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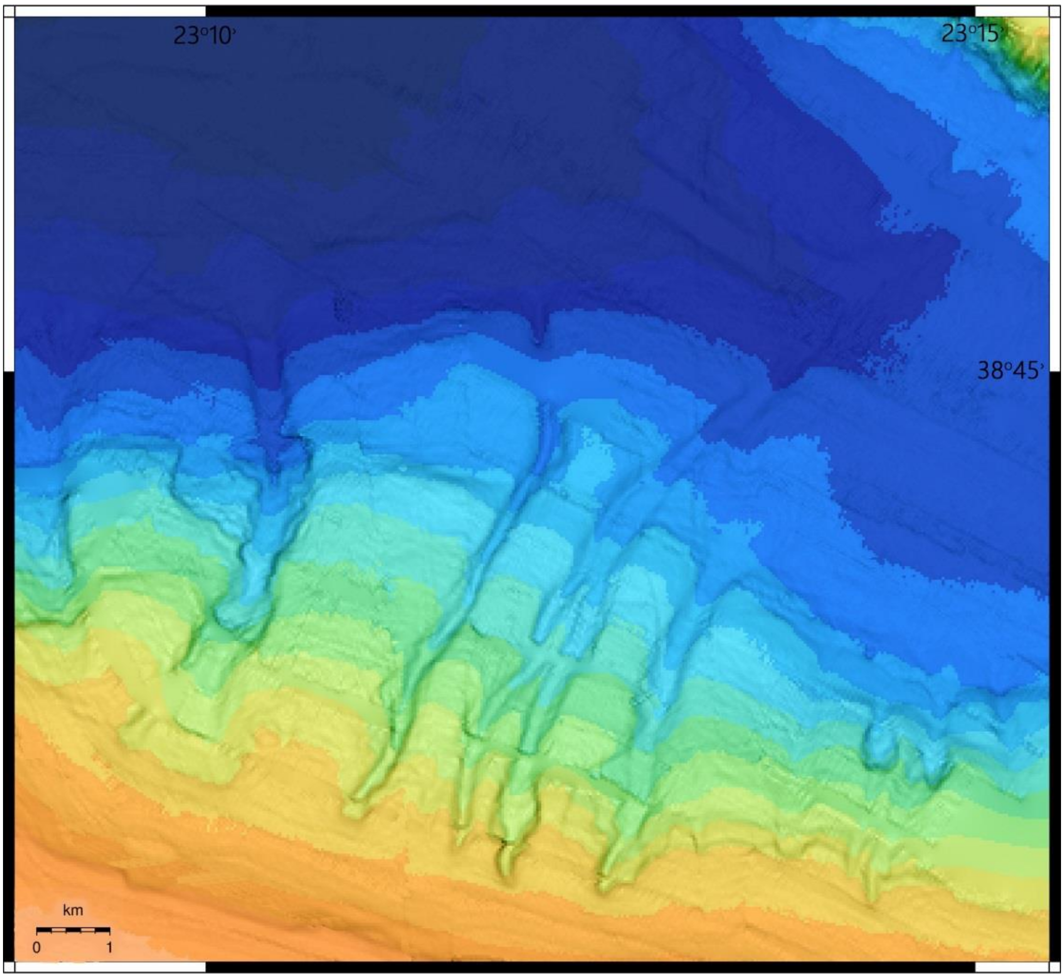
Διπλωματική Εργασία



"MORPHOTECTONIC ANALYSIS OF THE NORTHERN EVOIKOS GULF"

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Αθήνα, 2017

Διπλωματική Εργασία

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<u>Τριμελής επιτροπή</u>:

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Contents

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Abstract

The bathymetric mapping of Northern Evoikos Gulf was conducted with the use of the Multi-Beam System of the R/V AEGAEO, during the research program “Amphitrite” in January of 2014.

The NEG is a tectonically active region with intense micro-seismic activity and the GPS measurements show its extension, due to the increase in velocities from N. Evoia to Central Greece. The gulf is characterized by gentle morphology, in which in which a central basin is developed. The NE margin of the gulf consists of a fault zone of NW-SE direction that creates abrupt slopes. The gulf's main geomorphological structures are the submarine canyons developing on its W and SW continental slope, between the depths of 150 and 400 meters. They owe their existence possibly to the morphological discontinuity of the seabed and probably are associated with existing land river networks.

Key words: Northern Evoikos Gulf, Submarine morphology, Canyon, Morphotectonic Analysis.

Περίληψη

Η βαθυμετρική χαρτογράφηση του Βόρειου Ευβοϊκού Κόλπου πραγματοποιήθηκε με τη χρήση του SEABEAM 20 kHz 2120 Multibeam echosounder και το σκάφος R/V "AEGAEO" κατά τη διάρκεια του ερευνητικού προγράμματος «Αμφιτρίτη» τον Ιανουάριου του 2004.

Ο ΒΕΚ είναι μια τεκτονικά ενεργή περιοχή με έντονη μικρο-σεισμική δραστηριότητα και οι μετρήσεις των GPS δείχνουν τον εφελκυσμό του, λόγω της αύξησης των ταχυτήτων από την Β. Εύβοια στη Στερεά Ελλάδα. . Πρόκειται για έναν κόλπο με ήπια μορφολογία, στον οποίο αναπτύσσεται μια κεντρική λεκάνη. Το ΒΑ περιθώριο του κόλπου αποτελείται από μια ρηξιγενή ζώνη ΒΔ-ΝΑ διεύθυνσης που δημιουργεί απότομες κλίσεις. Κύρια γεωμορφολογική δομή του κόλπου είναι τα υποθαλάσσια φαράγγια που αναπτύσσονται στη Δ και ΝΔ υφαλοκρηπίδα του, μεταξύ των βαθών 150 και 400 m. Τα υποθαλάσσια φαράγγια οφείλουν την ύπαρξη τους πιθανώς στην μορφολογική ασυνέχεια του πυθμένα και ίσως αποτελούν συνέχεια του χερσαίου κοιλαδικού συστήματος.

Λέξεις κλειδιά: Βόρειος Ευβοϊκός Κόλπος, Υποθαλάσσια μορφολογία, Υποθαλάσσιο κοιλαδικό σύστημα, Μορφοτεκτονική ανάλυση.

1. INTRODUCTION

The study area includes the Northern Evoikos Gulf and its geological boundaries, which are encountered in northern Evia and Central Greece. The Northern Evoikos Gulf occupies an area of 400 km^2 and is developed in NW-SE direction, with a maximum length of 30 km from Halkida to the peninsula of Lihada in northern Evia and until Kammena Vourla in Central Greece. The gulf is a semi-enclosed marine environment that communicates with the open Aegean Sea through the Oreon narrow passage to the North and with the Southern Evoikos Gulf through the passage of Evripos to the South.

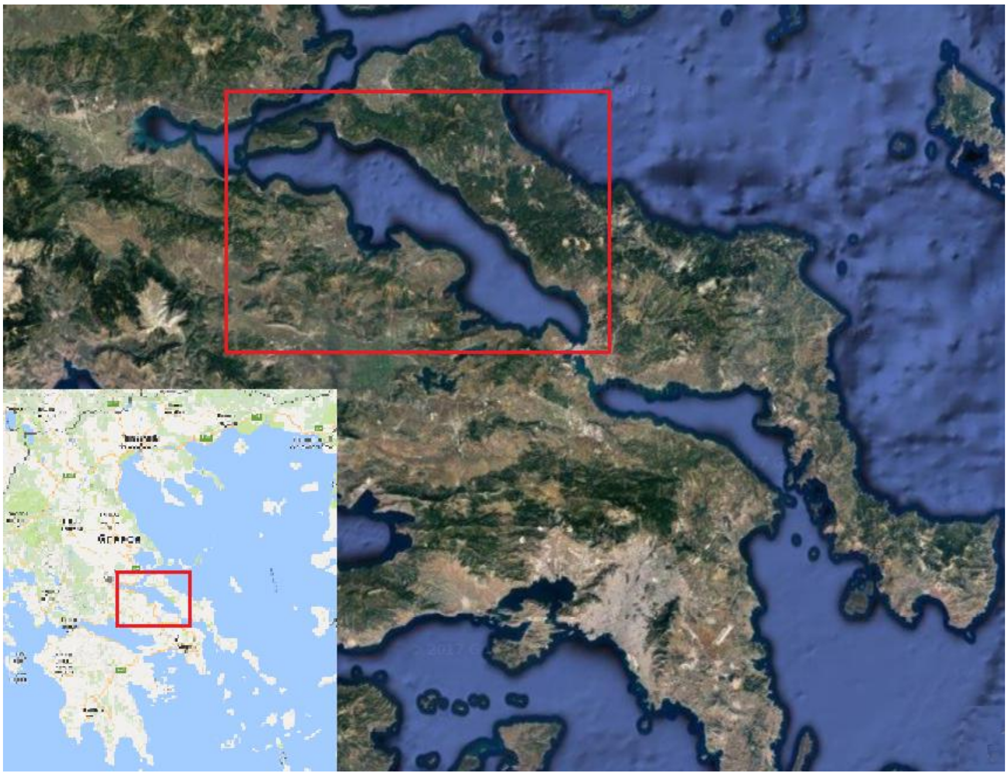


Fig. 1 *Study area*

The aim of this work is the exportation of morphotectonic features from the northern Evoikos Gulf seabed and their comparison with similar studies, utilizing the available bathymetric data.

2. GEODYNAMIC SETTING OF THE STUDYING AREA

2.1. Geological Setting

Greece lays on the edge of an active convergent plate boundary, where the African plate is subducting below the European plate at a rate of 10 mm/a. The subduction zone at its western part curves to a NNE-SSW direction and terminates on the Kefalonia fault, a major active dextral transform fault. North of the aforementioned fault, continental collision takes its place since Tertiary. Simultaneously the Arabian plate advances northwards at a rate of 20-25 mm/a causing the westward extrusion of the Anatolian block. This "westward extrusion" is accommodated on the North Anatolian Fault (NAF), a currently active dextral transform fault, which constitutes a plate boundary since 10-13 Ma ago. GPS measurements show that the current rate of displacement along the NAF is 23 mm/a. When entering the Aegean Sea the NAF branches out into two separate faults creating a diffuse zone of N-S extension and the subsidence of the North Aegean Trough. Consequently, the Aegean block moves towards the subduction zone at its own velocity (35 mm/a towards N2150, with respect to a fixed Europe).

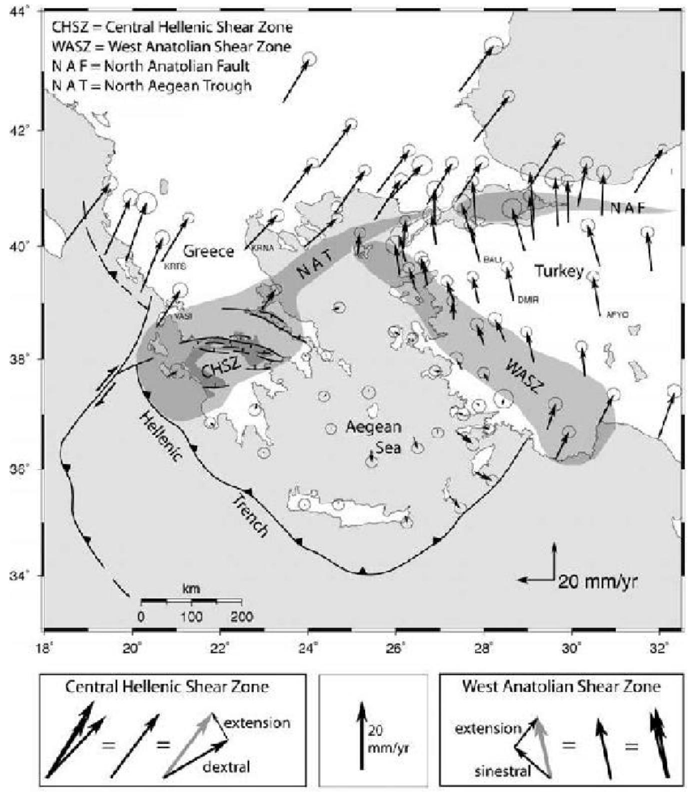


Fig. *2. Interpretation and analysis of GPS velocities, into components, the shear zones bordering the Aegean microplate (Papanikolaou & Royden, 2007).*

The Northern Evoikos Gulf constitutes just a part of a system of sub-parallel WNW-ESE basins, known as Central Hellenic Shear Zone (CHSZ). This system or zone consists of the Gulf of Corinth, the onland basins of Viotikos and Lokris and the Northern Evoikos Gulf and is the result of the intense tectonic activity that characterizes Central Greece. GPS measurements reveal that that the motion of Central Greece occurs in a NE-SW direction nad can be furthely analyzed into N-E extension, as well as, an E-W dextral shear motion. The average rate of extension for Central Greece is 1 cm/a, and the Corinth Rift's opening rate reaches 1.6 cm/a (probably the fastest opening rift worldwide) in its western part and makes it the most seismically active area in Europe. Whereas the average rate of extension for the NEG is around 1-2 mm/a, which is much slower. Nevertheless, it is an active region, producing low-magnitude earthquakes, with the exception of the catastrophic seismic event in Atalanti in the year 1894, that reached a magnitude of Mr=5. The NEG region is characterized by micro-seismic activity *(Papanastasiou et al., 2001).* Yet, since 2001, the Psahna area, has shown some seismic events of significant magnitudes. The most noted are two seismic events, five minutes apart, in 17/11/2014, where the first one reached a magnitude of Mw=5.2 and the following Mw=5.1. While the most recent one took place in 9/06/2015 reaching a Mw=5.2 magnitude.

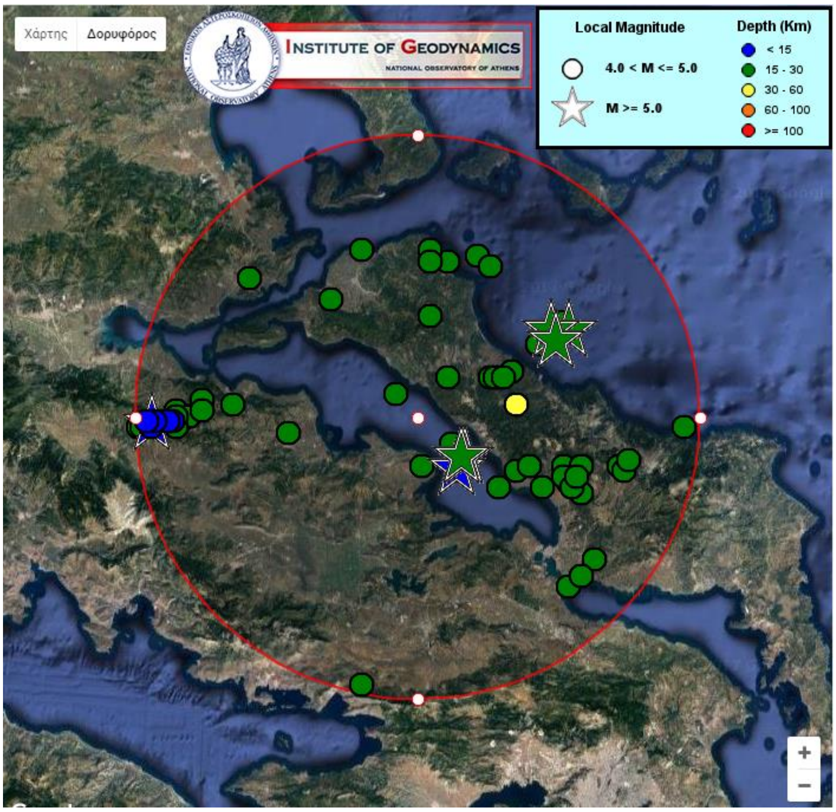


Fig. 3 *Map of the study area with seismic events for the period 2000-2017.*

The mechanism that is responsible for the thinning of Central Greece's crust is unclear. A possible interpretation is a zone of transtension, due to the soft-linking of the NAF to the Kefalonia Transform Fault. *Kranis et al. (2002)* in their work discussed the existence of an intensely deforming zone between two blocks with opposing relative motion and mentioned two tectonic boundaries trending NE-SW with a length of about 30 km. The Oiti-Oreoi zone consists of the active, oblique-normal Pavliani fz that bounds Mt Kallidromon from the NW and separates Mt Oiti from Mt Giona. The prolongation of the Oiti-Oreoi zone lies in the Oreoi straits, which is an NE-SW trending graben. The second boundary lies in the South and is known as the Delfi-Kalliaros zone, which consists of the Hyambolis fz. The latter breaks down to a 17 km long series of faults with a 2.5 km wide deformation zone. It is a typical representation of a structure that accommodates significant amount of strike-slip motion. Another explanation suggests that the crustal thinning of the Central Greece is an expression of back-arc extension due to slab rollback of the African plate. It could also be attributed to late orogenic collapse, which can be supported by the exhumation of metamorphic core complexes along low-angle detachment faults. A combination of the aforementioned explanations might also be true.

