebalin *et al.*, 1974; Papazachos and Papazachou, 1989, 1997, 2003; Papadopoulos and Plessa, 2001; Papadopoulos and Vassilopoulou, 2001; Ambraseys, 2009).

4.1. Historical and instrumental seismicity

In the parametric catalogues, earthquake epicentres and magnitudes were gradually revised by adding new or better-documented historical observations. The core idea in the techniques used for the determination of the epicentre, is the proximity of the earthquake epicentre to the meizoseismal area. Earthquake magnitudes were determined by the conversion of elements

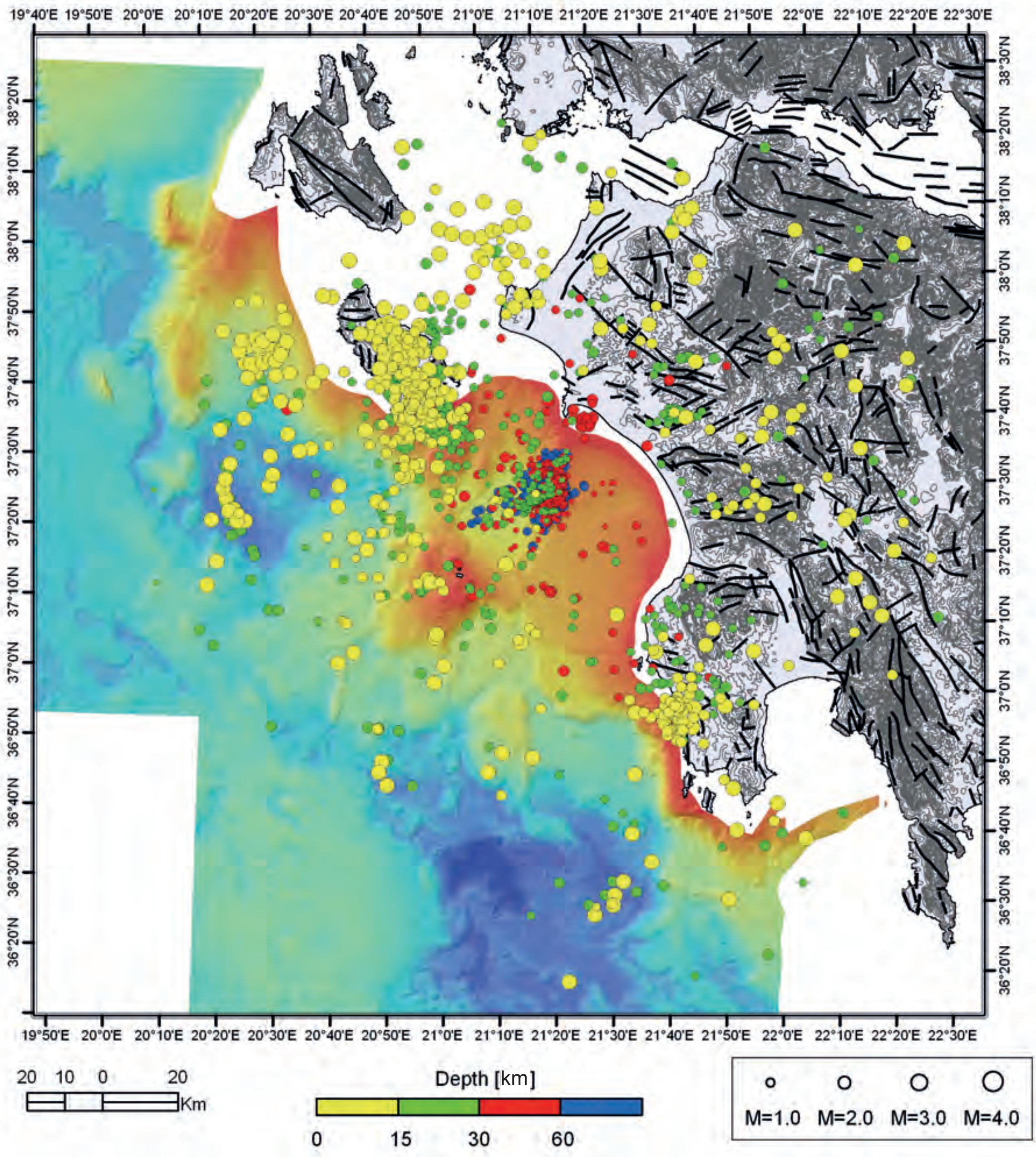

Fig. 3 - Seismicity recorded by the SEAHELLARC "amphibious" seismic array using a 3D velocity model defined from active seismic observations and 3D gravity modelling (Papoulia *et al.*, 2014b).

of the seismic intensity field to magnitudes based on empirical magnitude/intensity relations established from earthquake data of the instrumental seismology period, that is after 1910. Papadopoulos *et al*. (2014) have contributed to the project SEAHELLARC by revising the historical seismicity in the region of the Kyprissiakos Gulf and presenting a new parametric catalogue of historical earthquakes.

The instrumental catalogue of Greece, including the area of Kyparissiakos Gulf, starts in 1911 since when a seismograph instrument of the Mainka type has operated systematically in Athens. The gradual improvement of the monitoring capabilities became possible with the addition of more and more instruments by the National Observatory of Athens (NOA). The year 1964 represents a turning point since when the operation of modern seismographs was established by NOA according to the World Wide Standardized Seismographic Network requirements and the revision of the earthquake parameters by standardized procedures was started by the International Seismological Centre (Thatcham U.K.). Today the U.S. National Oceanographic Administration coordinates the earthquake recording by utilizing about 140 on-line stations, which are shared by NOA and by the seismological institutes of the Universities of Athens, Patras and Thessaloniki.

The available seismological information for Greece is highly variable in completeness and homogeneity due to the continuous procedure of improvement. To overcome this problem, a new catalogue was specifically constructed by NOA and used in the present study (known as the SEAHELLARC catalogue). It is derived from three data files: 1) the revised version (Papadopoulos and Plessa, 2001; Papadopoulos and Vassilopoulou, 2001; Papadopoulos *et al.*, 2014) of the historical earthquake catalogue of Greece (Papazachos and Papazachou, 1997) for the period between 550 B.C. to 1899; 2) the Thessaloniki instrumental earthquake catalogue of Greece, for the period from 1900 to 1999, and 3) the NOA earthquake locations from 2000 to December 2009 (see additional details in Slejko *et al.*, 2014).

The accuracy of epicentral location is estimated to be less than 30 km (Papazachos and Papazachou, 1997) for the historical period, and variable from 30 to 10 km for earthquakes after 1900 (Vlastos *et al.*, 2002). The depth estimate is more problematic, especially using macroseismic data: only a separation between shallow, intermediate, and deep events is generally feasible. The completeness of data is a very important aspect for seismic hazard assessment [see discussion in Slejko *et al.* (2014)] but less crucial for zonation purposes, where the qualitative space distribution is studied.

