

## **Delineation of active faults in offshore areas using velocity modeling, high resolution reflectivity and microseismicity**

Χαρτογράφηση ενεργών ρηγμάτων στον υποθαλάσσιο χώρο συνδυάζοντας μοντέλα ταχυτήτων, σεισμικά ανάκλασης υψηλής πιστότητας και μικροσεισμικότητα

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**ABSTRACT :** In order to assess geological and environmental hazard in the south Evoikos basin, between Grammatiko and Aliveri, we performed a combined geophysical, sedimentological and oceanographic study. The geophysical results obtained from velocity modeling from 38 ocean bottom seismographs, single channel high resolution seismics, microseismicity observations from local amphibious arrays and magnetic mapping revealed the following results: The Basin is 1900m thick at the SSW, and 1500m thick at the NNE part of it, and is developed in two phases. Extension opened first an 8 Km wide basin at its SSW part, causing 180m subsidence, adding another 220m of sediments during a second phase of stretching that caused the complete basin to subside, and is still active. These recent sedimentary layers overlie a 3.2Km/s sequence with inclusions of highly magnetized rocks transported during the last glaciation period from Evia to the SSW. The lower part of the Basin is floored by two layers of 4.25 and 5.2–5.8Km/s velocities, probably of Mesozoic age. Active faults were mapped at both ends of the Basin, having a maximum displacement of nearly 50 m offshore Grammatiko. The most intense deformation however was mapped onshore, at the NNE part of the Basin, in the area of Aliveri. Magnetic anomalies revealed several magnetized bodies at the seafloor causing contamination in the area offshore Aliveri, probably associated with waste products generated at the nearby power plant of electricity.

**ΠΕΡΙΛΗΨΗ :** Για την εκτίμηση γεωλογικών και περιβαλλοντικών κινδύνων στην περιοχή του νοτίου Ευβοϊκού, μεταξύ Γραμματικού και Αλιβερίου, έγινε συνδυασμός γεωφυσικών, ιζηματολογικών και ωκεανογραφικών μεθόδων. Τα αποτελέσματα της γεωφυσικής μελέτης από την εκτίμηση του μοντέλου ταχυτήτων από 38 υποθαλάσσιους σειсмоγράφους, σεισμικά ανάκλασης υψηλής πιστότητας, μικροσεισμικές παρατηρήσεις από τοπικά αμφίβια δίκτυα και μαγνητική χαρτογράφηση, συνοψίζονται ως εξής: Η λεκάνη του νοτίου Ευβοϊκού έχει πάχος 1900μ στο NND και 1500μ στο BBA τμήμα της και έχει αναπτυχθεί σε δύο φάσεις. Αρχικά άνοιξε ένα τμήμα 8χλμ στα NND της λεκάνης, προκαλώντας βύθισμα 180μ, προσθέτοντας επιπλέον 220μ ιζημάτων. Αυτή η πρόσφατη ιζηματογένεση καλύπτει έναν οριζοντα με ταχύτητα 3.2 με πετρώματα υψηλής μαγνητικής επιδεκτικότητας, μεταφερμένα από την Εύβοια, στη διάρκεια της τελευταίας παγετώδους περιόδου. Το κατώτερο τμήμα της λεκάνης αποτελείται από δύο στρώματα ταχυτήτων 4.25 και 5.2–5.8 πιθανόν Μεσοζωϊκής ηλικίας. Και στα δύο άκρα της λεκάνης χαρτογραφήθηκαν ενεργά ρήγματα, με μέγιστη μετατόπιση 50μ, στον υποθαλάσσιο χώρο του Γραμματικού. Η εντονότερη πάντως παραμόρφωση παρατηρήθηκε στο BBA άκρο της λεκάνης, στην χερσαία περιοχή του Αλιβερίου. Σημαντικές μαγνητικές ανωμαλίες χαρτογραφήθηκαν στον υποθαλάσσιο χώρο του Αλιβερίου.

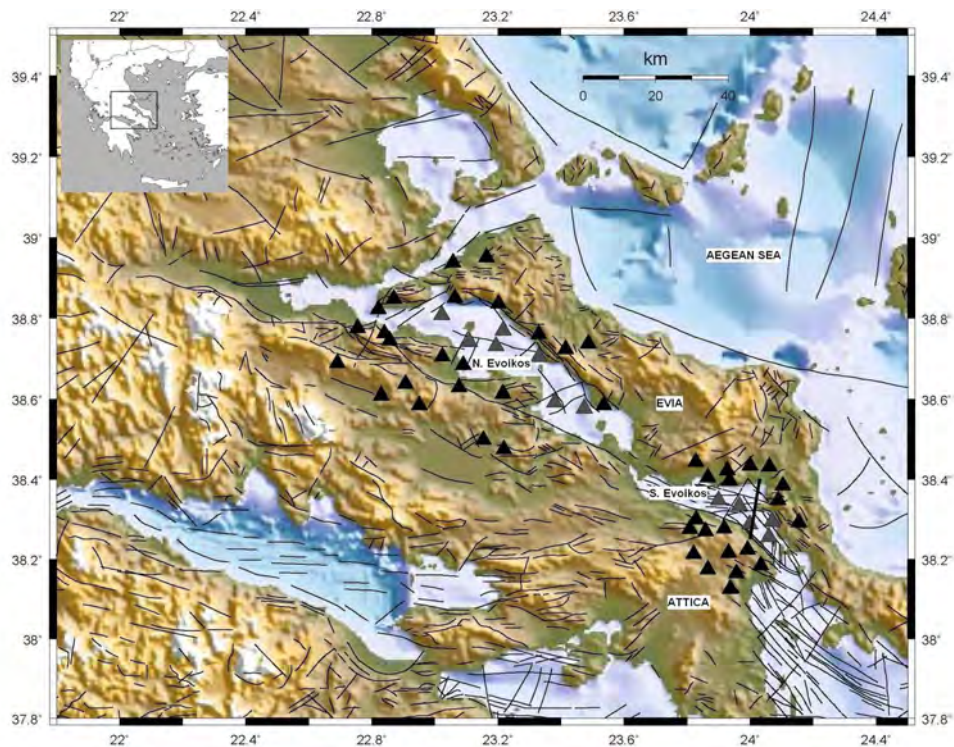
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## INTRODUCTION