Underneath the NEG's central basin, the crust is just 20km thick. *Karastathis et al. (2011) have* shown that the magnetic and seismic results defined a high temperature zone at 8 km depth, which is the top of a magmatic intrusion that is the source of the volcanic phenomena of this region. The hydrothermal activity of the region is linked to faults closely linked to the magmatic intrusives.

According to *Papoulia et al. (2006)* the surrounding region of the NEG is extremely influenced by the stress fields of the NAF on the NE and the Kefalonia transform fault on the West. Central Greece presents a complex tectonic fabric, represented by faults of any direction that are categorized in different stress fields and function as normal, oblique-normal or strike-slip. A progressive transition in trending is noticed from NE-SW trends in the North Aegean basin to the Corinth Rift which trends WNW-ESE, while rate of deformation increases progressively as well northwards. The interaction of these different stress fields blocks fault growth, consequently producing seismic events of low magnitude. In addition in its biggest part, the seismicity in the area takes place in the upper part of the crust (<15 km), meaning that the area is indeed under extension. Any other seismic event that takes place in greater depths (>100 km) is attributed to the subduction of Tethys' remains, under the Hellenides.

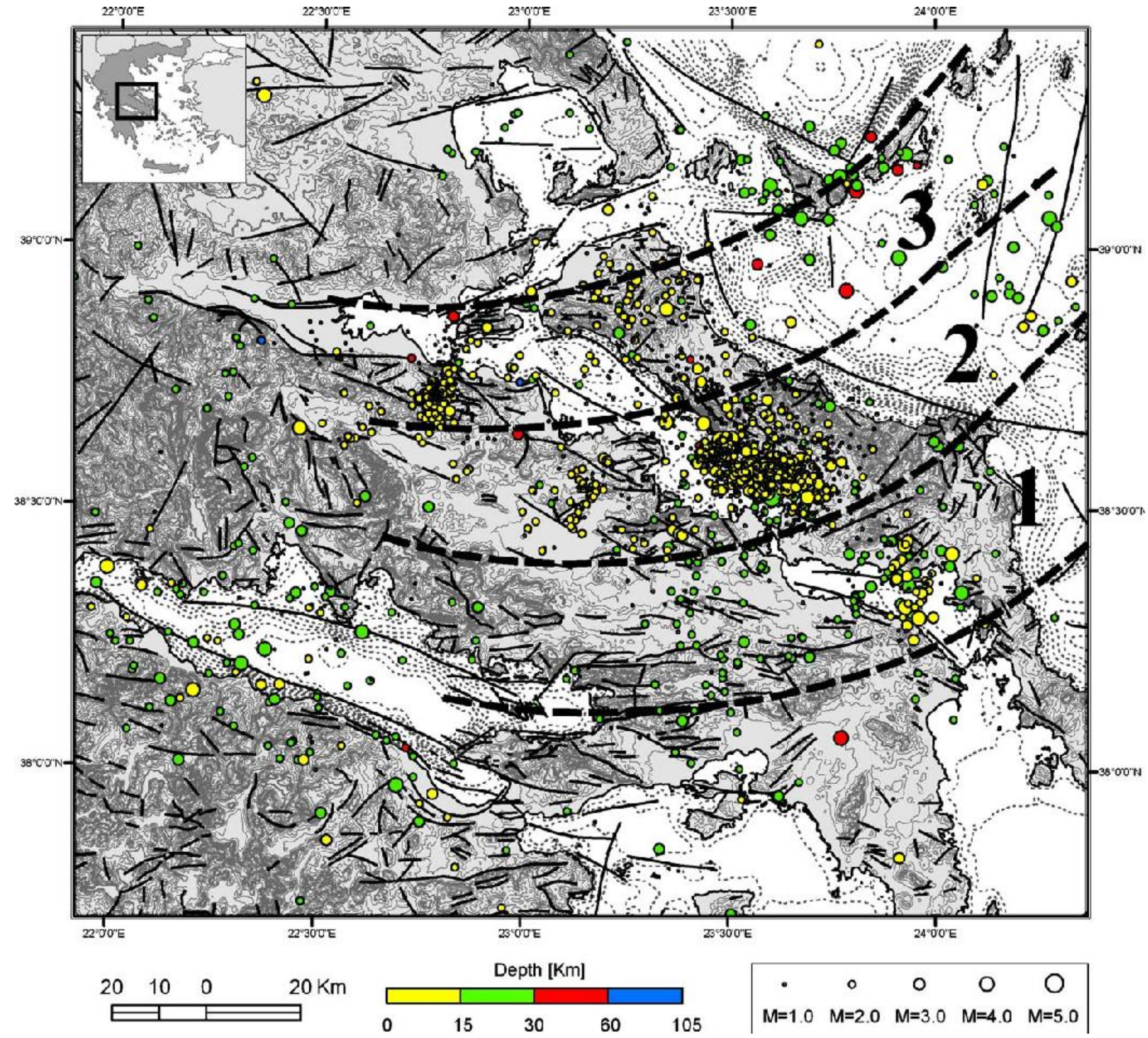


Fig. 4 *Progressive change zones of orientation of faults and of their relative seismicity by Papoulia et al. (2006).*

2.2 GPS measurements

After collecting GPS data from permanent GPS monitors (stations) in Central Greece-Attica-N. Evia and editing them, *Marinou* distinguishes "corridor" of the Aegean plate's boundary in Central Greece, due to the opposing motion of Central Greece and N. Evia in relation to Attica and S. Evia *(fig.5)*. This conclusion is strengthened by the calculation of the deformation tensors for three zones (Northern zone-Central zone-Southern zone) according to *Papoulia et al. (2006).* These calculations reveal great differences in the intensity and orientation of the Northern zone's deformation to that of Southern zone's, while the Central zone (zone of the Aegean plate's boundary) shows no signs of deformation. A Further division of the zones into western and eastern parts, depicts differences in the intensity and orientation of deformation in that direction as well. Moreover in her thesis, *Marinou* calculates the opening rate of N. Evoikos Gulf at 0.06-0.1 ppm/a and it is equal to the tectonostratigraphic calculation of the rate (1-2 mm/a).

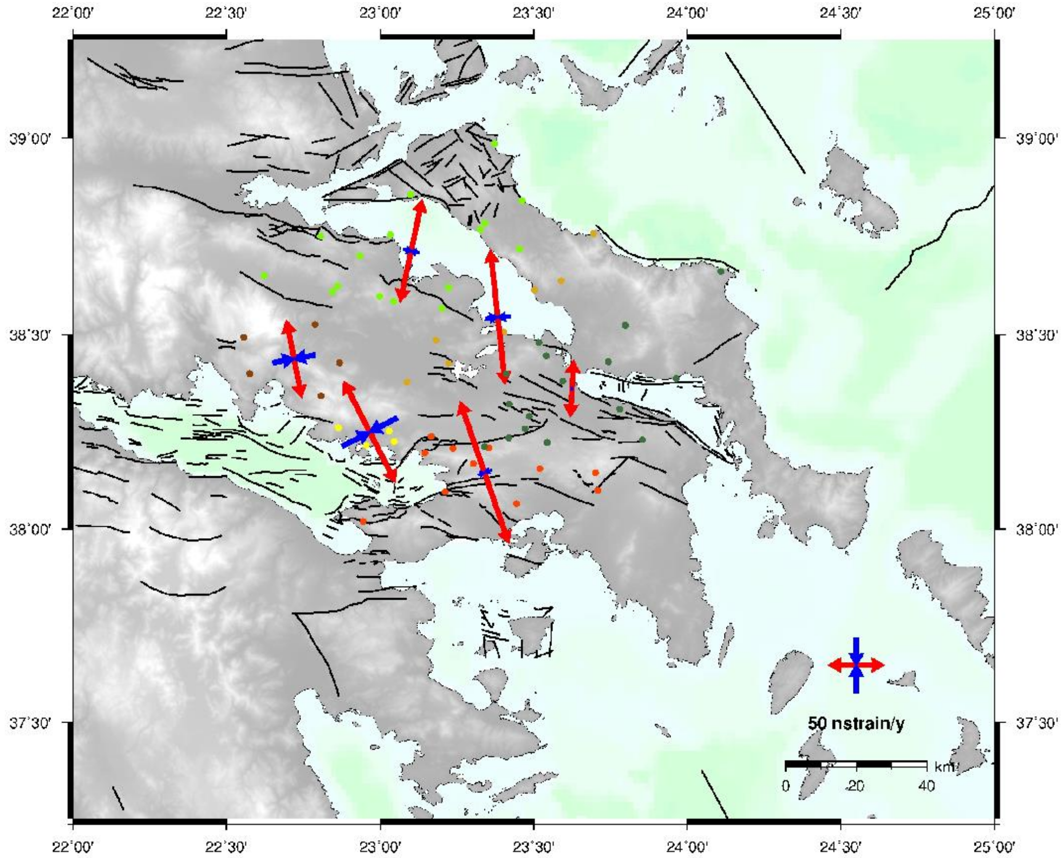


Fig. 5 *Shear of each zone into two parts, the limits of which follows the change of address faults after Marinou (2014) (unpublished data)*

Muller et al. (2012) provides GPS velocities for the Sporades islands, Northern Evia, Central Greece and Thessally. Reviewing the relief map of the Northern Evoikos Gulf's vicinity, some large tectonic structures stand out. Those tectonic structures are normal faults stretching the crust of the area and are perpendicular to the GPS velocity vectors. As seen on the GPS map the velocities increase about 2.4 mm/a from N. Evia to Central Greece. A southwards increase in the GPS velocities is also recognized. Taking all the above into account, two main boundaries were set where change of velocity is noticed, dividing the area into three zones, similar to Marinou (2014) and Papoulia (2006). Due to the fact that there are no GPS recordings from C. Evia and according to Marinou's view, that Central and Southern Evia's motion is the same as Attiki's motion, the southernmost boundary is drawn approximately. I have placed another boundary as well, that divides N. Evia from C. Evia and follows the trace of the Kechriae fault zonefault zone. In Central Greece there is little to no increase in the GPS velocities (towards SW), making it clear that, currently, tectonic activity is taking place on the coastal fault zone system. The Viotikos basin vicinity seems to be under transpression, which is common in areas that are under an overall transtensional regime, and has been mentioned by *Papoulia et al. (2006).*

2.3 Regional Geology

2.3.1 Northern Evia Island

Northern Evia is dominated by Pliocene lacustrine and fluvial sediments. The island's basement consists of a Permo-Triassic volcanoclastic complex at its base and a Triassic-Jurassic carbonate platform, known as Subpelagonian unit. Superimposed on this unit is an ophiolithic nappe off the Late Jurassic-Early Cretaceous.

Mt Kandili comprises the aforementioned Triassic-Jurassic carbonate platform, on top of which layw the ophiolithic nappe, which disappears northwards. The low area of Limni is widespread with fluvial and lacustrine sediments. The alpine basement reappears in Mt Telethrion that consists of the Subpelagonian unit's volacanoclastic base and in Mt Lichas, that is the Triassic-Jurassic carbonates.

2.3.2 Central Greece

The coast of Central Greece is dominated by fluvial and lacustrine sediments from the Pliocene. Deltaic and alluvial formations are also present, in contrast to Evia's steep coastline where that kind of formations are absent. The Alpine basement is the same as in Evia, with the addition of the Subpelagonian's Upper Cretaceous carbonates, and superimposed is the ophiolithic nappe. The forenamed Subpelagonian formations, same as in Evia, with the addition of the Upper Cretaceous carbonates, comprise the Alpine basement of Central Greece, again covered by the the ophiolithic nappe from the Upper Jurassic-Early Cretaceous period.

In detail, the Alpine basement appears in the Mountains that are formed due to uplift along the previously mentioned fault zones. Triassic-jurassic carbonates and ophiolites constitute Mt Knimis, while on the southern end of the Mt Range, at the Melidoni village the Subpelagonian base appears along the Arkitsa-Loggos fault zonefault zone Mt Chlomon is made up of the same formations, while the volcanoclastics appear in Atalanti. The Kallidromon Mt Range belongs to the footwall of its fault zonefault zone This Range at its biggest part consists of the aforementioned as well. However, on the northest part of Mt Kallidromon a post-alpine formation called The Brallos formation rests on the Upper Cretaceous carbonates of the Subpelagonian unit disconformably *(Tzanis et al., 2010).*

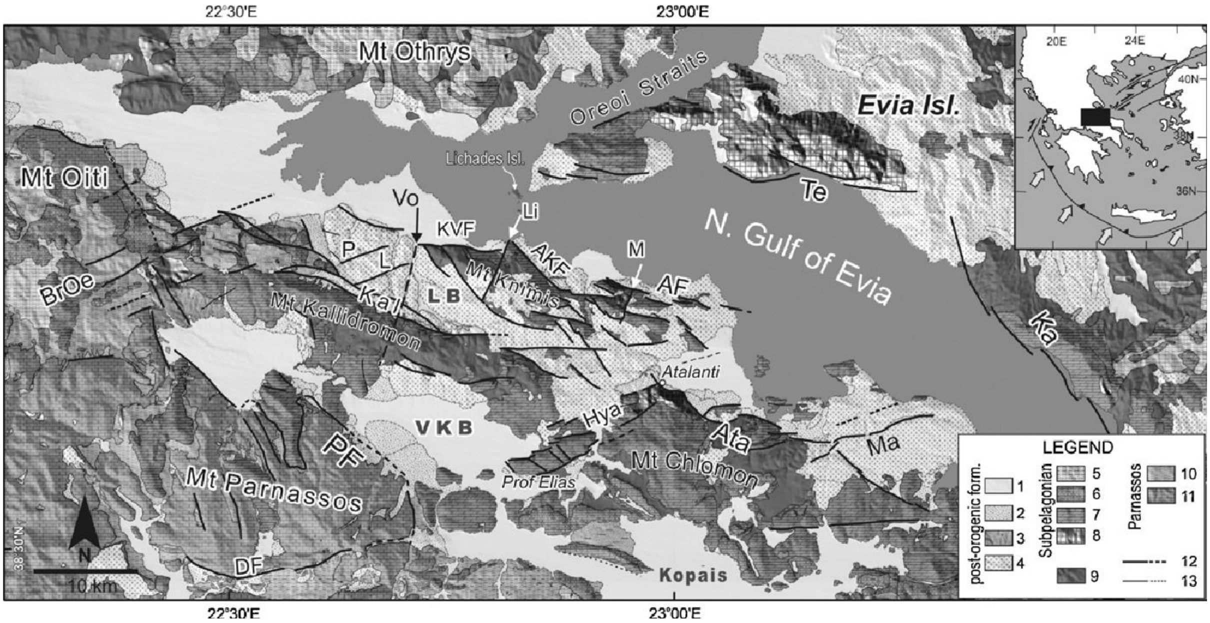


Fig. 6 *Geological map of the study area by Tzanis et al. (2010).*

2.4 Tectonic Regime

The NEG is a tectonic basin bounded by the NW-SE Telethrion fault zonefault zone and the E-W Edipsos fault in the North and the NW-SE Kandili fault zone in the East. This NE boundary forms the coastline of N. Evia Island, which is a very steep coastline, in contrast to the NW one in Central Greece, where the tectonic boundary is far more inland and there is a normal shelf shaped. This active NW boundary is composed by the fault zones of Kammena Vourla, Aghios Konstantinos, Arkitsa-loggos and the Atalanti.

Essentially, the western boundary breaks down into three main NW-SE fault zone systems. The first system just onshore stretches out from Arkitsa to Spercheios, uplifting Mesozoic carbonates and Neogene sediments. The relief reaches the altitude of 1 km, much like in the southern flank of the Corinth Rift, although they differ in that, right next to that, water depth reaches the 100 m, possibly due to high sedimentation rate.