4.2. Statistical treatment of the recent seismicity

To investigate the active tectonic structures and the associated seismicity, we have applied a statistical methodology: the hypocentral probability (Peruzza *et al.*, 1991; Gresta *et al.*, 1998), which helps to identify the 3D-distribution of earthquake by defining the volumes where the earthquakes are most likely to have occurred. In particular, the statistical parameters of the earthquake location are assumed to represent the actual reliability of the focus position. According to the location code considered, the horizontal and vertical errors define the standard deviation of a normal distribution; the hypocenter, usually treated as a point, is scattered by this method over a volume of non-uniform probability. A clear vision of the possible hypocentral locations, at different probability levels, can be therefore obtained. Given the location of an earthquake A, the "elementary probability" EP(A) is defined as the probability that its hypocenter is located inside an elementary sample volume of the crust, and is simply given by the product of the related probabilities along the three reference axes. The hypocentral probability (HP: i.e., the probability of having at least one earthquake in a sample volume) can be considered a probabilistic indicator to enhance the actual informative content of a traditional hypocentral location. HP is computed for a single chosen sample cell; the computation of its space pattern can be performed in the following steps: 1) by defining the orientation of the desired section (usually a vertical plane, but horizontal or oblique planes can be treated as well),

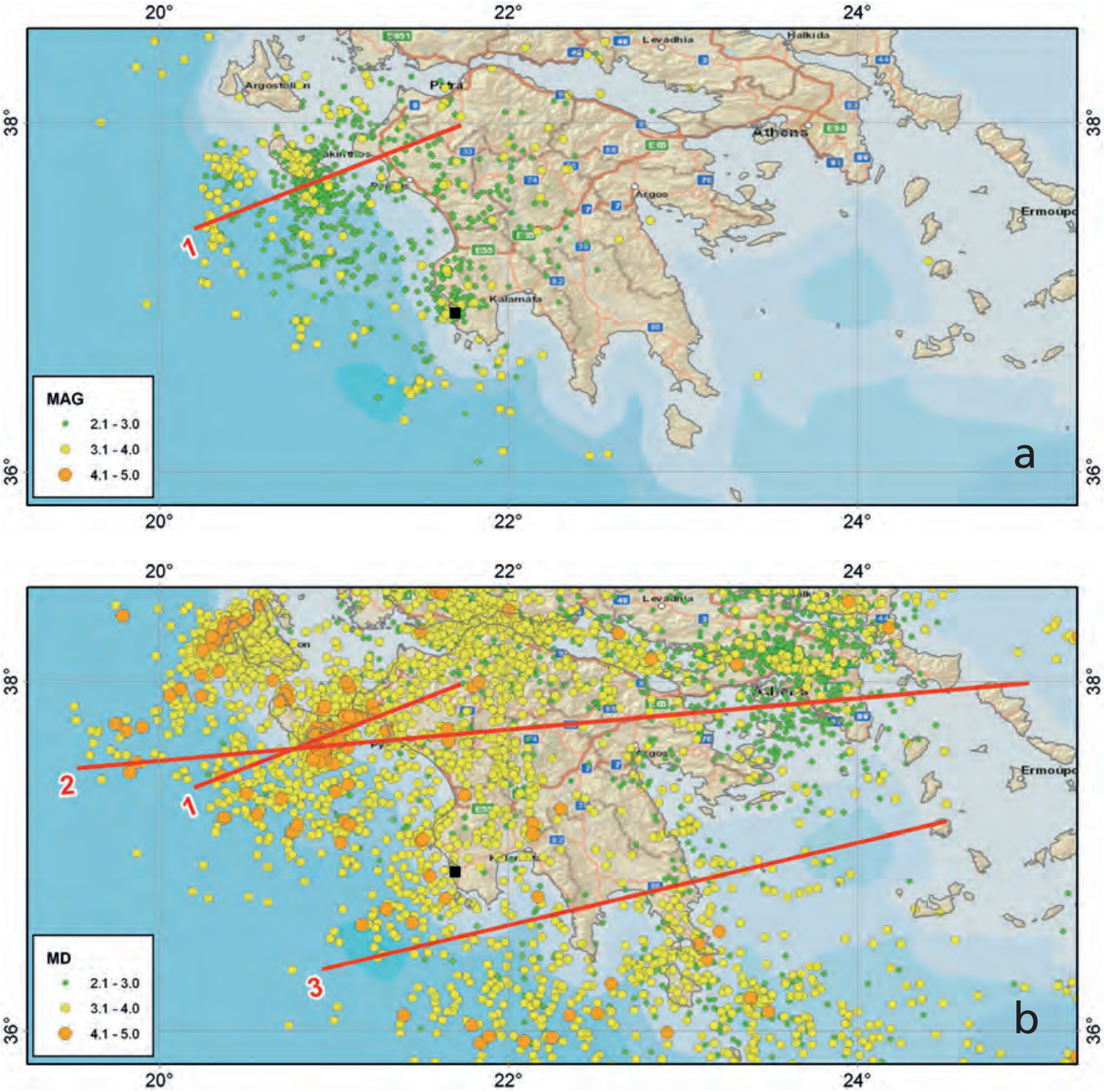

Fig. 4 – Characteristics of the seismicity data considered: a) recorded 2006 micro-seismicity; b) NOA00-07 earthquakes. The solid lines represent the 3 cross-sections investigated. The solid red lines represent the cross-sections investigated.

and the dimensions of the elementary cells lying in it; 2) by defining the database of earthquake locations; 3) by computing the EP of each event for each elementary cell lying in the section, and then computing the global HP values. In this way, 2D slices of the crust can be analyzed, with an automatic reduction in the importance of poorly located earthquakes and events outside the studied cross-section: the quality in the representation of the earthquake catalogue data is improved in this way, without losing the information carried by all the earthquakes, and the level of activity of a seismogenic source remains quantified.

The methodology described above has been applied to the earthquake data collected during the micro-seismicity survey (Papoulia *et al.*, 2014b), when 3503 earthquakes were recorded by a network of seismometers installed on land and offshore (OBSs). This methodology has also been applied in the same region to the data recorded by the Greek national network from 2000 till 2007 (NOA00-07 instrumental catalogue). This catalogue consists of 15,782 events located by NOA during the time they were using the HYPO71 (Lee and Lahr, 1975) computer program.

The distribution of the recorded micro-seismicity is represented in Fig. 3. The vertical error is rather small for the events located inside the area covered by the instruments recording the micro-seismicity (Papoulia *et al.*, 2014b) and depths gradually increase from offshore towards Peloponnese associated to the subduction plane suggested for the region (Papazachos *et al.*, 2000). For the NOA00-07 depth estimates, depth generally increases in Peloponnese from SW to NE, showing a pattern clearly associated to the subduction plane.

Three cross-sections (see the location in Fig. 4) approximately normal to the suggested subduction plane (Papazachos *et al.*, 2000) have been processed. Considering the general good quality of the two location datasets and the intrinsic characteristics of the statistical method applied, no filtering (e.g., according to the quality of the location) was applied to the data. The width of section 1 was fixed at 3 km in order to emphasise specific seismogenic features not contaminated by external characteristics. It cuts the bulk of the recorded micro-seismicity (Fig. 4a) as well as the most active sector of western Peloponnese according to the NOA00-07 catalogue (Fig. 4b).

Fig. 5 shows the HP calculated for the two catalogues along a SW-NE direction (cross-section 1, see its location in Fig. 4), i.e., normal to the subduction plane. A possible plane dipping around 35°E is not seen in this section (Fig. 5a): it may be due to the dominating shallow seismicity that is present in the SW part of the section. Fig. 5b shows a vertical bulk of higher HP, which reaches 90-km depth in the central part of the section. No clear evidence of the 35° dipping plane is seen, although a NE dipping plane can be hypothesised. An explanation of the vertical bulk is not easy and the large number of shallow earthquakes (with a depth of less than 30 km) in the central part of the section could mask other aspects.