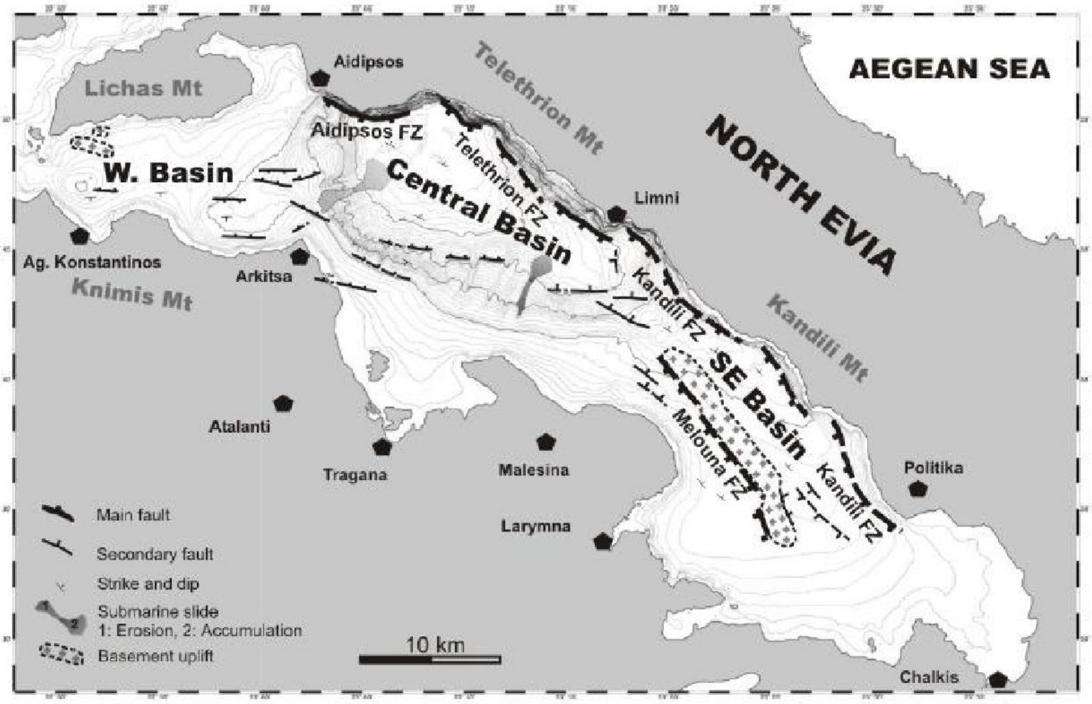


Fig. 7 *Tectonic map of North Evia Gulf .(Sakellariou et al. 2007)*

The second system subparallel to Mt Kallidromon is found about 8 km southwards. Mt Kalidromon rises 600-700 m above the Neogene fluvial and lacustrine sediments of the Lokris basin. The third southeast and oldest system bounds Mt Parnassos; it reaches 2300 m in altitude and trends NW-SE.

It seems to be a succession in the activity of these systems and given from the geomorphology of the region, it is understood that the coastal system is the dominant and most active, presently. At length, the coastal slope's morphology is much more distinct than that of the other systems. Also, the hydrographic systems on the hanging walls of the Parnassos and Kallidromon fault zone have been incised due to uplift on the footwalls of the coastal fault zone. Further evidence that confirms the northwards migration of tectonic activity is the findings of marine fossils. However, in his work *Cundy (2010)* mentions a series of uplifted and back-tilted terraces in the hanging-wall of the Arkitsa fault, which he/she attributes to the activation of and rotational faulting on a secondary fault strand at Livanates. In addition, he observed coastal uplift at Alope (on the hanging-wall of the Arkitsa fault). In this case, no rotation of bedding was found and Alope is about 8km away from the aforementioned Livanates fault, so the observed uplift might be the result of the activation of an offshore fault. Although, there has been no clear evidence for movement on this offshore fault.

The coastal fault zone system splits into four active main fault zones: (i) the Atalanti (AFZ)fault zone; (ii) the Arkitsa-Loggos (ALFZ); (iii) the Aghios Konstantinos (AKFZ): and (iv) the Kammena Vpourla(KVFX). The AFZ is the only fault zone that accounts for the opening of the NEG in its southern part. However, there is a second 6.5 km synthetic normal fault just offshore of Gaidouronisi. The AFZ (can be separated into three segments) is about 36 km long and trends ESE-WNW. There is no reference of any kinematic signs measured for some observations made on the ruptures of the 1894 earthquake, that support a sinistral motion. The ALFZ splits into four segments as well. Arkitsa fault's slip surface features $67^0/018^0$ and the displacement vector trends $N30^0W$, with 75% dip slip and 25% strike slip motion. For a 2.5 km distance, the ALFZ and AKFZ are overlapping each other. The AKFZ, in its eastern end trends E-W and through NNW-SSE transfer faults changes its trending into NW-SE. The KVFZ consists of three fault segments trending E-W to ESE-WNW with a minimum dip of 60^0. Linear markers trending NW to NNW show only on the central and western part of the fault zone and feature a $40^0/348.5^0$ mean slip vector *(Kranis et al., 2002).*

In the North Evia two neotectonic phases have been recognized. The first and oldest one, which is a Miocene-Early Pliocene extension phase in NE-SW direction, expressed with NW-SE or E-W trending faults, took place; tinhe Limni-Istiaia basin formed during this phase. The second successive extensional phase started in Pleistocene, trending from NNW-SSE to N-S and incorporating new faults trending from NE-SW to ENE-WSW, or the older ones trending from NW-SE to WNW-ESE refunctioned as oblique-normal. During this latter phase the NEG basin formed by normal faults trending NW-SE to WNW-ESE *(Palyvos et al., 2006)*.

The Northern Evoikos Gulf can be separated into three individual sub-basins: (i) The Western basin reaching 100m in depth; (ii) the Central basin reaching depths of circa 460m; and, (iii) the Southeastern basin of circa 100 m deep. These three sub-basins differ substantially when compared to each other, as they present different orientations, geological structure and stratigraphy *(Sakellariou et al., 2007)*. Alevizos *(2009)* has mentioned the existence of 8 large grabens in the Alpine basement which during the last glacial period were lakes. These grabens are correlated with the present extension of the area as they seem to have acted in an early (pre-) rift stage.

<u>Western basin</u>

It is an E-W trending basin and the prolongation of the Spercheios basin in the East. The thickness of the formations that lay on the bottom of the basin is greater than 400m in some areas in its southern part. The formations can be separated into two stratigraphic sequences, the Upper thin sequence (30-40m thick decreasing northwards) that onlaps on the Lower thick one. On the bottom of the basin has also been noticed the presence of volcanic sediments coming from the Lichadonisia island.

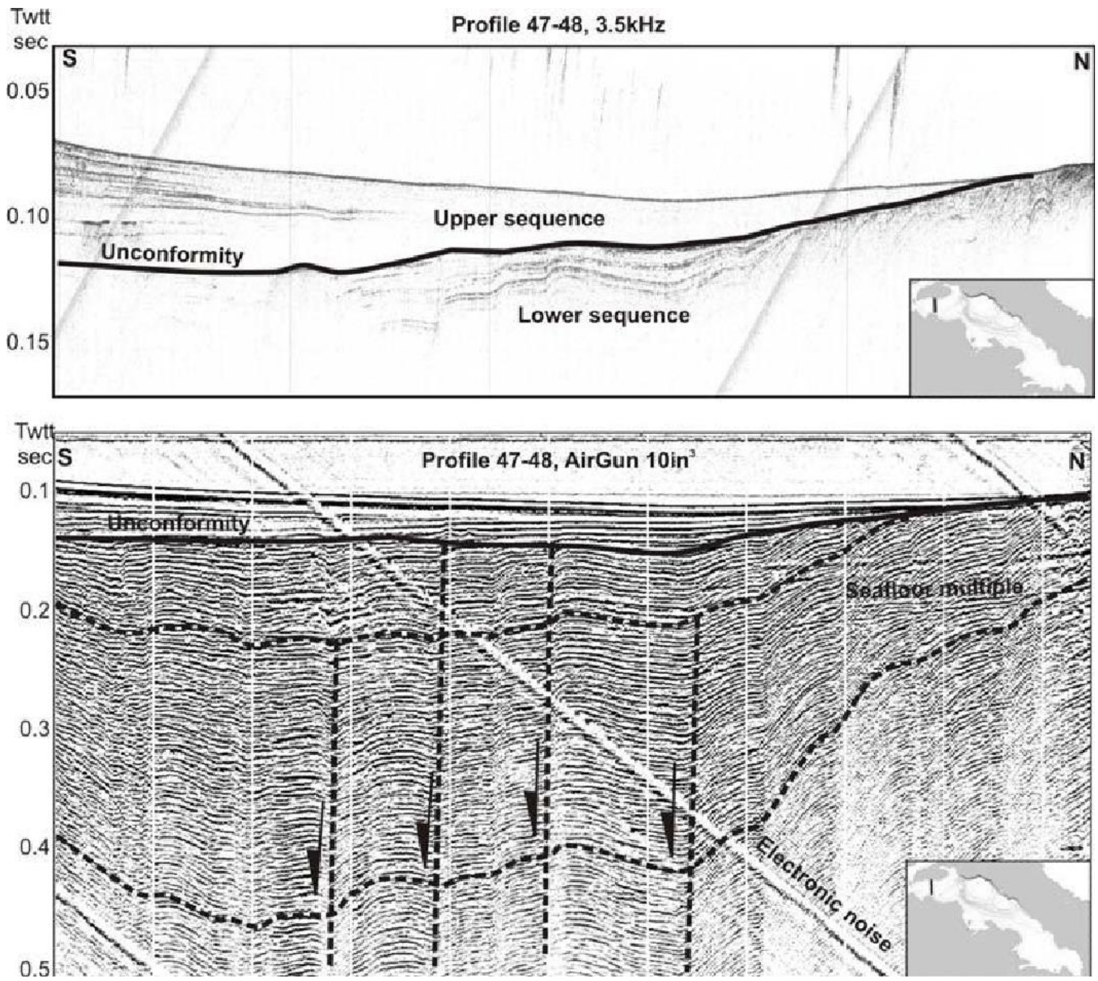


Fig. 8 *Seismic profile of the Western basin (Sakellariou et al, 2007)*

Southeastern basin

It is an elongated basin trending NW-SE bounded in the East by the Kandili fault which, much like the Telethrion and Edipsos faults, is solely responsible for the subsidence of the basin. In the West the transition from the basin to the Malesina peninsula is also abrupt, indicating the presence of a fault which, however has not yet been recognized. The active Melouna fault, which runs along the basin and separates it into two sub-basins, is the feature of the Southeaster basin. The eastern one is called Kandili sub-basin, and the western one is known as Malesina sub-basin.

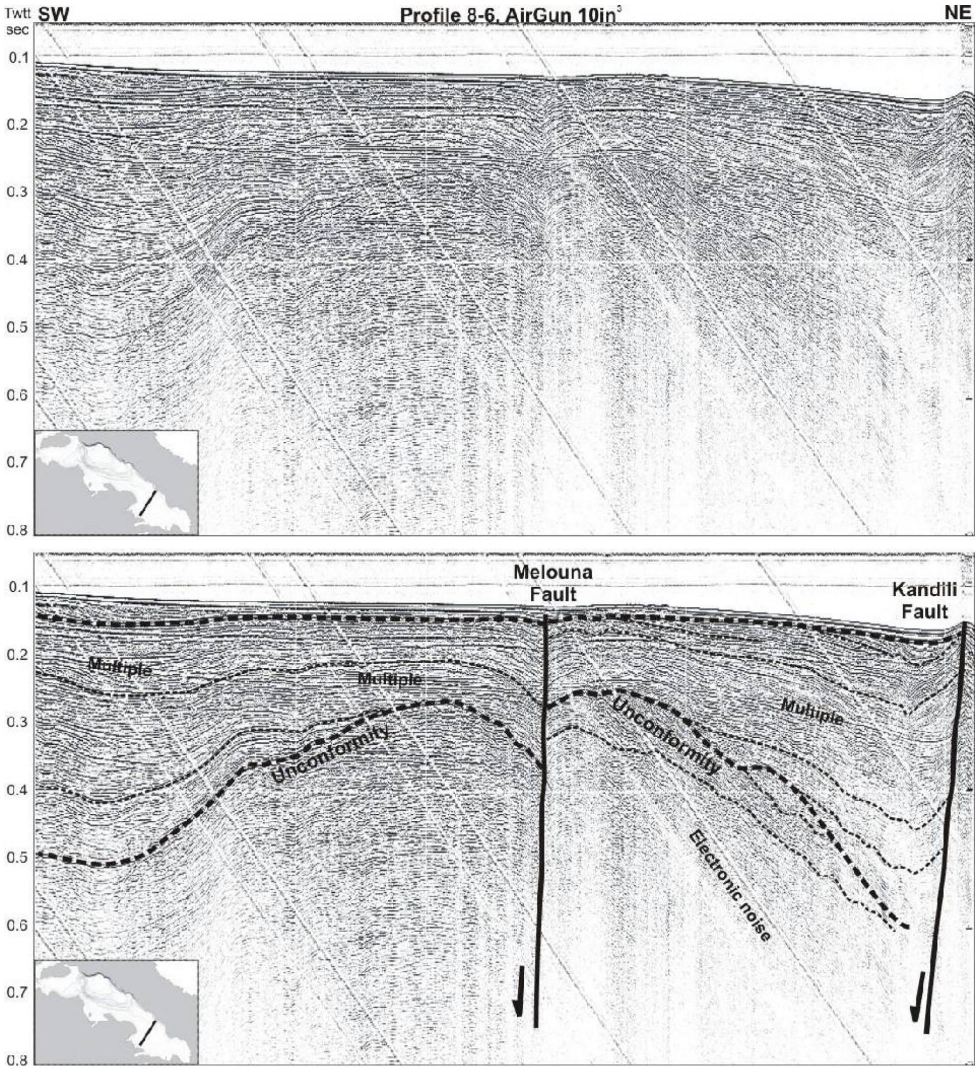


Fig. 9 *Seismic profile of the Southeastern basin (Sakellariou et al, 2007)*

In the Southeastern basin, three stratigraphic sequences can be recognized. The top of the Lower sequence has been eroded and the unconformity is the giveaway of Melouna fault's 80m throw. The fault cuts through the Medium sequence but its throw decreases the closer it gets to the surface. The sediments of the aforementioned sequences are possibly related to the Pliocene sediments of the Malesina peninsula and N. Evia island. If this suggestion is confirmed, that would mean a subsidence of about 400m.

Central basin

The area between the Central and Western sub-basin is of mild slope which coincides with the bending of the sediments due to the effect of local faults. The area between the Central and Southeastern basin shows a similar image with the difference that the bedding changes direction of tilting from one side of the faults to the other, while inside the Central basin the bedding tilts northwards. The northern boundary of the Central basin is actually the boundary of NEG and consists of the Telethrion and Edipsos faults. It is very steep and the vertical throw exceeds 1000m. It is practically a half-graben, considering that the subsidence happens on the northern flank of the basin.

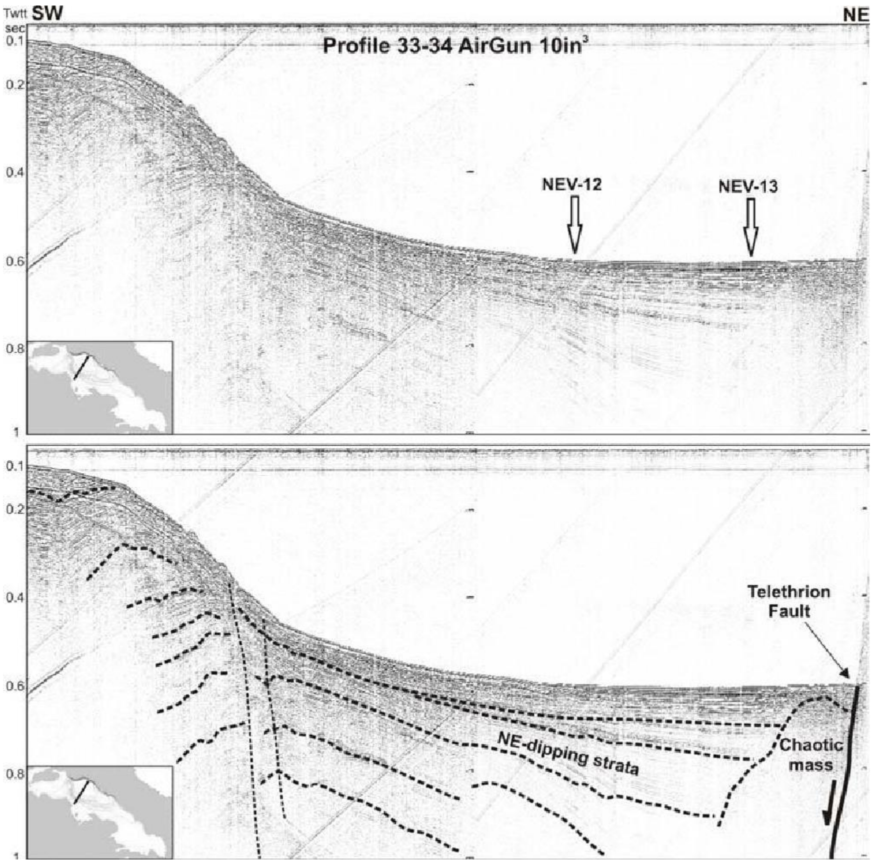


Fig. 10 *Seismic profile of the Central basin (Sakellariou et al, 2007)*

Near the northern boundary, gravitational sedimentation with extremely high speed takes place. From core samples near the Telethrion fault, sedimentation rate was measured to 0.33cm/yr for the last 100-120years. Same sediments, however, are found on the Southeastern flank of the basin even though the slope is not as steep.

3 DATA COLLECTION AND INTERPRETATION USING A MULTI-BEAM SYSTEM

This work is based on the analysis a data set of seabed morphology collected with the use of the Multi-Beam System of the R/V AEGAEO, during the research program “Amphitrite” in in January of 2014.

3.1 What is MB-System

Some pre-processing steps are required before the bathymetric data can be processed using MB-System. This includes checking the raw data format and the conversion into a usable format for processing. Actually the different swath sonar measurement devices used for bathymetric measurements support different raw data formats, which can be checked by using the command. This command lists all available formats used by the different swath sonar types along with a short description of the systems. We use the format ID 41.To simplify the conversion and avoid converting, every single data file manually it is advisable to create a data list, which contains all information about the raw data files indicated as format 41.

3.2 Kinds of Data Set that we used on MB-System

During data acquisition the computer systems are engaged on doing the real-time multibeam processing and displaying of bathymetry data. The multi-beam bathymetric survey was carried out in January 2004, as part of the research program “Amfitriti”, on the research vessel “Aegaeo” of the National Centre for Marine Research using the recently installed ‘SEABEAM 2120’ swath system, which is a fully mounted system operating at 20 kHz at water depths not exceeding 5000 m. It has an angular coverage sector of 150 degrees with 149 beams, covering a swath width from 7.5 to 11.5 times the water depth for depths of 1 to 5 km, respectively. The maximum swath coverage can reach 9 km at maximum depth and gives a satisfactory data quality with speed up to 10 knots.

During this mission the system was operated for a total of 4 days, surveying in a total track length of 872 km with an average vessel speed of 10.8 knots.The total area that was mapped was about 500 km2 and the maximum coverage area reaches up to 2 km.

The system SEABEAM 2120 except a very good interactive, real-time, display tool that is the SeaSurvey Advanced package does not possesses it own post processing tool. For all the procedures described above it employs tools and modules of the MB-System package and algorithms of the GMT software.

The processing of bathymetric system of multi-channel data includes the following procedures through the programs MB System, GMT and GIS performing the following processes in order: 1) navigation editing, 2) data editing, 3) corrections in the speed of sound, 4) gridding and 5) creation of the maps that will be analyzed below.

Data processing and generation of final bathymetric maps:

During data acquisition the computer systems are engaged on doing the real-time multibeam processing and displaying of bathymetry data. Thus on-board very limited data processing can be performed and only for the SEABEAM 2120 system on the third machine specifically design for the post-processing.

3.3 Editing and cleaning

For the data cleaning of SEABEAM 2120 system two basic steps have been followed, the first is an intensive checking and filtering and the second a very elaborative ping by ping examination and correction.

Studying the artefacts presenting on the data of 2120 system, flexible scripts have been specifically designed to apply a series of filters to swath data, utilizing algorithms of MB system. Thus, all swath data (of this system) were passed file by file, through a number of flagging algorithms applied in the following order:

1. Flag specified number of outer beams.
2. Flag soundings outside specified acceptable depth range.
3. Flag soundings outside acceptable depth range using fractions of local median depth.
4. Flag soundings outside acceptable depth range using deviation from local median depth.
5. Flag soundings associated with excessive slopes.
6. Zap "rails".
7. Flag all soundings in pings with too few good soundings.

The above procedure removed isolated beams that satisfy only the selected criteria but the remaining outliers had to be examined and subjectively flagged in a line by line mode. This has been completed checking file by file, ping by ping all the beams on the graphical interface of MBedit swath editor.

3.4 MB-System Command Reference

3.4.1 Creation of a new datalist and ancillary files, containing all 41 formatted data

- ls -1 *mb41 > datalist.mb-1
- mbdatalist -F-1 -I datalist.mb-1 -N –V

-1 = place holder, e.g. if the format is unknown
-N = necessary for the generation of the three ancillary files (*inf; *fbt; *fnv)
-V = if added the program will work in a "verbose mode" and outputs the used program version

mbdatalist is a utility for parsing datalist files. Datalist files, or lists of swath data files and their format ids, are used by a number of MB-System™ programs. These lists may contain references to other datalists, making them recursive.

Get a first impression over the data set/Generation of a plot:

- mbm_plot –I datalist.mb-1 –G2 –NF

-G2 = colour fill swath plot is turned on and the style of the plot is defined, different modes: in this case Mode 2 = color shaded relief bathymetry
-N = causes a navigation track plot

- ./datalist.mb-1.cmd -creates a postscript

mbm_plot is a macro to generate a shellscript of MB-System and GMT commands which, when executed, will generate a Postscript plot of the specified swath sonar data. The plot may include bathymetry colour fill, bathymetry color shaded relief, bathymetry shaded with amplitudes, greyshade fill amplitude, greyshade fill sidescan, contoured bathymetry, or annotated navigation. The plot may also include text labels, xy data in lines or symbols, and coastlines.

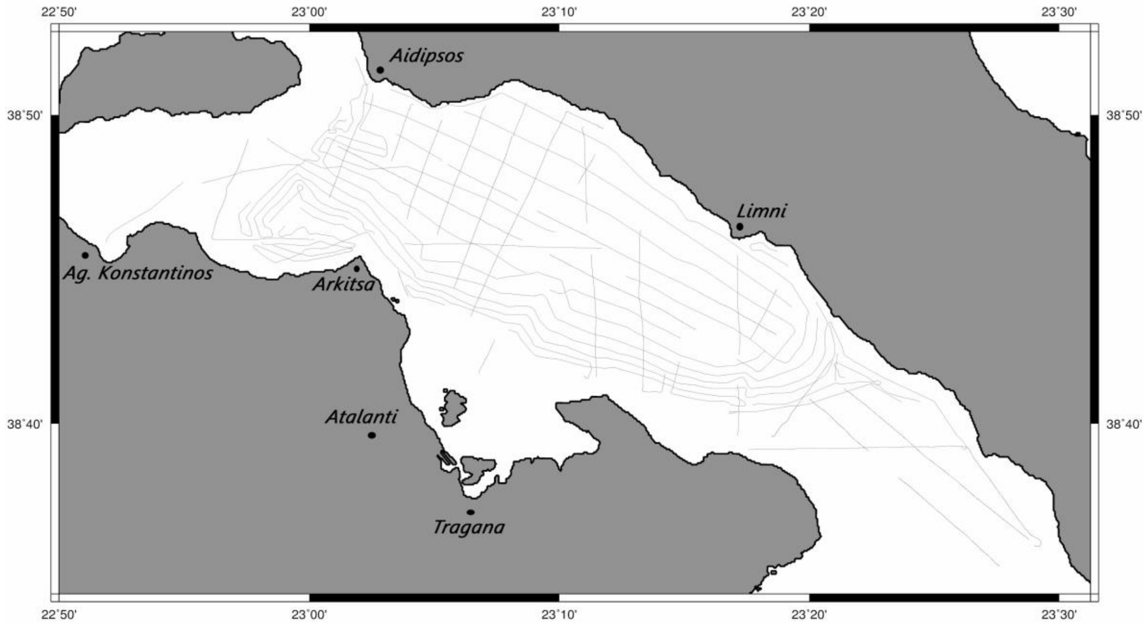


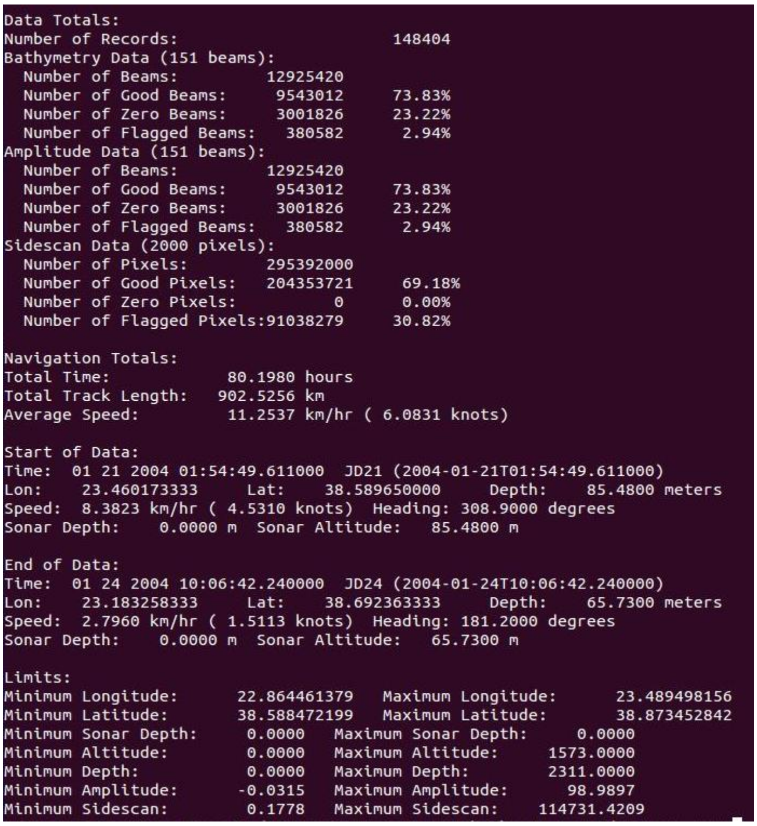
Fig. 11 *Survey navigation map of Northern Evoikos Gulf*

3.4.2 Extracting Statistics

MB-System provides mbinfo as a simple tool to extract statistics about a data_set.

mbinfo –F-1 –I datalist –G

The results are sent to STDOUT by default rather than an ".inf" file. One can optionally redirect the results to a file of the same name as the original with ".inf" appended to the end with the -O flag. The resulting file will be automatically read and utilized by several of the other MB-System processes.



```
Data Totals:
Number of Records:                           148404
Bathymetry Data (151 beams):
  Number of Beams:          12925420
  Number of Good Beams:      9543012      73.83%
  Number of Zero Beams:      3001826      23.22%
  Number of Flagged Beams:    380582       2.94%
Amplitude Data (151 beams):
  Number of Beams:          12925420
  Number of Good Beams:      9543012      73.83%
  Number of Zero Beams:      3001826      23.22%
  Number of Flagged Beams:    380582       2.94%
Sidescan Data (2000 pixels):
  Number of Pixels:         295392000
  Number of Good Pixels:    204353721      69.18%
  Number of Zero Pixels:            0       0.00%
  Number of Flagged Pixels:91038279      30.82%

Navigation Totals:
Total Time:             80.1980 hours
Total Track Length:   902.5256 km
Average Speed:          11.2537 km/hr ( 6.0831 knots)

Start of Data:
Time:  01 21 2004 01:54:49.611000  JD21 (2004-01-21T01:54:49.611000)
Lon:    23.460173333     Lat:    38.589650000     Depth:    85.4800 meters
Speed:  8.3823 km/hr ( 4.5310 knots)  Heading: 308.9000 degrees
Sonar Depth:    0.0000 m  Sonar Altitude:   85.4800 m

End of Data:
Time:  01 24 2004 10:06:42.240000  JD24 (2004-01-24T10:06:42.240000)
Lon:    23.183258333     Lat:    38.692363333     Depth:    65.7300 meters
Speed:  2.7960 km/hr ( 1.5113 knots)  Heading: 181.2000 degrees
Sonar Depth:    0.0000 m  Sonar Altitude:   65.7300 m

Limits:
Minimum Longitude:      22.864461379   Maximum Longitude:      23.489498156
Minimum Latitude:       38.588472199   Maximum Latitude:       38.873452842
Minimum Sonar Depth:      0.0000   Maximum Sonar Depth:     0.0000
Minimum Altitude:         0.0000   Maximum Altitude:     1573.0000
Minimum Depth:            0.0000   Maximum Depth:        2311.0000
Minimum Amplitude:       -0.0315   Maximum Amplitude:      98.9897
Minimum Sidescan:         0.1778   Maximum Sidescan:    114731.4209
```

Fig. 12 *The result of executing the mbinfo line above.*

So, we can see that the surveys lasted some 80 hours covering 902 km at an average ship speed of about 6 knots. We can also see the number of beams recorded, and had any processing been done on these data files, the number of beams that had been flagged for removal. We can finally see the data bounds, in latitude, longitude, minimum and maximum water depth, and start and stop times.

3.4.3 Adjustment of the data/Examination of the data-points and cleaning

- mbedit and mbeditviz

Mbedit is an interactive editor used to identify and flag artifacts in swath sonar bathymetry data. Once a file has been read in, Mbedit displays the bathymetry profiles from several pings, allowing the user to identify and flag anomalous beams *(fig. 13 and 14)*.

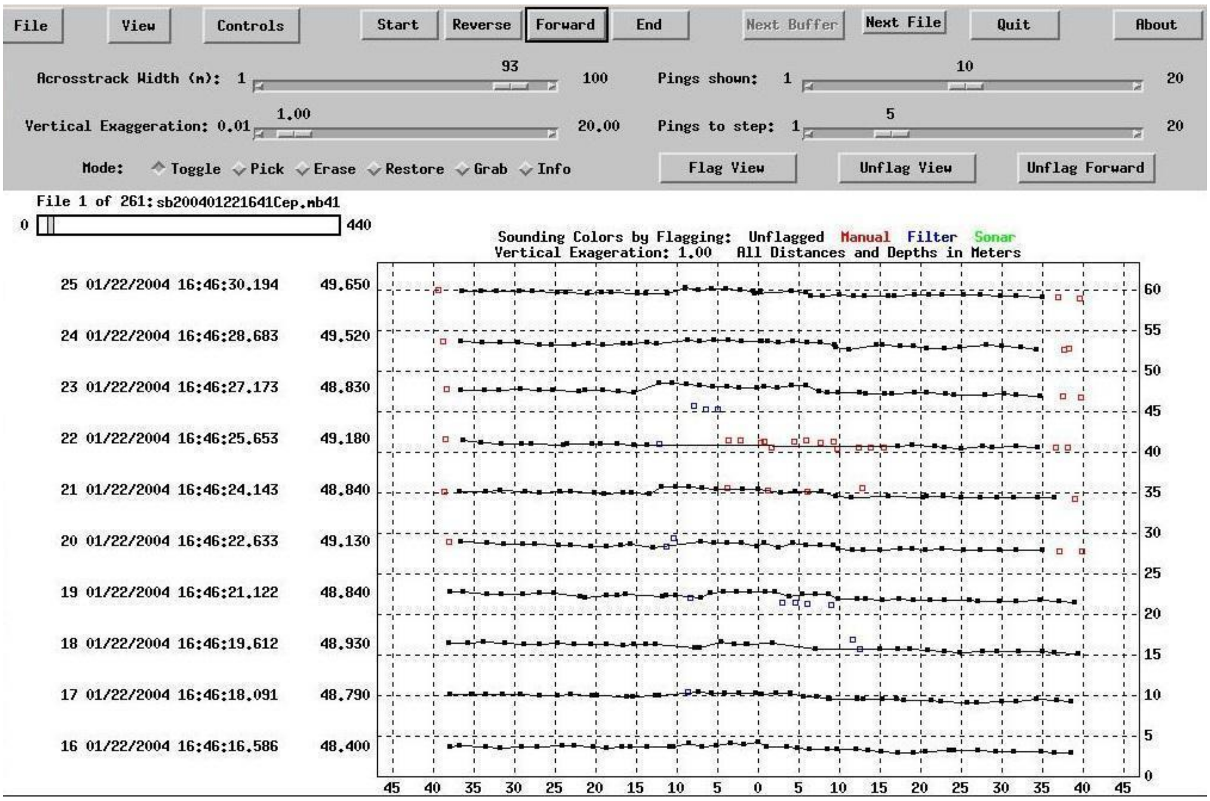


Fig. 13 Cleaning files using MBedit

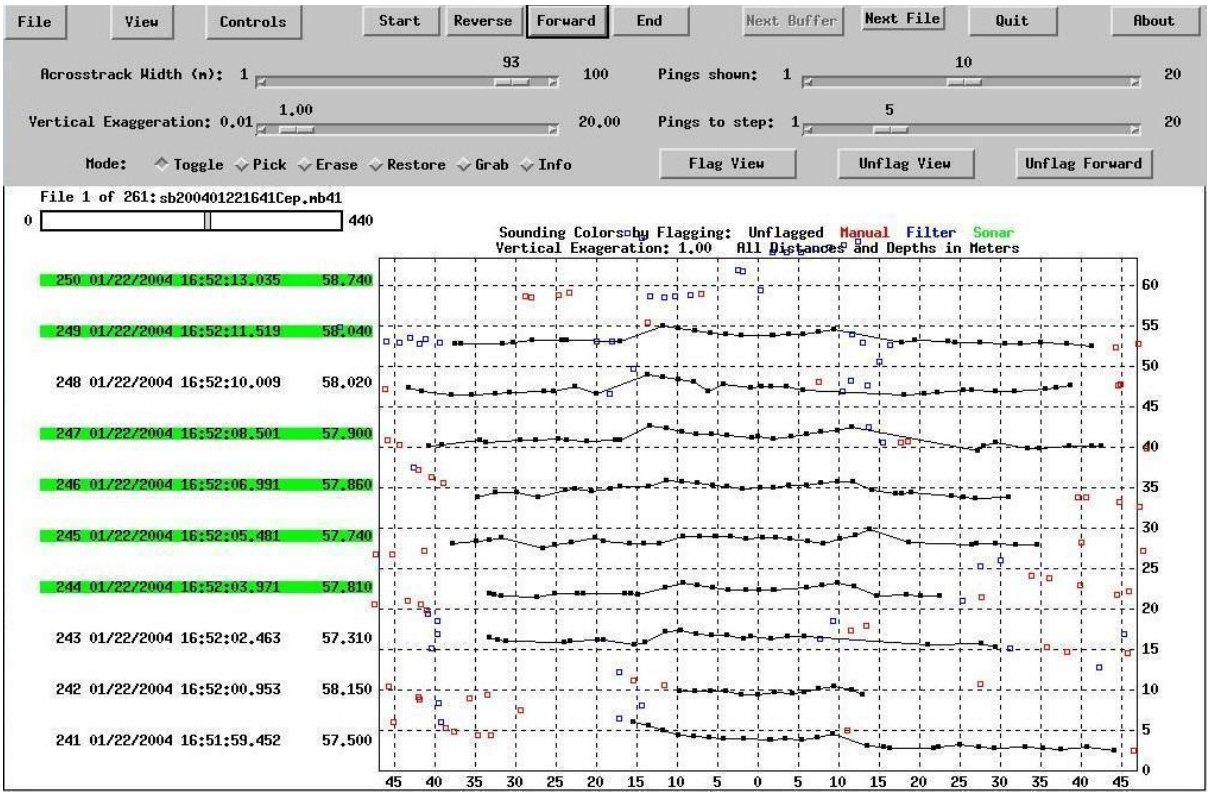


Fig. 14 Cleaning files using MBedit

MBeditviz is an interactive 2D/3D visualization-based tool for editing swath bathymetry data. The bathymetry data from selected files are read into memory, gridded *(fig. 15)*, and displayed in the same 2D/3D visualization environment used by MBgrdviz. In this environment, we can select arbitrary areas or regions. All of the soundings in the selected areas are displayed in a 3D "cloud" that can be rotated, zoomed, and exaggerated *(fig. 16 and 17)*.