To overcome this problem, two additional cross-sections have been processed (Fig. 6, see the location in Fig. 4b) using the NOA00-07 earthquake catalogue to investigate areas where the geometry of the Wadati-Benioff zone is thought to be deeper than in the area covered by the recorded micro-seismicity. In this case, a larger width of 10 km has been chosen to capture more events. We tried to cut the hypothetical Benioff plane perpendicularly with two sections, one in the northern part of our study area and the other in the south. The northern cross-section corresponds exactly to a section proposed by Papazachos *et al.* (2000). There is a quite good agreement (Fig. 6a) between the depth distribution of the highest values of HP calculated in this work and the Benioff plane suggested by Papazachos *et al.* (2000): the 35° dipping plane is highlighted for intermediate depths with a corner around the 100-km depth, continuing with a 45° dipping plane for larger depths (Fig. 6a). The same features can also be identified on the southernmost cross-section (Fig. 6b).

4.3. Focal mechanisms

In the Ionian islands the strike-slip motions are well connected to the presence of the Cephalonia-Lefkas Transform Fault Zone. Shear motions are also observed along the western coast of Peloponnese especially in the Kyparissiakos Gulf (Kiratzi *et al.*, 2007). The aftershock distribution of some recent moderate earthquakes, Patras and Pirgos in 1993, Killini in 1988, and Vartholomio in 2002, shows evidence of sinistral strike-slip motions in this region.

Table 1 reports and Fig. 7 shows selected focal mechanisms of the main earthquakes that

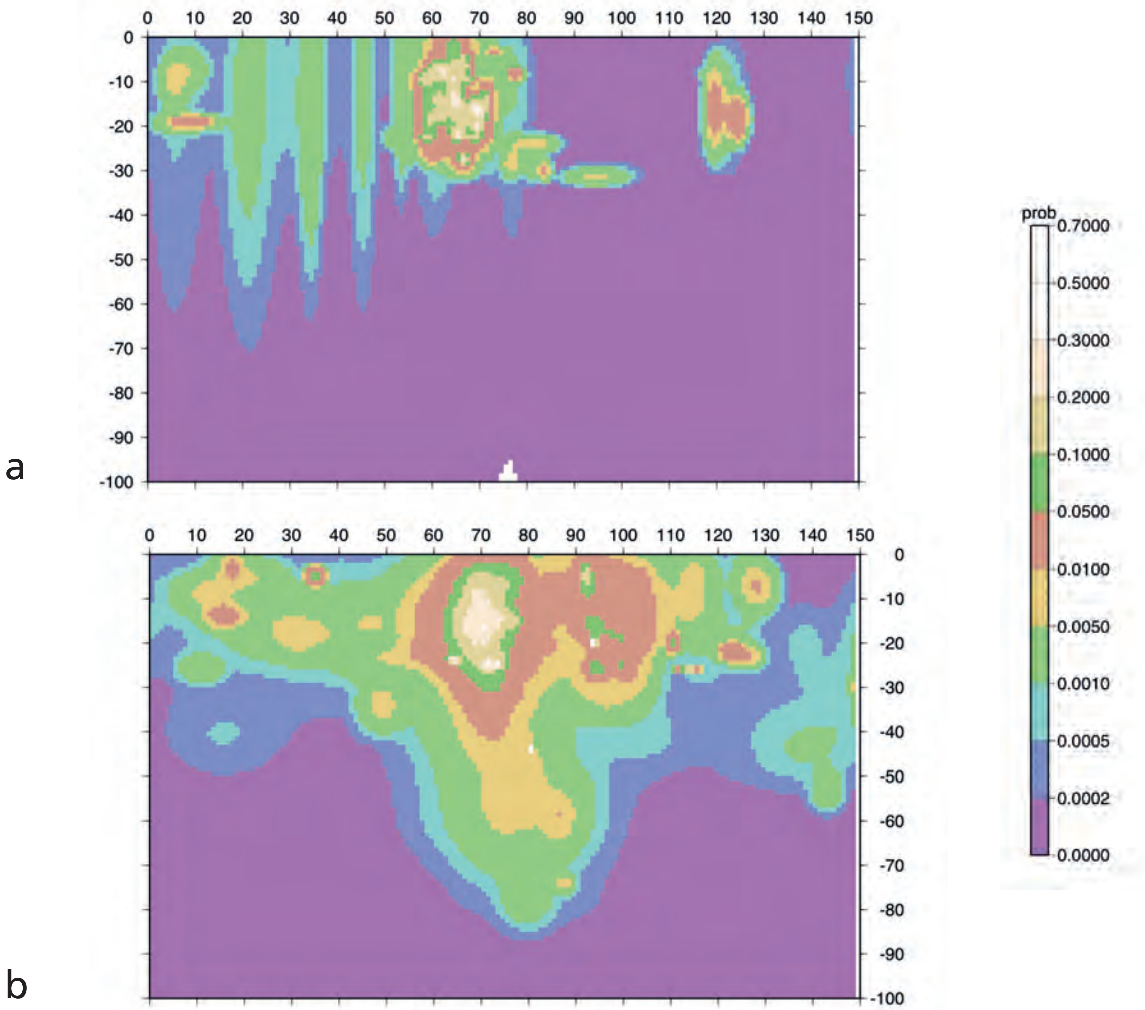

Fig. 5 - Distribution of the HP along the studied section 1 cross-section (see Fig. 4 for its location): a) 2006 microseismicity; b) NOA00-07 earthquakes.

occurred in the study area; their details are reported in Table 1. We considered the fault plane solutions contained in three databases in order of priority: the EMMA database (Vannucci and Gasperini, 2003, 2004), the NOA database of the U.S. National Oceanographic Administration (www.gein.noa.gr/index-en.htm), and finally the Central Moment Tensor database (www.globalcmt.org). The selection of the representative mechanisms has been driven by the quality of the solution; we have given priority to recent events of large magnitude. All the solutions have been checked with other basic studies (e.g.: Papazachos *et al.*, 1998).

Almost all major earthquakes, which occurred in the vicinity of the Cephalonia Island, show a strike-slip character with the exception of the moderate 1973 quake (M_W=5.8) that was characterized by a reverse mechanism (n. 7 in Table 1 and Fig. 7), probably related to a minor offshore thrust, and the 1953 event (M_W of 6.9) also of a reverse type (n. 1 in Table 1 and Fig. 7).