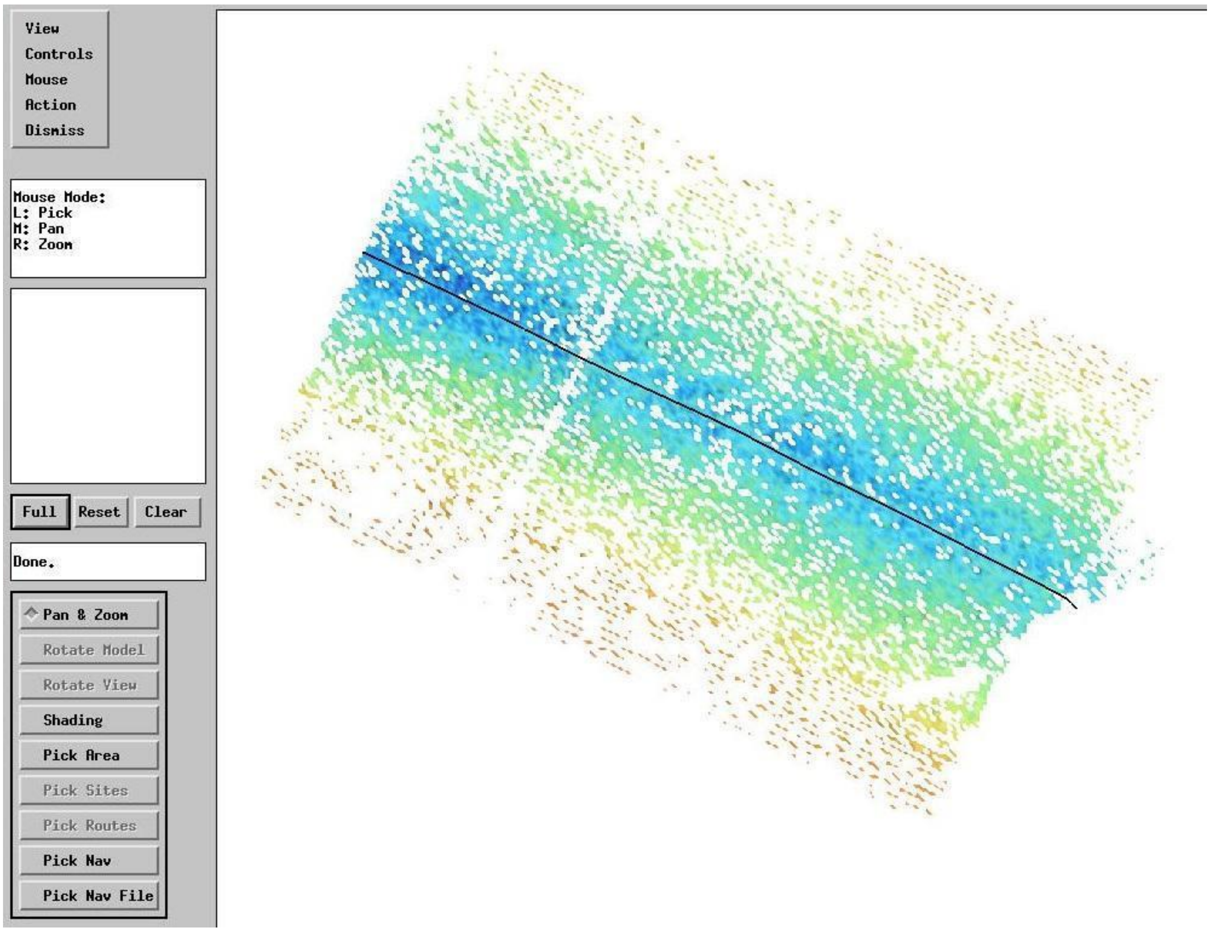


Fig. 15 *Cleaning files using MBeditviz*

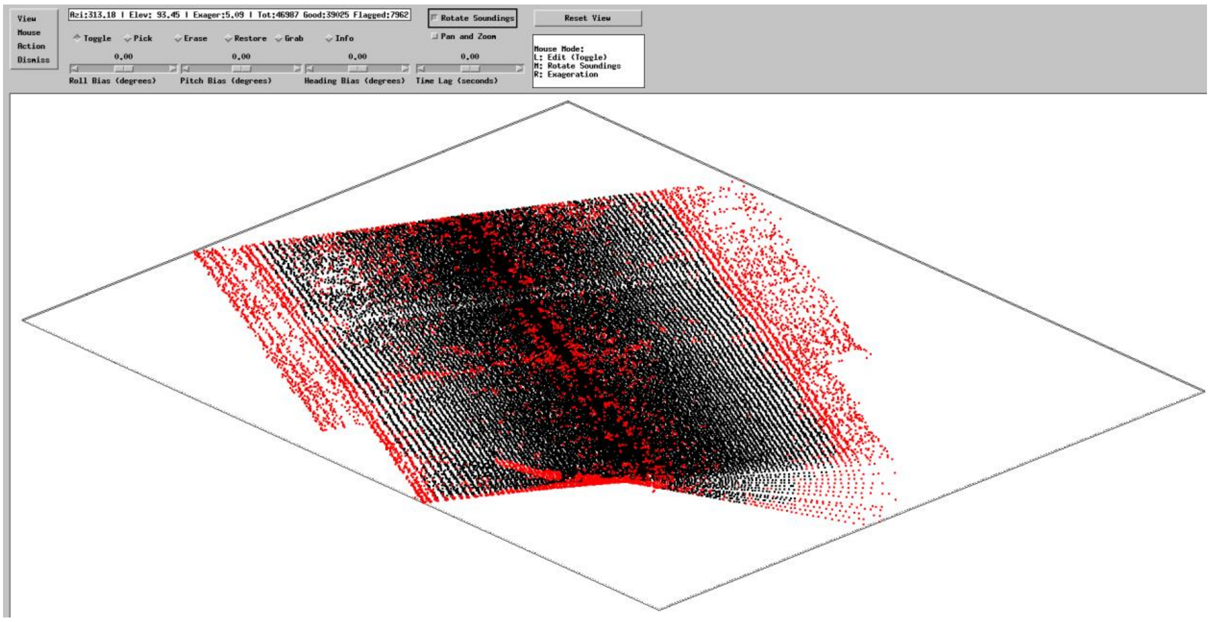


Fig. 16 *Cleaning files using MBeditviz*

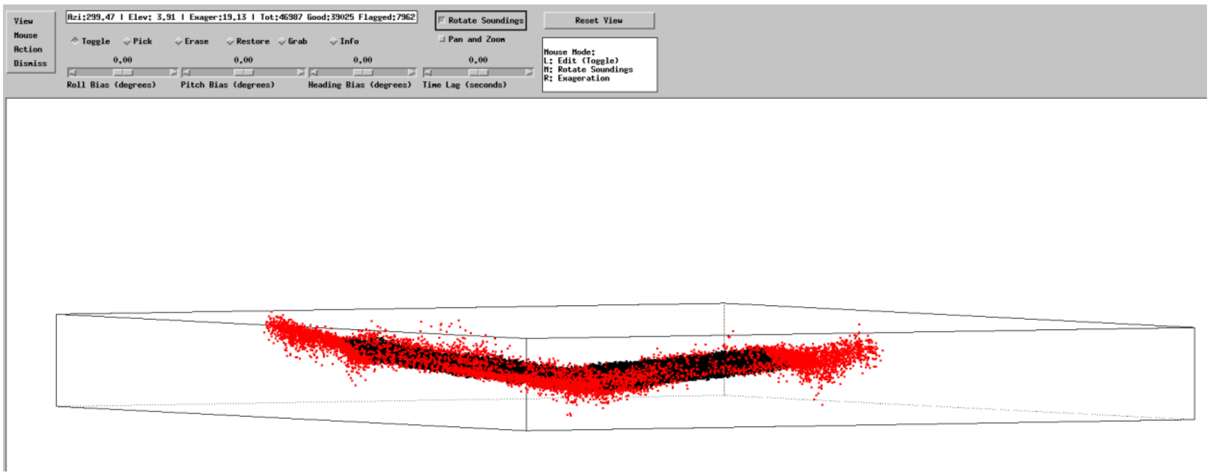


Fig. 17 *Cleaning files using MBeditviz*

3.4.4 Processing of the data

- mbprocess –I sb(name).mb41 –V –P
- ls -1 *p.mb41 > datalistp.mb-1
- mbdatalist –F-1 –I datalist.mb-1 –N -V

mbprocess is a tool for processing swath sonar bathymetry data.

3.4.5 Creation of a grid

- mbgrid –I datalistp.mb-1 –A2 –E50/50 –F1 –G3 –C25/1 –S2 –N –O(outputname)

-E = specifies the grid cell size
-A = type of data, topography or bathymetry
-F = mode = sets the gridding algorithm, "1" = Gaussian Weighted Mean is used
-G = gridkind = sets the format of the output grid file; "3" stays for a netCDF file (GMT version 2 GRD file)
-C = interpolates gaps
-S = defines the minimum speed of the vessel: here S2 means that data, which were collected during a ship velocity of smaller than 2 km/hr should be neglected
-N = with this command grid cells without data + interpolation are set to a value of NaN, which is expected by GMT = avoids the setting of the default value of 99999.9
-O = used to create an output name

- ./filename.grd.cmd

Mbgrid is a utility used to grid bathymetry, amplitude, or sidescan data contained in a set of swath sonar data files. This program uses one of four algorithms to grid regions covered by swath sonar swathes and then can fill in gaps between the swathes (to the degree specified by the user) using a thin plate spline interpolation *(fig. 18 and 19)*.

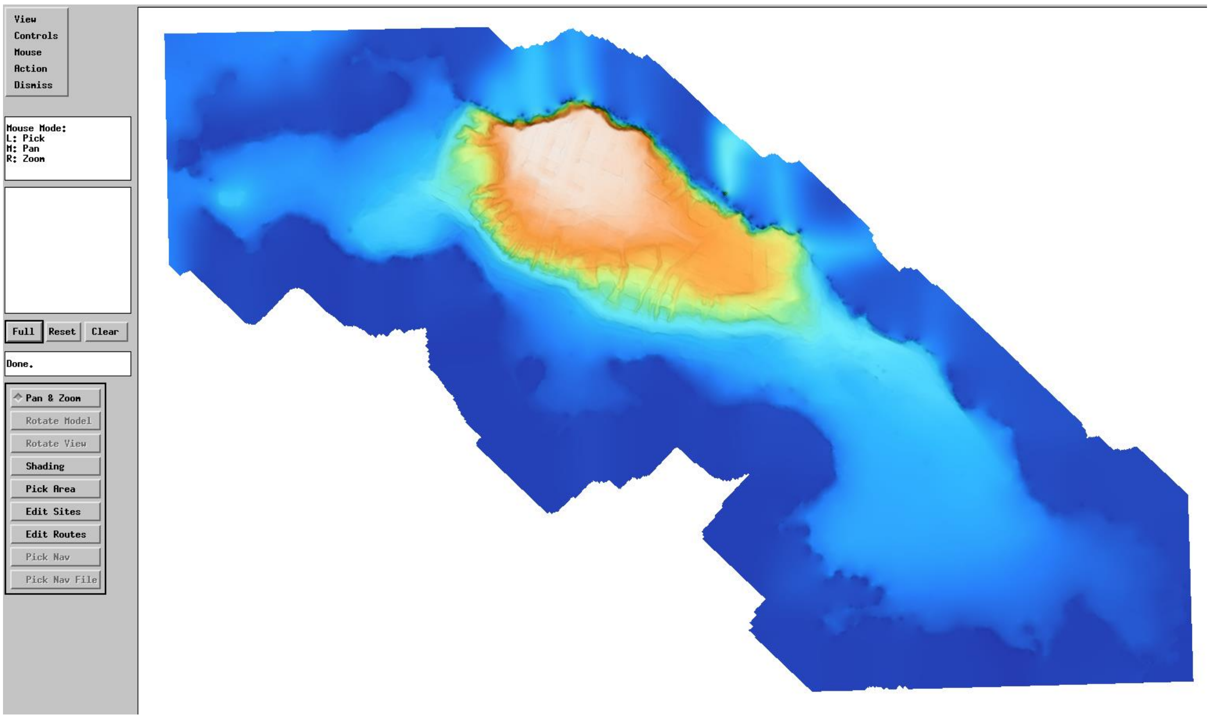


Fig. 18 *The grid file that was generated for the northern Evoikos gulf.*

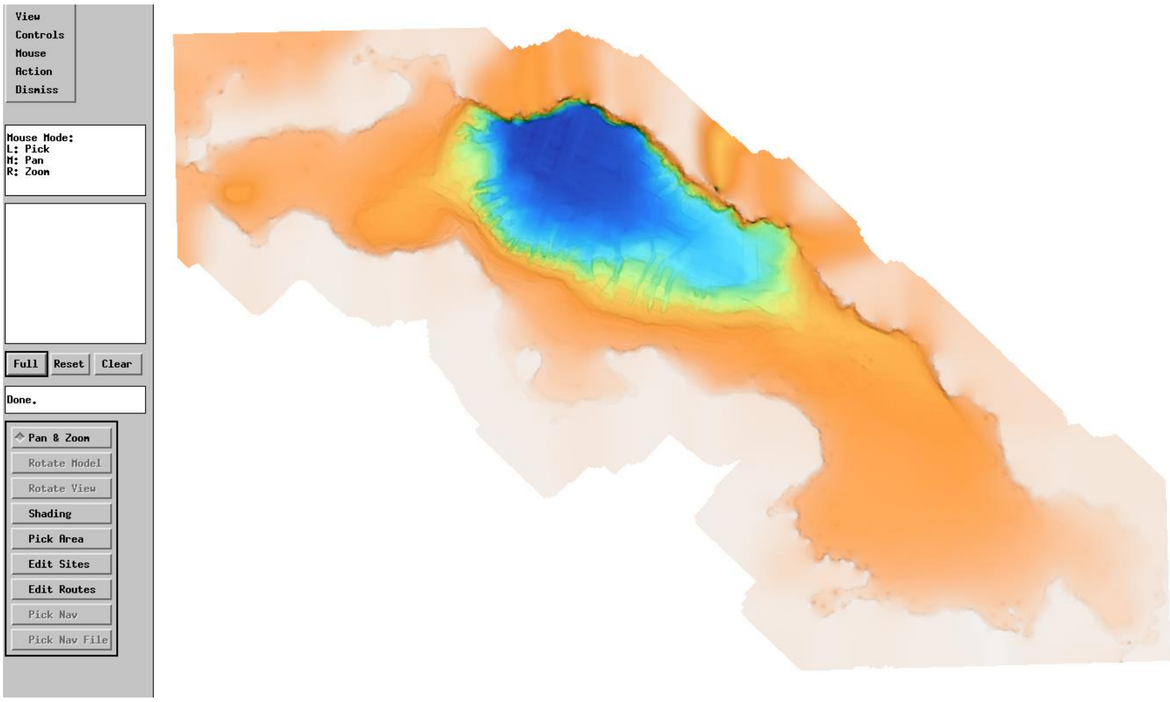


Fig. 19 *The grid file that was generated for the northern Evoikos gulf (after the appropriate correction and processing).*

3.5 Generic mapping tools graphics (GMT)

MB-System is used in conjunction with the Generic Mapping Tools (GMT) created by Paul Wessel of the University of Hawaii and Walter Smith of NOAA. GMT is a powerful set of processes used to manipulate data and to create Encapsulated Post Script maps and charts.

3.5.1 Generation of the final maps

The maps have finally been constructed using the mapping algorithms of the GMT package. The maps are georeferenced to a WGS-84 ellipsoid using Mercator projection at 38°N, 23° E.

4 RESULTS AND DISCUSSION

4.1 Swath Bathymetry

The submarine topography of the Northern Evoikos Gulf is relatively gentle morphologically, with NW-SE direction, along the coastline of North Evia *(fig. 20)*.

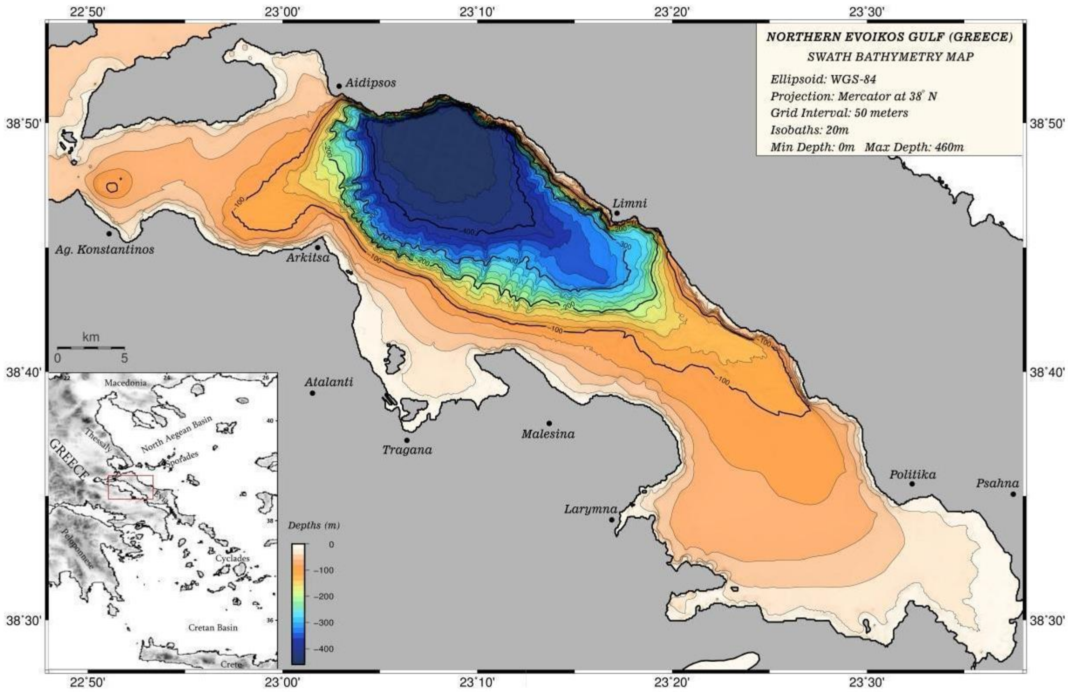


Fig. 20 *Bathymetric map of the northern Evoikos Gulf (1:150.000)*

The continental platform is developed mainly in the southern and western slopes of the gulf where depth spans from 80 to 120 m, having its largest width at the NW and SE parts of the gulf. However, the continental platform is absent from the abrupt slopes of the western coast of northern Evia, from Aidipsos up to Lake. This absence is presumably justified by the existence of a marginal fault of approximately E-W direction, which creates the abrupt slopes.

At the Gulf region there are three distinct basins as Sakellariou et al. (2007) has previously mentioned: the western, the southeastern and the central. Through the seismic profiles he managed to observe the western and southeast basins and study the composition of their sediments. The bathymetric data alone are not sufficient to designate these two as basins, since their depth is not great and their boundaries not visible. Unlike the central one, which is considered to be the only basin of the NEG, the two aforementioned areas are characterized as "plateaus".

More specifically the central basin is the main basin of the gulf and reaches 450 m depth, characterized by gentle morphology with sparse contours that gradually form the bottom of the basin from south to north. The slopes of the basin present asymmetries; the northern slope is more abrupt than the southern one which is by submarine canyons *(fig. 21)*.

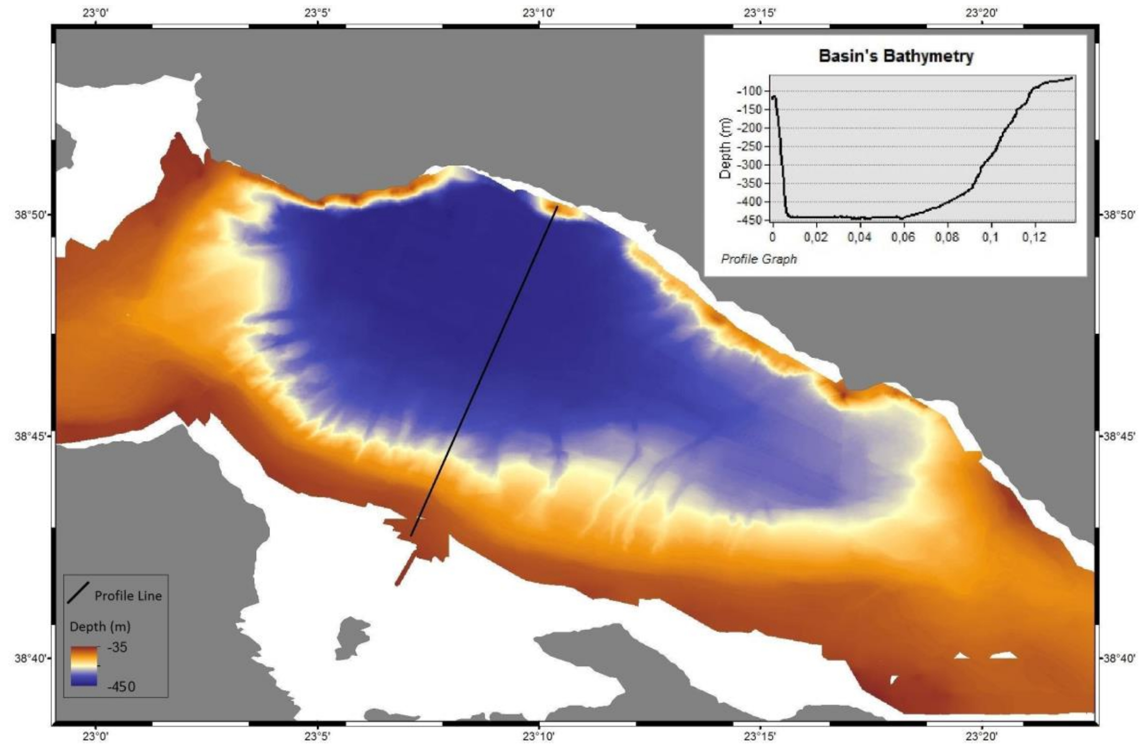


Fig. 21 *Bathymetric profile of the central basin of northern Evoikos gulf that shows the asymmetry of the slopes (1:100.000).*

Alevizos et al. (2009) confirm the existence of the central basin of the NEG. According to him the conditions of the deposits compared with the tectonics of the Northern Evoikos gulf, can be categorized it under "Syn-depositional basins". In fact, outside the trench, a slow sedimentation is observed resulting the morphology of the sediments to obey the morphology of the basin. Also the thickness and the extent of sediments vary spatially and temporally. The slip rate of the grabens (~ 0,1 mm/yr) *(Sakellariou et al., 2007)* is approximately consistent with the sedimentation rate (0,3 mm / yr) in Holocene. Therefore, the allocation that the sediments follow is proportional to the morphology of the terrain of the gulf which is constantly changing depending on the vertical movements that take place in it *(fig. 22)*.

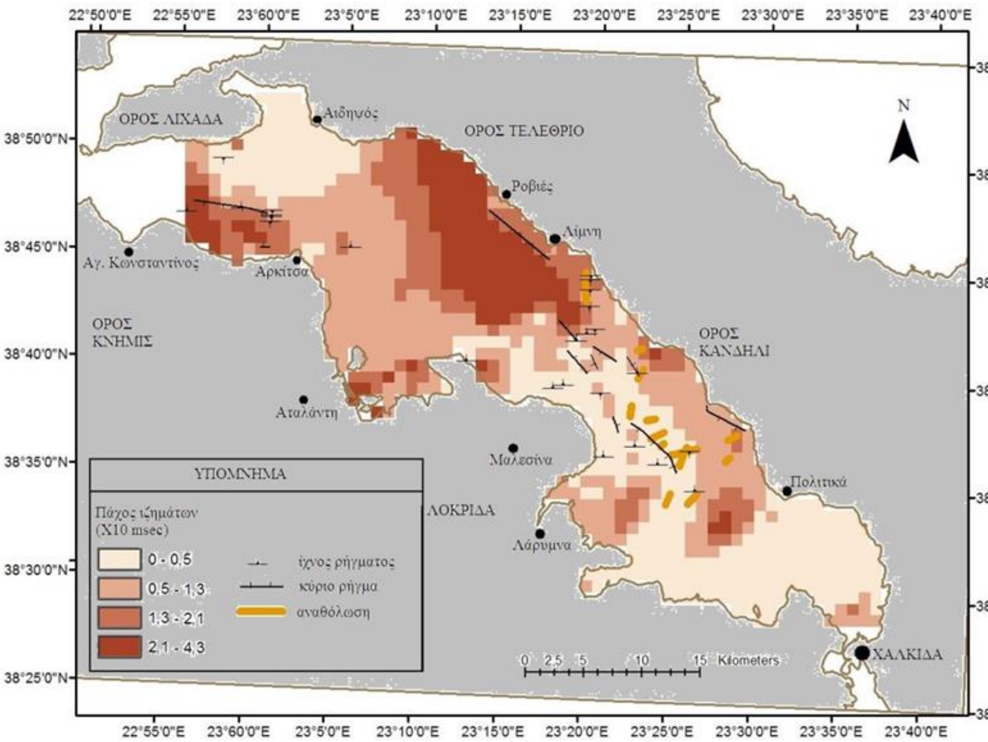


Fig. 22 *Tectonic and sedimentation Map of the northern Evoikos Gulf. Effect on Holocene sediments (Alevizos et al, 2009).*

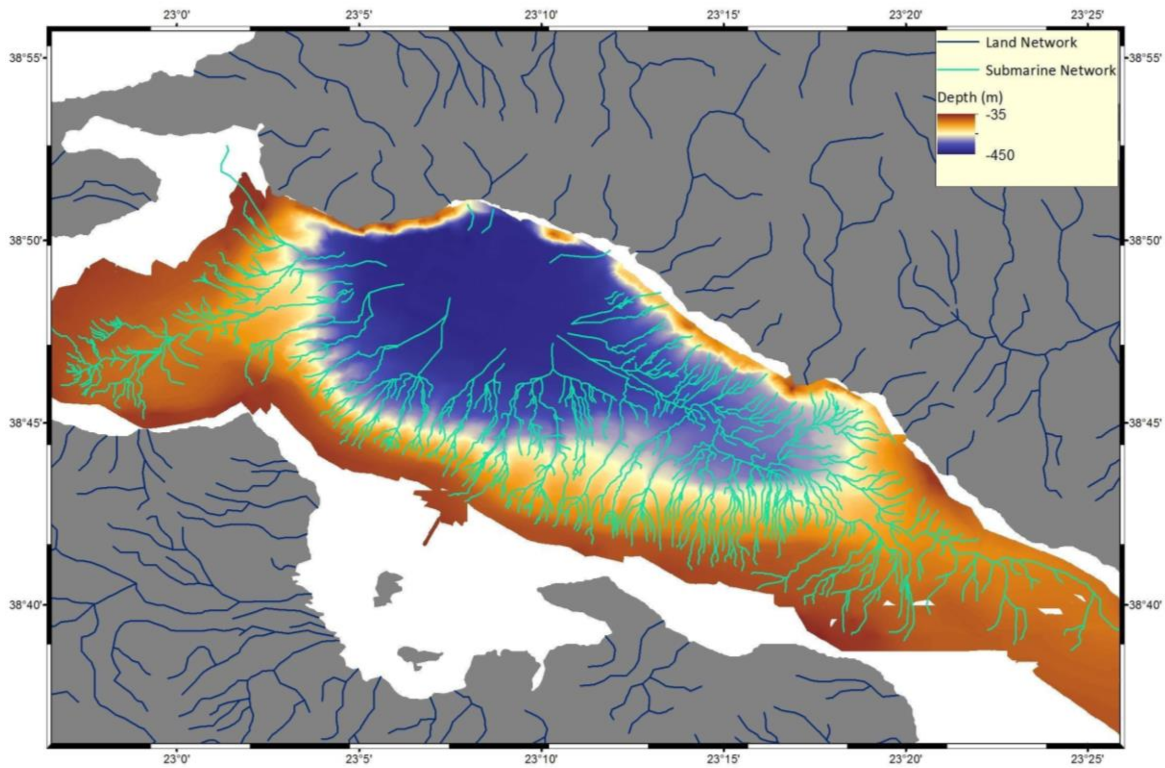


Fig. 23 *Land and Submarine Network of northern Evoikos gulf (1:125.000)*

The main branch of the submarine river network's has a direction NW-SE and is parallel and close to the coastline of North Evia *(fig. 23)*. In this main branch are abutted many smaller branches, whose number is increasing near the basin, indicating flow activity and intense relief of the area. The branches on the NE side of the gulf are shorter because of the abrupt slopes of this area and they probably constitute an extension of the land river network of North Evia's hinterland.

The submarine canyons are part of the most significant morphological structures of the Northern Evoikos Gulf. They are developed along the coasts of NE Central Greece, perpendicularly to the contours, between the depths of 150 and 400 m. Furthermore, they are created by slope discontinuities of the seabed and probably show a connection or continuation with the main branches of the land river network. The canyons can be categorized into three groups:

The first group is located north of the cape of Theologos, at depths between 150 and 350 m (*fig. 24 and 25)*. This group is composed by 4 elongated-shaped canyons that flow from along the SSW side of the basin. Counting from east to west *(fig. 28)*, the first canyon is up to 3 km long, having an altitude difference of circa 150 m and its width between 200 and 300 m. The altitude difference of the second and the third canyons is up to 200 m, with length of 6 km and width of circa 300 m. The altitude difference of the fourth canyon is 250 m, with length of 4.5 km and width of 350 - 550 m on the top of the slope *(table 1)*.