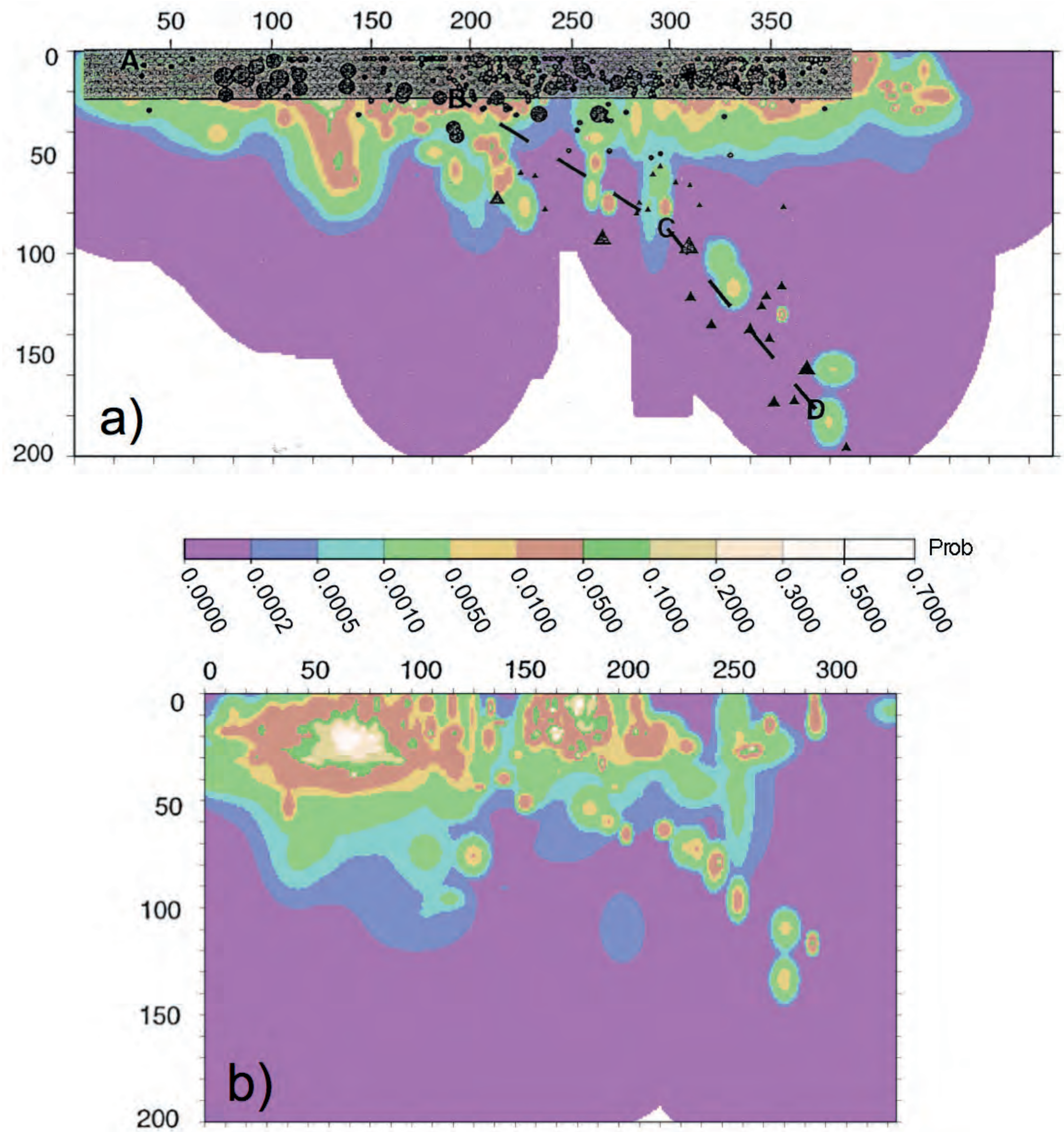

Fig. 6 - Distribution of the HP along the studied cross-sections with the NOA00-07 earthquakes (see Fig. 4b for their location): a) section 2; b) section 3. The cross-section of Papazachos *et al.* (2000) is also reported in panel a, the dashed line indicates the dipping plane.

Several reverse mechanisms can be roughly associated to the major thrust offshore Zakynthos Island. It must be pointed out that the location of the seismicity for thrust structures is expected to be far away from the appearance of the fault at the surface in agreement with the geometry of a gently dipping plane. The strike-slip mechanism of the 2008 Achaia-Ilia earthquake (n. 21 in Table 1 and Fig. 7) remains associated to the Andravida transcurrent fault. The reverse mechanisms offshore the Messiniakos Gulf (event n. 14 in Table 1 and Fig. 7) agree with the general thrust character of the south-western Peloponnese.

Table 1 – Selected focal mechanisms for the study region. *f*, *d*, and *l* are the strike, dip, and rake of the focal mechanism, *h* is the focal depth in km. RF is the original source of information for the fault plane solution: 1 = Anderson and Jackson (1987), 2 = Papadimitriou (1993), 3 = Baker *et al*. (1997), 4 = Louvari *et al*. (1999), 5 = Kiratzi and Louvari (2003). SZ is the seismogenic zone.

N	Year	Mo	Da	Ho	Mi	Se	Lat N	Lon E	h	Mw	f	d	l	web	RF	SZ
1	1953	8	12	09	23	0.0	38.30	20.80	10	6.9	163	34	101	EMMA	1	2
2	1959	11	15	17	08	40.0	37.80	20.50	12	6.8	46	37	-173	EMMA	2	2
3	1963	12	16	13	47	53.0	37.00	21.00	7	5.9	296	16	101	EMMA	2	4
4	1968	3	28	07	39	0.0	37.80	20.90	6	5.9	120	71	64	EMMA	1	2
5	1969	7	8	08	09	13.0	37.50	20.30	10	5.8	346	13	108	EMMA	3	3
6	1972	9	17	14	07	15.0	38.30	20.30	8	6.2	45	68	-174	EMMA	2	1
7	1973	11	4	15	52	14.0	38.89	20.44	23	5.8	324	50	81	EMMA	3	1
8	1976	5	11	16	59	45.0	37.40	20.40	16	6.3	335	14	106	EMMA	2	3
9	1976	6	12	00	59	0.0	37.50	20.60	8	5.8	115	70	90	EMMA	1	3
10	1983	1	17	12	41	31.0	38.10	20.20	11	6.8	39	45	175	EMMA	2	1
11	1983	3	23	23	51	5.0	38.29	20.26	7	6.1	31	69	174	EMMA	2	1
12	1987	2	27	23	34	0.0	38.42	20.36	13	5.8	26	61	168	EMMA	4	1
13	1988	10	16	12	34	13.3	37.95	20.90	29	5.8	301	76	-3	CMT	-	2
14	1997	10	13	13	39	40.0	36.45	22.16	32	6.3	123	72	84	EMMA	5	6
15	1997	11	18	13	07	41.0	37.54	20.53	32	6.5	354	20	159	EMMA	5	3
16	2003	8	14	05	14	54.0	38.82	20.60	12	6.2	18	60	-168	NOA	-	1
17	2007	3	25	13	58	4.2	38.36	20.24	12	5.7	30	65	164	CMT	-	1
18	2008	2	14	10	09	22.8	36.55	21.77	25	6.7	290	16	69	NOA	-	5
19	2008	2	14	12	08	54.8	36.35	21.93	10	6.1	292	18	61	NOA	-	6
20	2008	2	20	18	27	5.5	36.21	21.71	14	6.0	343	82	-157	NOA	-	5
21	2008	6	8	12	25	28.4	37.96	21.53	11	6.4	26	89	-152	NOA	-	4

5. The new seismogenic model for the Kyparissiakos Gulf and surrounding area

Some seismogenic zonations are available in the literature, e.g., those proposed Papazachos and Papazachou (1989, 1997, 2003) and Papaioannou and Papazachos (2000). Those zonations consider surface zones, based on earthquakes of focal depths up to 60 km, intermediate zones (60-100 km), and deep zones (100-160 km).