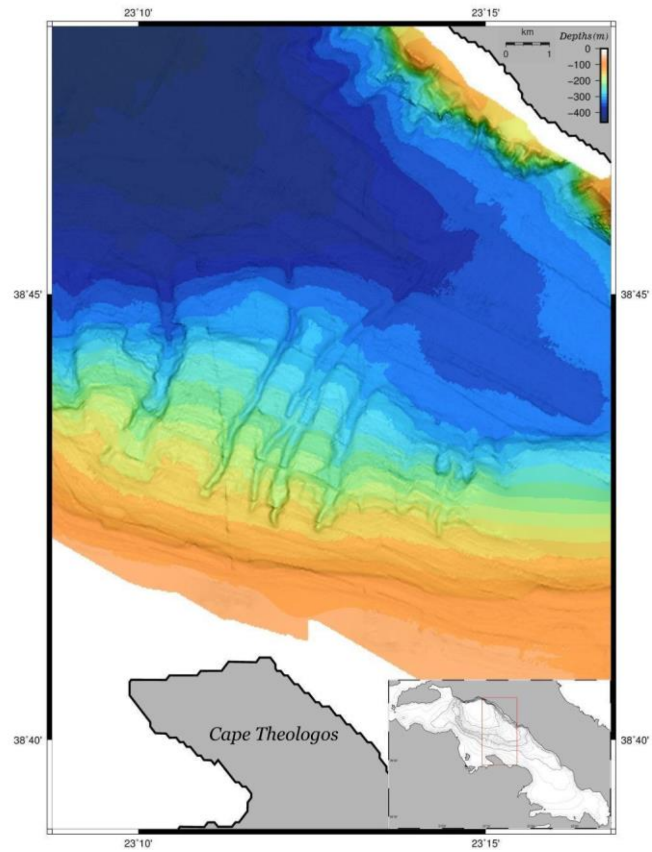


Fig. 24 *Bathymetric map of the eastern submarine canyons (1:60.000).*

Table 1 *Main characteristics of the identified eastern canyons*

	Length (km)	*Altitude difference (m)*	*Width (m)*
1	3	Approx.. 150	f 200 - 300
2 & 3	6	up to 200	Approx.. 300
4	4.5	Approx.. 250	350-550 (on the top of the slope)

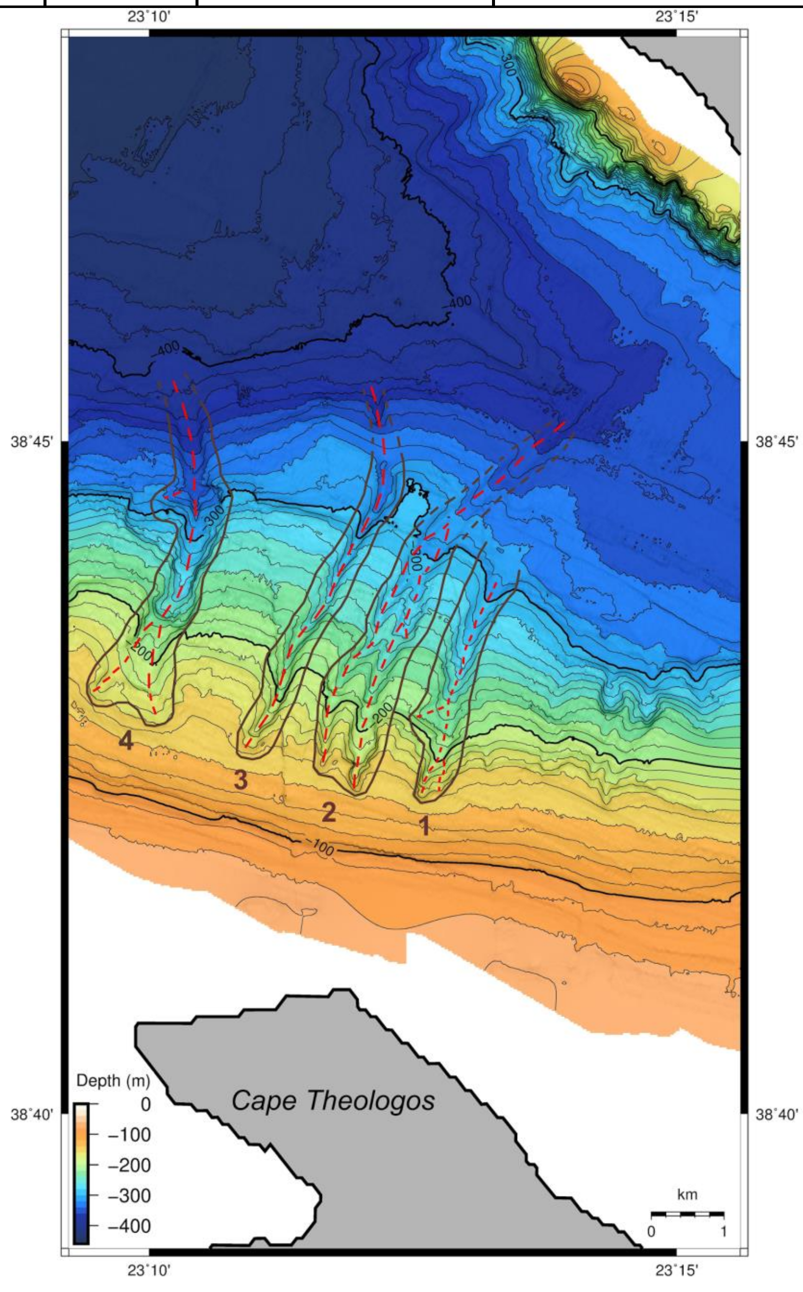


Fig. 25 *Identified eastern canyons (1st group)*

The second group is located east of the cape Arkitsa and flows along the NW side of the main basin *(fig. 26and 27)*. These canyons are shorter than the canyons of the first group *(fig. 28)*, being from approximately 2 km at the easternmost part up to 3 km at the westernmost part. Their altitude difference is 200 m and their width varies from 200 to 400 m, on the top of the slope.

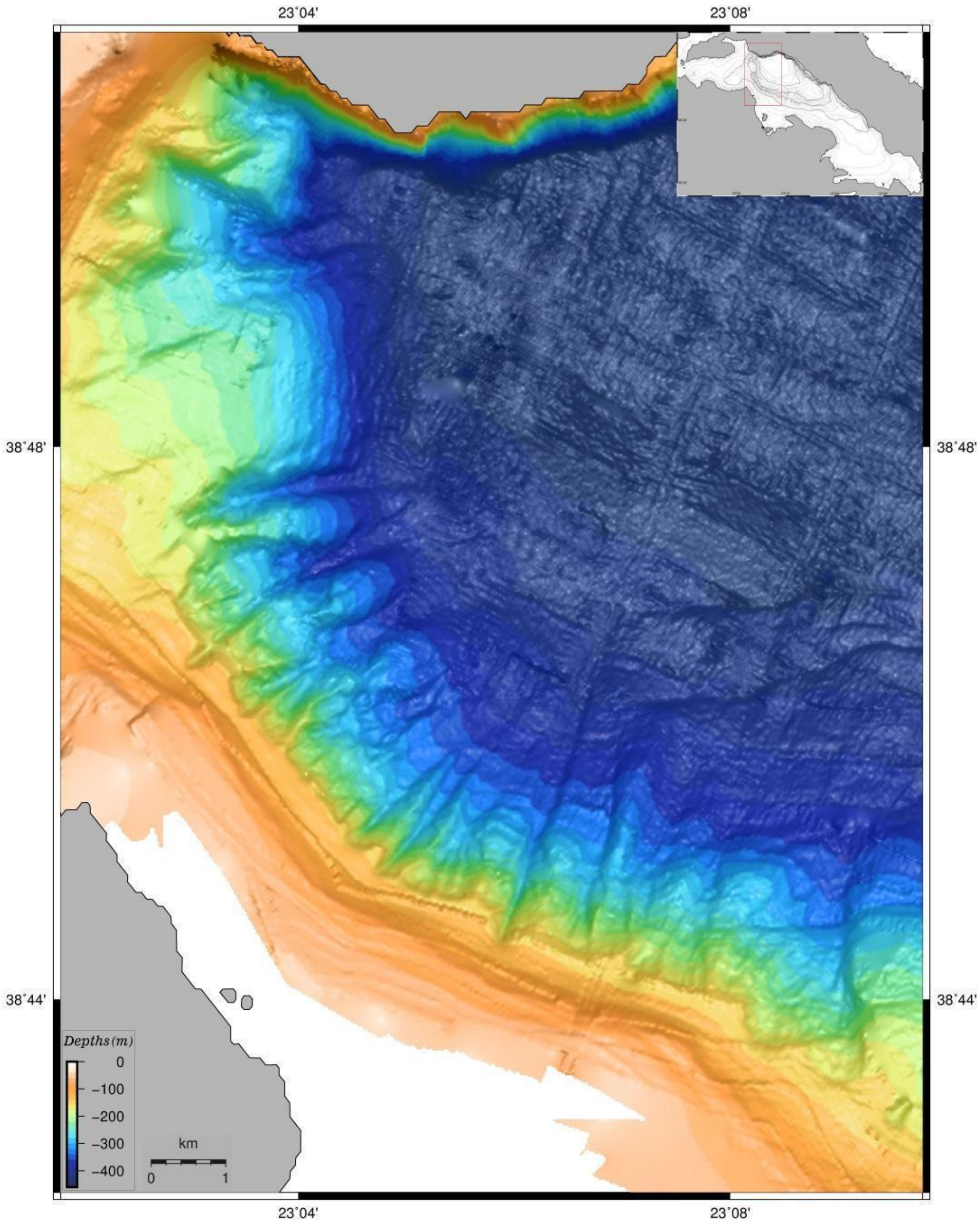


Fig. 26 *Bathymetric map of the western submarine canyons (1:55.000).*

The third group is located south of Aidipsos *(fig. 25 and 26)* and flows along the west side of the main basin at depths between 150 and 400 m and having lengths of circa 2.5 km and widths of 600 m *(fig. 27)*.

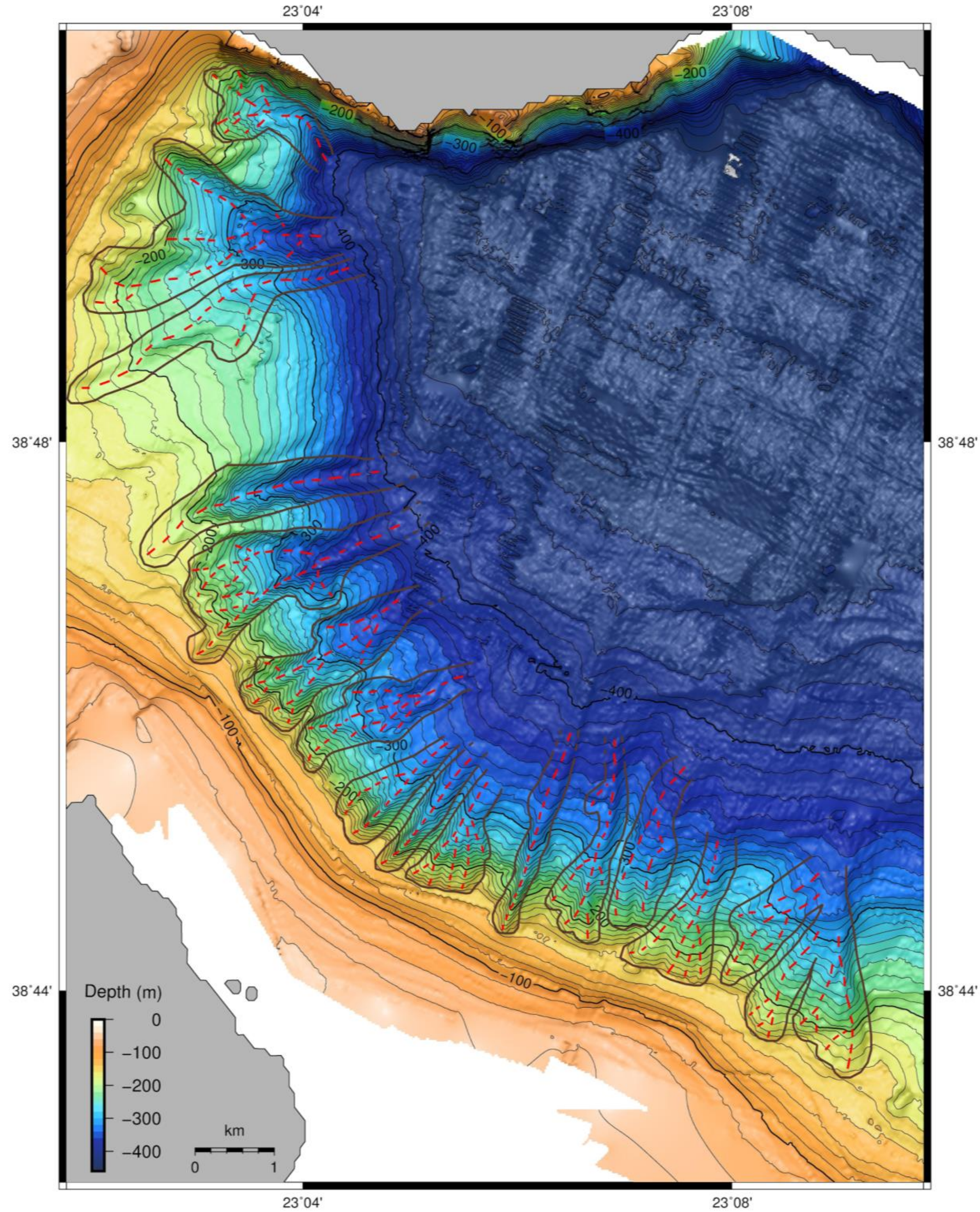


Fig. 27 Bathymetric map of the western submarine canyons (2nd & 3rd groups).

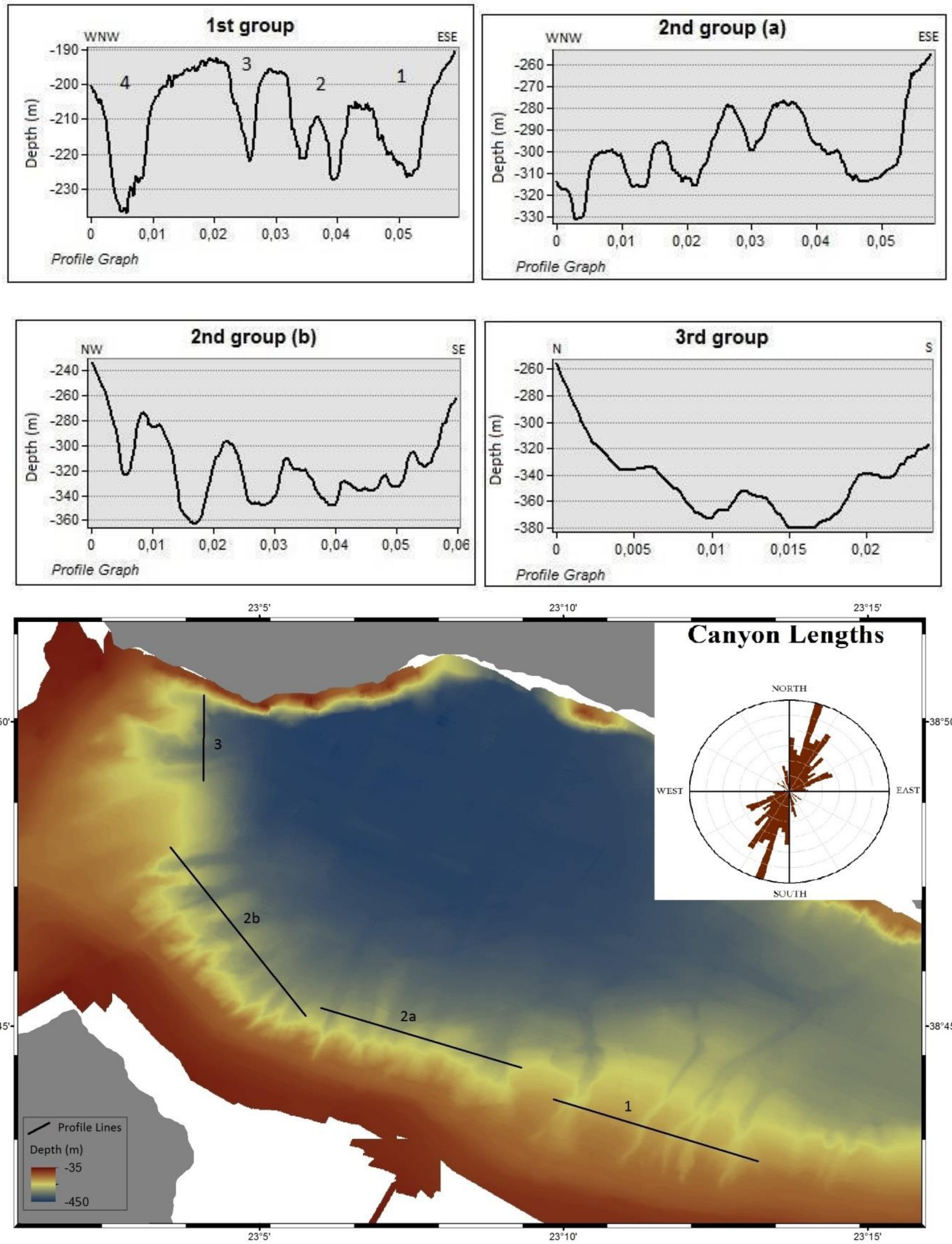


Fig. 28 Bathymetric profiles and rosediagram showing the length and the orientation of the submarine canyons of the NEG.

4.2 Morphological slope analysis

The bathymetric map of the area was analyzed with respect to slope spatial variation. The results of this slope analysis are presented on *fig. 29.* On the basis of the distribution of slope values, the studied area could be distinguished in six categories: (1) areas of 0-1%, (2) areas of 1-3%, (3) areas of 3-6%, (4) areas of 6-12%, (5) areas of 12-20% and (6) areas >20%.