The area of the Corinthiakos Gulf corresponds to the Central Hellenic Shear Zone: an extensional system with trans-tensional mechanisms probably connected eastwards to one of the strands of the North Anatolian Fault (Papanikolaou and Royden, 2007; Shaw and Jackson, 2010). The shear zone separates the counter clockwise rotation of Anatolia-Aegean to the SE from the clockwise rotation of the northern Greece, north of the Corinthiakos Gulf (Le Pichon *et al*., 1995). A more accurate seismotectonic reconstruction is given by Shaw and Jackson (2010), who consider the overall NE-SW right lateral shear, evidenced by the prominent Cephalonia fault, which terminates the E-W grabens of the central Greece. The grabens accomodate the NE-SW shear by clockwise rotation of blocks, with extensions and normal faults in the main extensional basins of Corinthiakos-Patraikos gulfs, of Trichonis Lake, of Preveza-Arta Gulf, which have all been active in Quaternary. This tectonic setting is generating mainly strike-slip faulting earthquakes and N-S normal faulting earthquakes. In conclusion, the present E-W extension with a well-identified system of approximately E-W oriented trans-

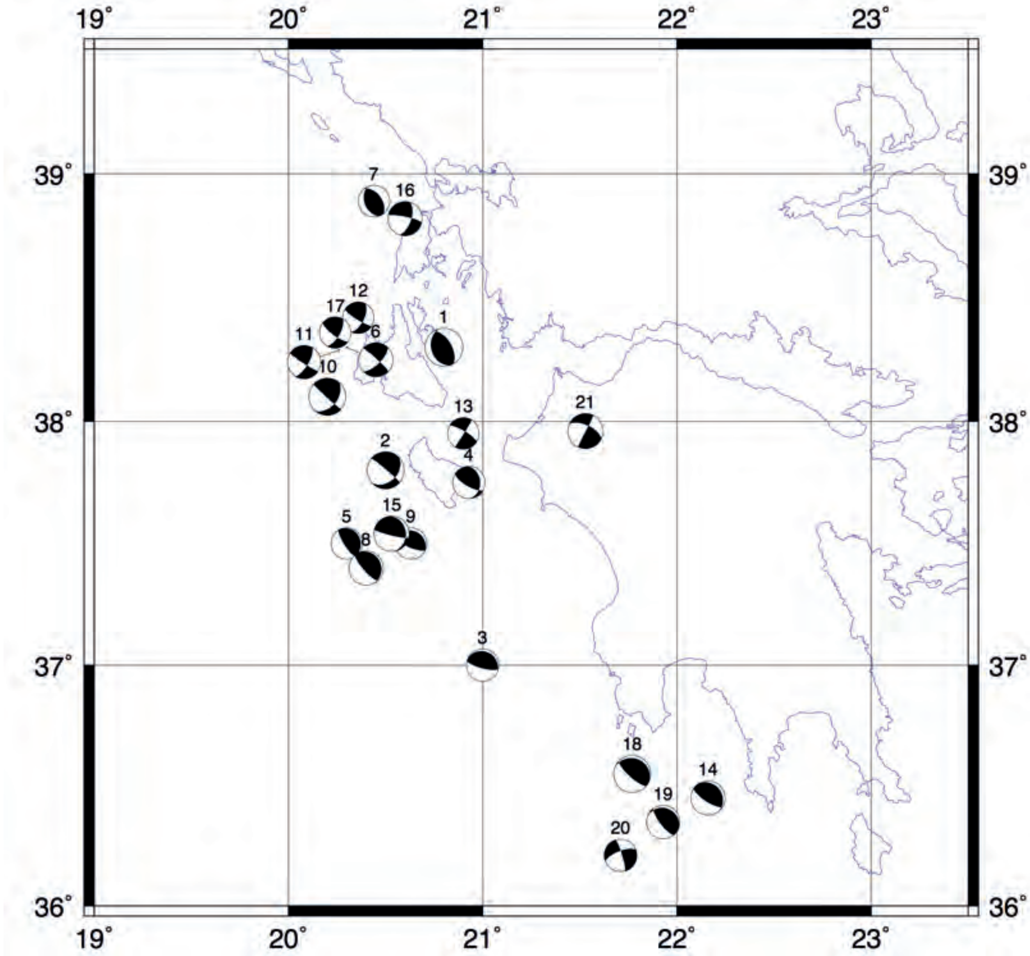

Fig. 7 - Focal mechanisms of the major earthquakes in the Kyparissiakos Gulf and western Peloponnese.

tensional normal faults, bound and surround the Corinthiakos Gulf and is associated with several earthquakes with an M_W larger than 6 (Fig. 8).

Central Peloponnese is characterized by two fault systems; a first one is E-W oriented while the second shows a NW-SE trend. The identification of the main seimogenic features and related earthquakes is problematic. The present day morphology of southern Peloponnese is determined by the fairly recent opening of the Messiniakos and Lakonikos gulfs (Fountoulis *et al*., 2014). Some of the thrusts have been identified on seismic profiles (Papoulia *et al*., 2014b): we suspect they all are now reactivated in the extensional regime.

With the help of the results from the active (Barison *et al*., 2014; Camera *et al*., 2014; Makris and Papoulia, 2014; Wardell *et al*., 2014) and passive (Papoulia *et al*., 2014b) seismic surveys conducted during the SEAHELLARC project, and by considering all historical and instrumental seismicity data (Papadopoulos *et al*., 2014) and geological information, a new seismogenic source model, based on 14 seismogenic zones (SZs), for the Kyparissiakos Gulf and surrounding region of south-western Peloponnese, is proposed. The remaining SZs used for probabilistic seismic hazard assessment [PSHA, see the results in Slejko *et al*. (2014)]) have

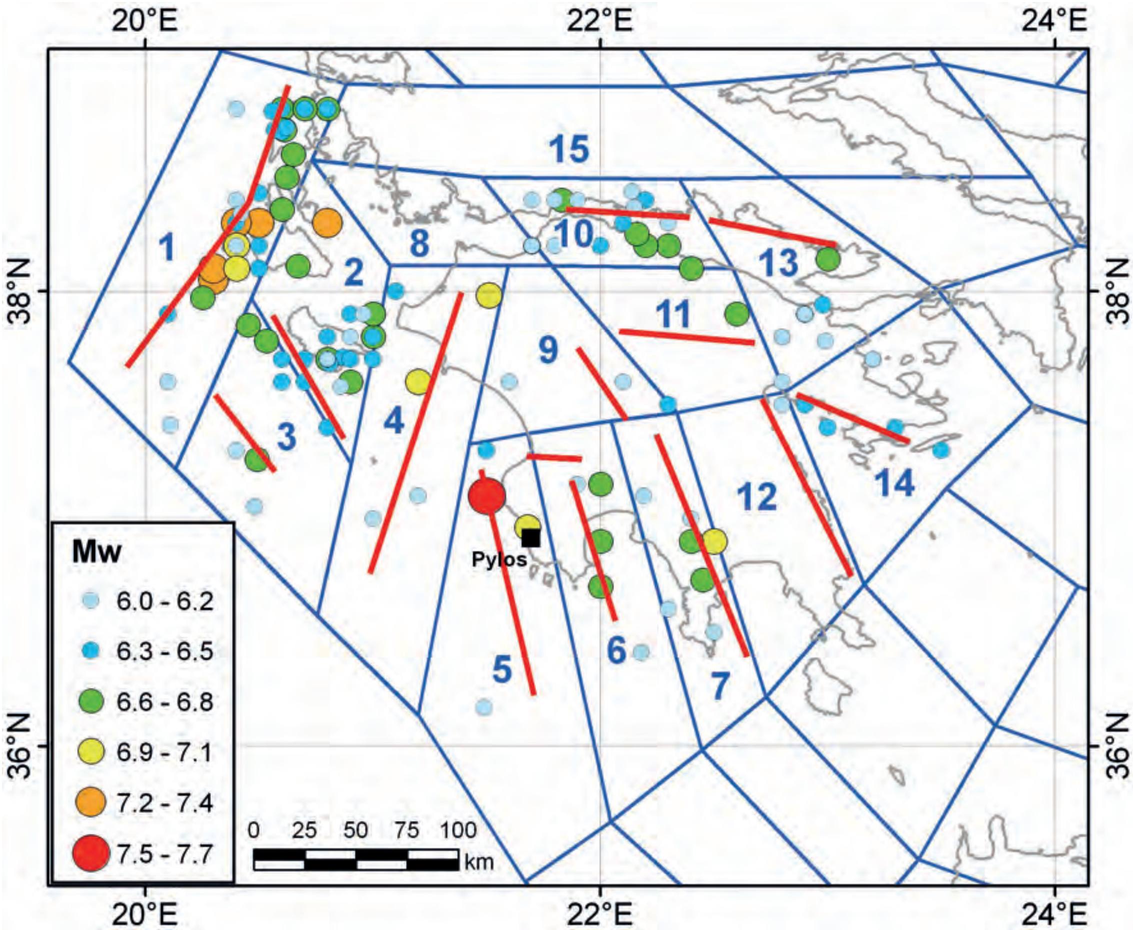

Fig. 8 – The new seismogenic zonation of Kyparissiakos Gulf and western Peloponnese: SZs (blue boxes), major tectonic lineaments (red lines) associated to seismogenic faults, and earthquakes with an $M_w \geq 6$ in the SZs.

less impact on the Kyparissiakos Gulf area and, consequently, are mainly based on the national zonation of Papaioannou and Papazachos (2000). This new model is crucial in optimizing seismic hazard estimations, which was the main scope of the SEAHELLARC project. The new seismogenic zonation is presented in Fig. 8 and described below.

The application of the geological approach for the determination of M_{max} implies the identification of the tectonic characteristics of each seismogenic source. More precisely, the main tectonic feature was identified for each SZ on the basis of both geological evidence on land and seismic images offshore and its total length was estimated (Fig. 8). The main information for derived structures on land was extracted from neotectonic activity maps of Greece (Mariolakos and Papanikolaou, 1981; Fountoulis and Mariolakos, 2008; Fountoulis *et al.*, 2014). This was integrated with data used by Pavlides and Caputo (2004) to calibrate a scaling law between surface rupture length and earthquake magnitude for Greece. For the offshore tectonic structures the information was extracted from interpretation of the SEAHELLARC seismic profiles (Barison *et al.*, 2014; Camera *et al.*, 2014; Makris and Papoulia, 2014; Papoulia *et al.*, 2014b; Wardell *et al.*, 2014) integrated with the available literature. For the identified faults, the maximum magnitude has been calculated (Table 2) according to two scaling laws using rupture length and magnitude (Wells and Coppersmith, 1994; Pavlides and Caputo, 2004). When it has not been explicitly declared, half of the total length has been taken as the rupture length, (Pavlides and Caputo, 2004) [more discussion on this topic can be found in Slejko *et al.,* 2014)].

SZ 1: Cephalonia. The Cephalonia transform fault represents the western tectonic boundary of the continental crust of the External Hellenides at the front of a thrust overriding the undeformed Ionian lower plate. The fault is somewhere close to ongoing collision between the Hellenic front and the eastern tip of the "Puglia" platform nose. The fault exhibits dextral strike-slip motion and cuts the entire upper plate, which is deformed by compressive tectonics east of the fault. The approximate total length of this NE-SW-oriented, right lateral, strike-slip fault is 130 km and it is apparently composed of two segments. The length of the northward bending Lefkas segment was fixed at 40 km by Louvari *et al*. (1999), but this segment may reach the onshore region of Preveza and Arta. Sachpazi *et al*. (2000) and Kokinou *et al*. (2005), using seismological observations with OBSs and interpretation of seismic profiles, moved the southern segment westerly and fixed the length at about 90 km. Also for this segment a continuation is possible to the Ionian abyssal plain. This is the zone of highest seismicity in the western Hellenic Arc area and has produced earthquakes in the order of M_W 7.0. The main quakes are the M_W 7.4 1867 event (Fig. 8) that caused extensive damage on Cephalonia Island (Papazachos and Papazachou, 1997) and the M_W 6.2 August 14, 2003 quake in the Lefkas segment (Louvari *et al*., 1999; Karakostas *et al*., 2004; Papadimitriou *et al*., 2006; Benetatos *et al*., 2007). Events with a M_W larger than 6 have however occurred along the entire fault length (Fig. 8). The rupture lengths proposed here for the two segments are in reasonable agreement with those estimated by Papazachos *et al*. (2004). The computed maximum magnitude according to both formulae agrees quite well with the largest observed magnitude for the northern segment, while this value is slightly lower for the southern one (Table 2)

SZ 2: Zakynthos. It mainly consists of uplifted Apulian Ridge shelf carbonates, dominated by compressive structures from the crustal shortening during Pliocene and Quaternary times, with the emplacement of the Ionian thrusts over the Apulian margin by the westward and SW-ward movements of the upper plate. A NW-SE tectonic lineament limits the ridge offshore Zakynthos to the west and in front of the Ionian Sea SZ. This block shows relatively high seismicity. A NW-SE oriented Zakynthos thrust belt (Papazachos *et al*., 2004) has been identified offshore the south-western coast of Zakynthos Island (SZ 2). The length of this feature is estimated at about 66 km and several earthquakes with M_W larger than 6 are associated to this tectonic lineament. Specific attention should be given to 2 large events which have occurred in the northern domain of this SZ: the M_W 6.8 1912 and the M_W 7.3 1953 quakes. Although their location (see Fig. 8) appear somewhat different, Stiros *et al*. (1994) place the 1953 epicentre in the south-easternmost part of Cephalonia Island where the 1912 event also occurred, at least according to the reported damages (Papazachos and Papazachou, 1997). From the seismogenic point of view, we are thus inclined to connect both earthquakes to SZ 01. The rupture length proposed here for the Zakynthos fault, and based on geological and geophysical observations, is smaller than that estimated by Papazachos *et al*. (2004) and determines a maximum magnitude smaller than the largest observed so far.

SZ 3: Ionian Sea. The zone coincides with a downthrown block of the External Hellenides at the northern end of the Mediterranean Ridge and Hellenic Trench and it is primarily characterized by interplate thrusting and crustal shortening due to compression. It is characterized by moderate seismicity considered to originate from flat thrusts, strike-slip and normal faults. Structural mapping has effectively revealed the presence of a NW-SE trending thrust system marked by a fault, which has an estimated length of about 46 km. The largest associated earthquake is a M_W 6.6 event in 1997. The computed maximum magnitude according to both formulae agrees quite well with the largest observed magnitude.