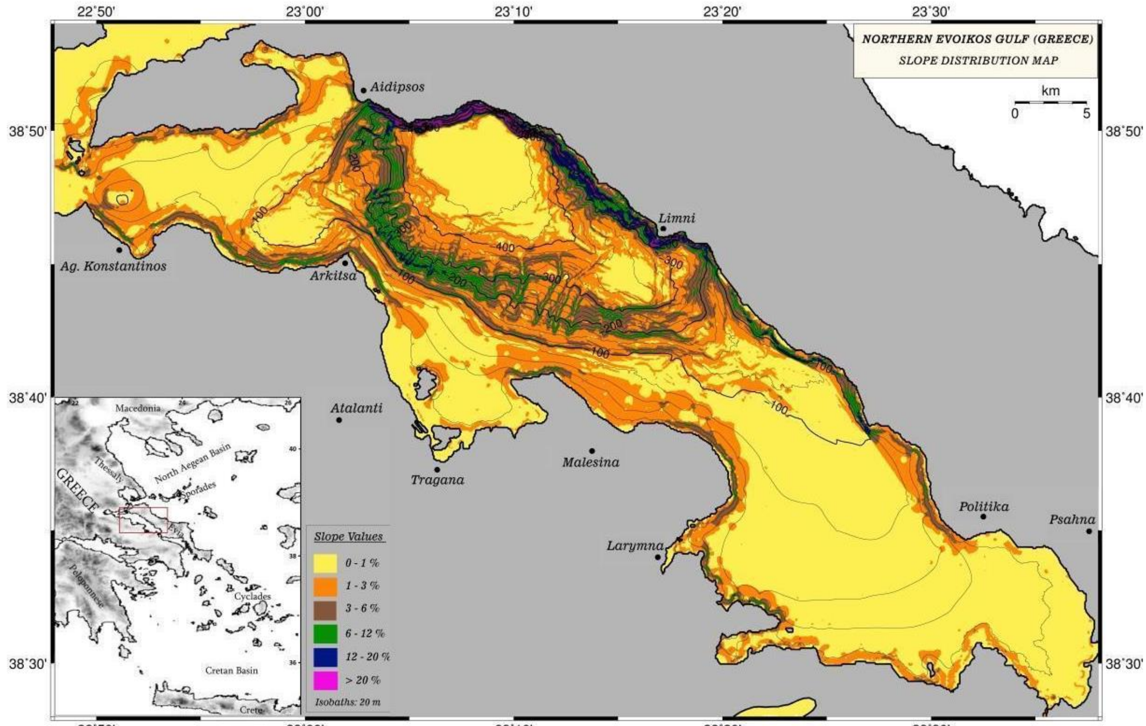


Fig. 29 *Slope distribution map (1:150.000).*

Areas with negligible morphological changes, which cover 40% of the study area, represent the presence of flat areas of the seabed, such as basins, submarine terraces and platforms. Another 40% of northern Evoikos Gulf has slope values that range from 1% to 5%, which mainly belong to the slopes of the gulf. Morphological slope values between 5% and 20% cover the 15% of the study area. The areas around the main basin that present similar slope values are the NE slopes of the gulf, as well as the abrupt slopes of the south and west parts of the gulf (where the canyons are also developed). The areas with slope value >20% cover only the 5% of the overall basin and reflect the abrupt scarp zones at the NE part of the gulf, being probably controlled by active fault tectonics.

4.3 Morphotectonic structure

The morphotectonic interpretation of the two previously presented maps allows the compilation of the morphotectonic sketch map of the basin, which presents the major morphotectonic features *(fig. 30 and 31)*. The results of this work are in accordance with *Sakellariou et al. (2007),* which also helped with the correct drawing of the faults on the the map. The overall morphology of the sea bottom is controlled by the major faults, forming a fault zone in the NE part of the gulf, and a slope discontinuity which is located in the SW part of the gulf.

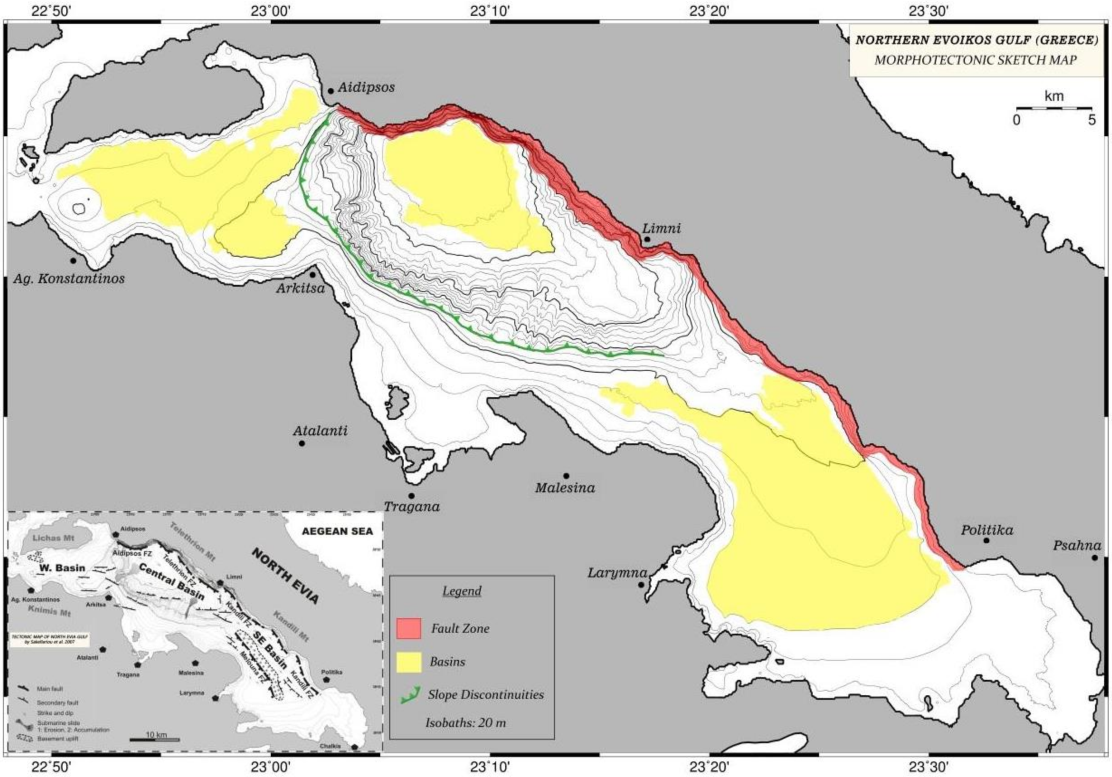


Fig. 30 *Morphotectonic sketch map (1:150.000).*

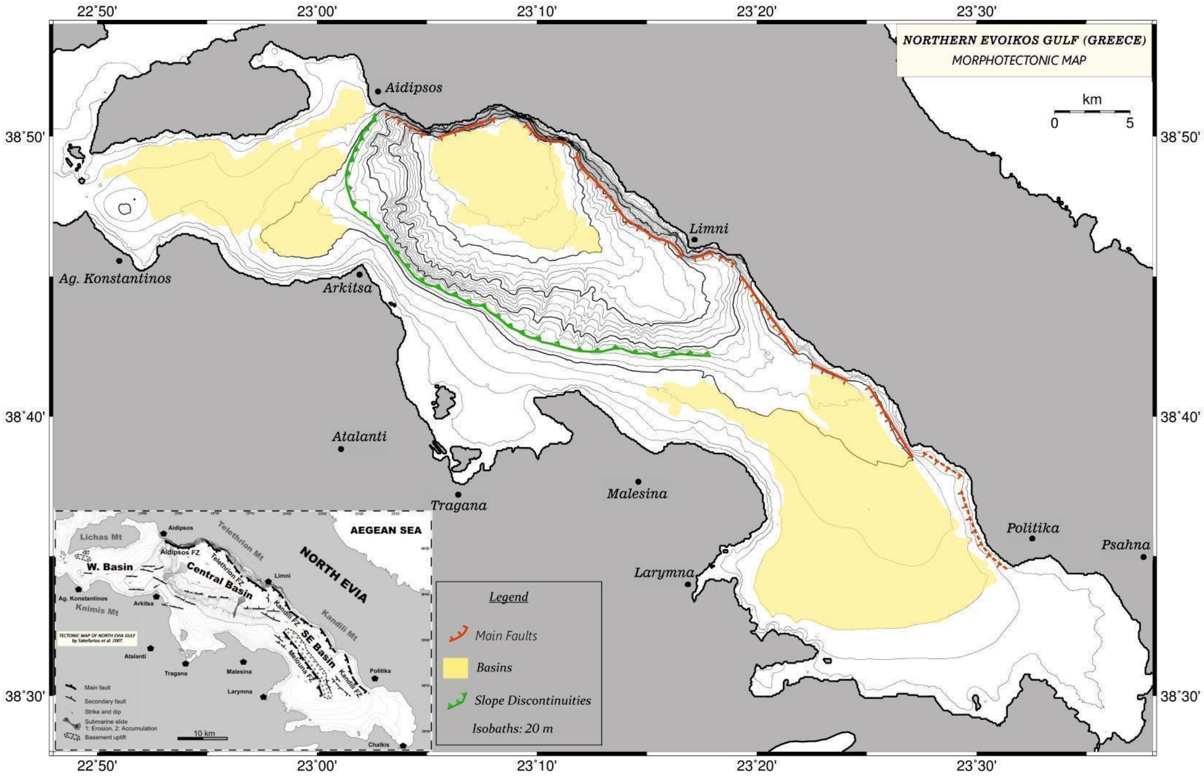


Fig. 31 *Morphotectonic map (1:150.000).*

More specifically, the fault zone is formed by main faults in NW-SE direction, which is given by the same direction as most of the faults that have little variety in their azimuths *(fig. 32)*. This fault zone delimits the central basin from the NE part of the gulf and is parallel to the coastline of north Evia. The associated faults are active, with an upthrow of hundreds of meters, exceeding 1000 m in the fault zones of Telethrio and Aidipsos. However, there are two faults of approximately E-W direction, creating morphological steps in the fault zone. One of these steps is the east part of the fault zone of Aidipsos that seems to connect the fault of Telethrio with the west part of the fault zone of Aidipsos and being almost parallel.

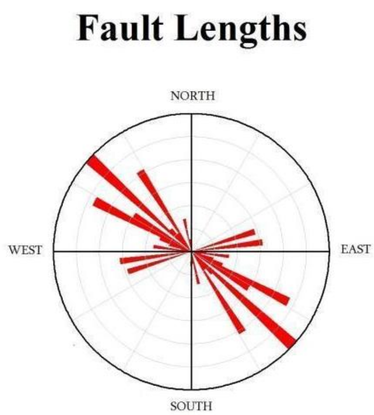


Fig. 32 *Rosediagram of the fault length*

The secondary faults form a long slope discontinuity in NW-SE direction, almost parallel to the coastline of Central Greece and delimits the main basin from the SW part of the gulf. In the SW side of the basin the continental shelf is developed, however at the depth of 150 m there is a steep increase of the slope values where the canyons begin to develop. This change of the slope values betrays the presence of the slope discontinuity. The change of the slope values and the submarine river network's form declare the possible existence of a fault zone, which is a fairly active area, as the submarine slides in this area reveal.

The construction of the morphotectonic map aimed to provide a clearer picture of the NEG's geological and tectonic regime as well. The combination of the basin's morphology that is mainly shaped by tectonic activity with its tectonic fabric (provided by *Sakellariou et al.,. 2007*) into one map, reviled the importance of the smaller, secondary faults inside the NEG in the formation of the gulf's subbasins. The closer to the central basin of the Gulf, the higher the fault count. The surrounding area of the central basin is indeed active tectonically, as betrayed by the countless slides, as well. Thus, the formation of the canyons possibly coincides with an intensified tectonic activity inside the Gulf being expressed morphologically by the abrupt change of the slope. This argument is also strengthened by the fact that a couple of canyons seem to have been diverted due to tectonic activity.

4.4 Aspect Map Analysis

The aspect map created by the bathymetric map in ArcGis *(fig. 33)*. The first observation of the aspect map is the absence of a stable orientation in the basin, which shows that the central basin is almost a flat sedimentary basin. The Eastern and Northeastern slopes of the Northern Evoikos Gulf gravitate towards West or/and Southwest. Also the regions South/Southwest of Aidipsos gravitate towards East or/and Southeast. The Southwest part of the continental platform up to the peninsula of Arkitsa presents mainly a North orientation and between Arkitsa and Aidipsos the orientation change to SouthEast or/and East.

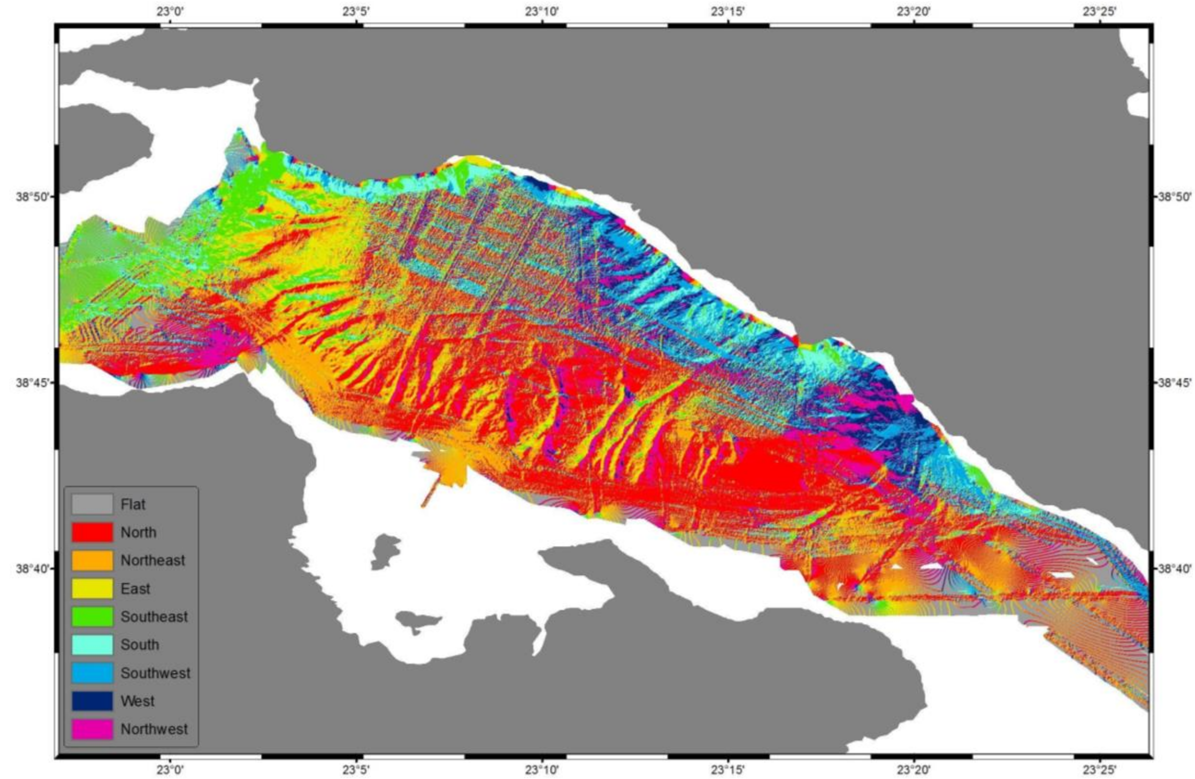


Fig. 33 *Aspect map (1:125.000)*

5 CONCLUSIONS

The southernmost boundary coincides with the "corridor" of the Aegean Microplate boundary according to *Marinou*. As mentioned above, the boundary that separates Central from N. Evia coincides with the Kechriae fault zone *(Kranis et al., 2002)*. GPS velocities reveal that the coastal fault zone system is in control of NEG's subsidence, indicating a migration of tectonism from the earlier Kallidromon and Parnassos fault zone systems, as mentioned by *Goldsworthy (2001)*. Another important point is the transpression that probably takes place inside the Viotikos basin, while the overall regime is transtensional.

The submarine river network consists of a main branch, of NW-SE direction, parallel to the east margin of the Northern Evoikos gulf. Numerous smaller branches abut to the main branch and the central basin of the gulf.

The canyons being present in most of the continental slope/shelf areas. It seems to be related directly to the morphotectonic setting and are probably associated with existed land river networks. The reason of their existence is the morphological discontinuity at the depth of 150 m. Their length increases from the cape of Theologos to the NW and the length values range between 1.5 and 3.5 km *(Nomikou et al., 2006)*.The faults that exist in the gulf create a fault zone with NW-SE direction, parallel to the coastline of north Evia. The fault zone`s uplift of Telethrio and Aidipsos exceeds 1000 m.

The formation of the submarine river network, canyons' characteristics and the 1000 m uplift denote tectonic activity along the NE margin of the gulf.

The morphotectonic map was created solely by use of bathymetric data and morphological slopes. The results of this work are in accordance with *Sakellariou et al. (2007),* which also helped with the correct drawing of the faults on the morphotectonic map. However, there are differences between the two morphotectonic maps, mostly due to the fact that *Sakellariou et al. (2007)* drew the faults using seismic profiles. Because of the lack of corresponding seismic profiles, the smaller faults could not be demonstrated.

The northern Evoikos gulf and the surrounding area are undoubtedly undergoing intense deformation. The tectonic processes, that cause this extreme and rapid deformation, are expressed through relatively short faults that vary in direction and are only able to generate low-magnitude seismic events. Due to the fact that this microseismicity is unceasing *Papoulia et al. (2006)* were able to record a plethora of seismic events and distinguish three zones of deformation. Tectonic forces of an area are also recognised by the movement of the tectonic fragments. GPS monitors measure those movements and these measurements can be used to determine the intensity of deformation in the area, just like *Marinou* did in her work. GPS velocities in the NEG's vicinity also reveal that the coastal fault zone system is in control of NEG's subsidence, indicating a migration of tectonism from the earlier Kallidromon and Parnassos fault zone systems as mentioned by *Goldsworthy (2001).*

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