SZ 4: Strophades-Katakolo basin. This zone is located in the Ionian furrow, a tectono-stratigraphic domain with the presence of thick flysch, Triassic evaporites and pelagic carbonates probably overthrusting the Apulian Ridge massive limestones at depth. The presence of a morphologically well-defined pull-apart basin that results from recent trans-tensional motion of dextral orientation is represented by the offshore prolongation of the Andravida fault zone and by the present day deformed Strophades uplifted block. SZ 4 is characterized by the development of the NNE-SSW trending, right-lateral, transcurrent fault. This fault is well identified on land by unambiguous geological and seismological evidence and extends offshore and is known as the Andravida fault. It is a major tectonic lineament, parallel to the Cephalonia transform fault. It has a total length of about 130 km, as defined by the SEAHELLARC project results from the interpretation of reflection seismic and OBS profiling (Barison *et al*., 2014; Camera *et al*., 2014; Makris and Papoulia, 2014; Papoulia *et al*., 2014b; Wardell *et al*., 2014). It is characterized by moderate magnitude deep seismicity, which appears to be confined within the basin limits. The M_W 6.5 earthquake of June 8, 2008 was located not far from the northern edge of the Andravida fault and its focal-mechanism is consistent with a shock caused by right lateral strike-slip faulting. The many aftershocks line up quite well, supporting the presence of a deep-rooted fault that would pass through the Katakolo Peninsula to the south and then likely follow a line of salt diapirs observable on the sea floor. Also in this case, the computed maximum magnitude from both formulae agrees quite well with the largest observed magnitude.

SZ 5: Pylos block. It is located at the transition between the strong and rigid Gavrovo-Tripolitza shelf carbonates to the east, and to the Ionian furrow domain to the west. The onshore structures correspond to the Gabrovo peripheral bulge induced by bending at the front of Pindos obduction. E-W elongated basins and strike-slip faults dissect the Gavrovo block on-land and offshore. The buried offshore front is indicated by a NNW-SSE trending fault zone, indicated as the Sfaktiria fault and presently active with normal displacements and characterized by high seismicity. The rupture zone of the large earthquake of 1886, related to a NW-SE trending and NE dipping fault, falls within this zone. A NNW-SSE oriented, and about 111 km long, thrust front, re-activated as a normal or listric fault and cut by W-E strike-slip lineaments is suspected offshore Messinia Peninsula. It may have ruptured in 1886 giving rise to the M_W 7.5 [recalculated as 6.8 in the framework of the SEAHELLARC project, see Papadopoulos *et al*. (2014)] Filiatra earthquake, which destroyed more than 100 villages in the area (Papazachos and Papazachou, 1997). It is also worth mentioning the 1947 M_W 7.0 Messinia earthquake, which caused serious damage in 54 settlements in Pylia province. Originally this event was located on the eastern coast of the Messinia Peninsula, i.e., in SZ 6 (Galanopoulos, 1949). As for the 1886 event, the distribution of the damage was anomalous without a clear area of maximum intensity (Papazachos and Papazachou, 1997). This quake was more likely a thrust at depth. Given the notable length of the proposed dominating thrust, the computed maximum magnitude according to both formulae is quite larger than the largest observed magnitude.

SZ 6: Messiniakos Gulf. This zone belongs to the Gabrovo-Tripolitza domain, overlain by the Pindos units and underlain by the Arna and Mani metamorphic units, the latter interpreted as the autochthonous basement of the Ionian carbonates. The area contains the Messiniakos basin bordered to the east by the Taygetos uplifted thrust unit with normal faults at the front. E-W directed normal faults and strike-slip structures are, at present, dissecting the area. They are related to the transtensional stress-field of the central Hellenic shear zone with N-S extension. The zone is characterized by high sub-crustal seismicity; the M_S 6.0, 1986 Kalamata earthquake occurred within the SZ. A NNW-SSE trending fault segment, 70-km long has been proposed in this SZ (see also Mariolakos and Papanikolaou, 1981; Fountoulis, 1994; Fountoulis *et al*., 2014). However the structures of this area are disrupted by E-W to SW-NE oriented strike-slip faults (Le Pichon *et al*., 2002; Wardell *et al*., 2014) and the extension of this segment might be not continuous. It has been associated with the M_W 6.8 1642, 6.7 1842, and 6.6 1846 earthquakes [the magnitude of these latter ones has been reduced to 6.3 and 6.2, respectively (Papadopoulos *et al*., 2014)]: all those events caused damage in a wide area including Kalamata. The Kalamata fault is itself a minor, NNW-SSE oriented, listric fault, which runs along the western coast of the Mani peninsula, and was generated along the previous frontal thrust of the Hellenic basement nappes. Its northernmost segment is visible on land and has been associated with the 1986 M_W 6.0 Kalamata earthquake (Pavlides and Caputo, 2004). It is worth noting, the presence in this SZ of the E-W-oriented, and 27 km long, Kyparissia active fault, which has also been identified on some offshore seismic profiles as well as onshore from surface geological evidence. Its length, does not support however the likelihood of large magnitude earthquakes. The computed maximum magnitude according to both formulae agrees quite well with the largest observed magnitude.

SZ 7: Taygetos block. The Taygetos uplifted block consists of low metamorphic limestones of Tripoli (western part) and Mani units (eastern part), and partly by the highly metamorphosed units of Arna placed in between. The Taygetos low angle detachment fault, NNW directed, follows the eastern flanks of the chain and accommodates the extensions in the Lakonia plain and Lakonikos Gulf. It is considered the most western original break-away zone in structural continuity with the main east Peloponnese detachment structures. Seismicity is low and of shallow depth. The Sparta-Gythio fault consists of a NNW-SSE trending, about 110 km long, extensional detachment fault-system, which runs along the eastern flanks of the Mani-Taygetos Ridge. It represents one of the examples of extensional tectonics disrupting the Hellenic Arc (Armijo *et al.*, 1991; Papanikolaou and Royden, 2007) during Early Pliocene. Its activity is documented by some historical earthquakes with M_W around 7, the most recent of which is the M_W 6.8 (Papazachos and Papazachou, 1997) or 6.5 (Papadopoulos, 2011) 1867 event, which probably occurred in the Lakonia Gulf because it generated a strong tsunami and caused extensive damage to the villages of the Mani Peninsula. Given the notable length of the proposed dominating thrust, the computed maximum magnitude according to both formulae is quite larger with respect to the largest observed magnitudes.

SZ 8: Patraikos Gulf. This domain is intensively tectonized by the Alpine compression with Ionian units thrust over the Apulian Ridge, and is presently deforming by normal faulting associated with active extension. The gulf was formed during Quaternary times in response to approximately N-S extensional stress and may represent an incipient graben structure developing into a major basin similar to the structures of the Corinthiakos Gulf. This western part of the Corinthiankos Gulf area is opening faster than the eastern part with deformations representing a very recent phenomenon. It shows an average low seismicity, no larger than 6. A dominant structure might be an E-W strike-slip 10-km long segment, or N-S oriented normal fault, not considered among the main sources for PSHA. The computed maximum magnitude according to both formulae agrees quite well with the largest observed magnitudes.

SZ 9: North Peloponnese. The superposition of the Gavrovo zone on the Ionian zone in this area with a N-S directed thrust front, gave rise to kalokinetic movements of Triassic evaporites with further folding of the Ionian formations. The Gavrovo carbonates are overthrust by the Pindos nappe, but all the Alpine structures are at present crossed by post orogenic, nearly E-W normal faults and extensions according to the transtensional displacements related to the Central Hellenic Fault Zone. The zone is characterized by moderate shallow to intermediate depth seismicity. Following Pavlides and Caputo (2004), the Megalopolis fault, 40-km long and responsible of the 1966 M_W 6.0 earthquake, has been selected on the basis of surface neotectonic evidence (Mariolakos and Papanikolaou, 1981; Fountoulis, 1994). Also in this case the computed maximum magnitude according to both formulae agrees quite well with the largest observed magnitude.

SZ 10: Western Corinthiakos Gulf. It is still part of the Corinth extension graben and part of a broad zone of extensional deformation extending in the gulf and in the western Peloponnese. Low angle normal faults with nearly WNW-ESE direction are present towards the southern rim of the gulf (Sachpazi *et al.*, 2007). The seismicity is superficial, quite frequent with a few large events. A 61-km long segment, WNW-ESE oriented, which includes the structures present in the Corinthiakos Gulf and the Trichonis fault system (Kiratzi *et al.*, 2008), has been taken as the dominant structures.

SZ 11: Argolida-Corinthia. This seismic zone is characterized by broad E-W to WNW-ESE extensional deformation related to the central Hellenic shear zone centred in the Corinthiakos Gulf and cutting the Alpine thrusts and the successive east directed detachments. In response to the N-S extensional stress, E-W elongated basins have been created. The seismicity is relatively low and superficial with few large earthquakes.

Following Pavlides and Caputo (2004), an almost E-W oriented and 66-km long fault has been chosen on the basis of surface neotectonic evidence (Mariolakos and Papanikolaou, 1981; Fountoulis, 1994). Also in this case the computed maximum magnitude according to both formulae agrees quite well with the largest observed magnitude.

SZ 12: Molai. A low angle east Peloponnese detachment fault running parallel to the coast line from Lakonia to Argolida accomodates NNW-SSE extension in this seismic zone and in the neighbouring Argolikos Gulf. Crustal thinning resulted from the extension, which can be lengthened northwards towards the Corinthiakos Gulf where the detachment is definitively cut and stopped by present day E-W extension. The seismicity is rather low and superficial. A NNW-SSE oriented, 92-km long, extensional detachment fault system runs along the eastern coast of the Molai peninsula (Papanikolaou and Royden, 2007); this area is characterized by a rather low seismicity. This is the only case where the disagreement between the maximum computed and the largest observed magnitude is very large, around one degree.

SZ 13: East Corinth. A N-S directed extension is forming the Corinthiakos Gulf and crosses the earlier Alpine structures of the Hellenic thrust belt. This SZ is part of the central Hellenic shear zone, a corridor of young tectonic activity, which extends eastwards into the northern Aegean area where it merges with the Northern Anatolian Fault Zone. The southern normal faults (with E-W to WNW-ESE direction) control the rift in a time progression from the east towards the Western Corinthiakos and Patraikos gulf SZs. The normal faults within the corridor of the Central Hellenic Shear Zone exhibit transtensional displacements with a dominant component of dextral shear. Seismicity is quite frequent but with only rare large earthquakes. An E-W oriented segment, 63-km long, has been taken as the dominant structure.

SZ 14: Argolida Peninsula. Along the eastern coast of the Peloponnese a general E-W directed extension is prevailing (Makris *et al.*, 2004; Papanikolaou and Royden, 2007). The crust was extended and thinned within the space accommodated by the east Peloponnese extensional detachment fault. The Paleozoic basement of the Pelagonian units outcrops in the peninsula with Paleozoic and Mesozoic carbonate cover and Jurassic ophiolites. The presence of a 59-km long, NW-SE oriented, fault is documented by surface geological evidence (Mariolakos and Papanikolaou, 1981; Fountoulis, 1994): the rupture along this fault is suspected to have generated historical earthquakes with M_W larger than 6. The computed maximum magnitude according to both formulae agrees quite well with the largest observed magnitude.

SZ 15: Central Greece. It is characterized by a low to medium seismicity [the largest magnitude of 6 was observed in occasion of the Amphiloxia earthquake in 1921 (Papazachos and Papazachou, 1997)]. In this area Gavrovo-Tripolitza shelf carbonates are overthrusting Ionian zone units and are overthrusted by Pindos tectono-stratigraphic units. The dominant structure is the approximately N-S oriented 60-km long, Amvrakia fault (Underhill, 1989; Kiratzi *et al.*, 2008). It links extensions in the gulfs of Preveza and Patras, and in the Lake Trichonis with a sinistral transtensional motion. Smaller extensional basins are present on both sides of the fault. SZ 15 lies quite far from the Pylos area and, consequently, no linear source has been considered for PSHA.

Table 2 - M_{max} values obtained using the Pavlides and Caputo (2004) (M_{PC}) and the Wells and Coppersmith (1994) (M_{WC}) formulae considering the half of the total length (L) as rupture length. M_{obs} is the maximum observed magnitude. All magnitudes are M_W.

SZ	L (km)	M_{obs}	M_{PC}	M_{WC}
SZ 1	130	7.4	7.2	7.3
SZ 1 north	40	6.7	6.8	6.8
SZ 1 south	90	7.4	7.0	7.0
SZ 2	66	7.3	6.9	6.8
SZ 3	46	6.6	6.7	6.7
SZ 4	130	7.0	7.1	7.2
SZ 5	111	7.5	7.1	7.1
SZ 6	70	6.7	6.9	6.9
SZ 7	110	6.8	7.1	7.1
SZ 9	40	6.4	6.7	6.6
SZ 10	61	6.8	6.8	6.8
SZ 11	66	6.8	6.9	6.9
SZ 12	92	6.1	7.0	7.0
SZ 13	63	6.8	6.8	6.8
SZ 14	59	6.7	6.8	6.8

6. Conclusions

The evidence obtained from the data acquired during the SEAHELLARC project and the most recent literature have suggested a new seismogenic zonation (Fig. 8) for the Kyparissiakos Gulf and surrounding region for purposes of seismic hazard assessment. The main differences introduced with respect to the previous zonations (Papaioannou and Papazachos, 2000) refer to the presence of a transcurrent zone in the Kyparissiakos Gulf related to the Andravida transcurrent fault system. A significant modification is proposed for the SZs in the broader Pylos region and a more complex shape trend is suggested for the Hellenic Arc.

The micro-seismicity survey (Fig. 3) developed during the SEAHELLARC project has emphasized the activity of tectonic structures located offshore and has allowed us to link some of them to the geologic evidence onshore. The spatial distribution of the historical earthquakes (Fig. 4b) also supports the existence of these currently active tectonic structures.

On the basis of the tectonic characterization of the study region (see section 5), a reasonable seismic source has been roughly sketched geometrically in each SZ (Fig. 8) for the estimation of the maximum expected magnitude. Several faults so defined are quite new in a main seismogenic characterization of the region and need further investigation (e.g., specific geophysical surveys) to fully understand their present role in the regional seismogenesis. As the role of maximum magnitude is not crucial in PSHA, the model of seismic sources that is proposed has a more scientific relevance than an actual impact on the computations.

We strongly believe that the present seismogenic model is an important ingredient for a properly conducted PSHA and for the definition of tsunami scenarios that can significantly reduce the seismic risk and can optimize the budgets of new constructions.

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