In order to define geohazards for engineering purposes multidisciplinary studies combining geophysical, high resolution seismic surveys, geological mapping and soil mechanical properties are essential and represent the present day state of the art (Galavazi et al., 2007). Particularly velocity information obtained from wide-angle seismic data and structural information delineated by high resolution reflection seismics are indispensable in understanding the tectonic situation and provide means of accurately defining active faults in sedimentary basins. The purpose of the present study was the definition of geohazards and particularly identification of active faulting along the 16 Km long natural gas pipeline of south Evoikos basin, central Greece. From the accomplished comprehensive investigation that included hydrological, as well as sedimentological and sediment mechanical sampling analyses along the pipeline route, we will present in the following communication only the geophysical results. Particularly the high resolution single channel reflection data, the Ocean Bottom 4C seismic data, and to some extent the magnetic data of the total magnetic field collected along the seismic line will be discussed, and their results will be combined with the microseismic observations in order to define the active faults.

In the evaluation process we will include results from previously performed subbottom profiling in the south Evoikos basin by Papanikolaou et al. (1988), who demonstrated the existence of several fault systems aligned parallel to the coast line (see fig. 1). Also microseismic results from local amphibious networks operating at the north Evoikos area (Papoulia et al., 2006) showed intense microearthquake activity in the south Evoikos gulf, and will be integrated in this evaluation.



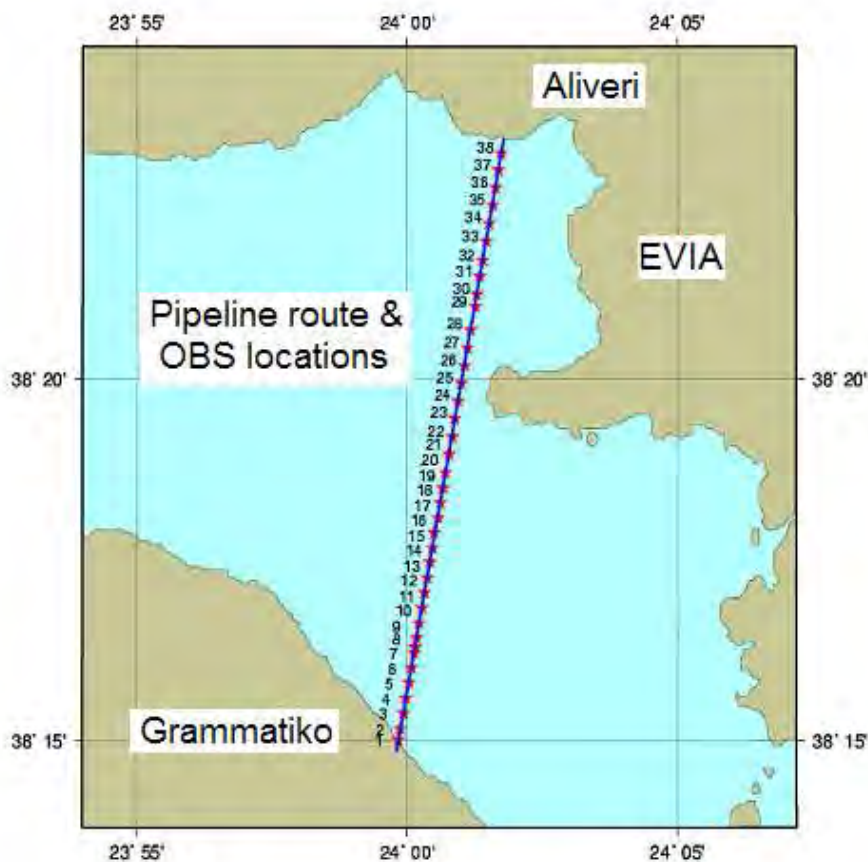
**Figure 1.** Tectonic map of central Greece (after IGME, 1989; Papanikolaou et al., 1988) and local onshore/offshore seismic array (OBS positions in light gray and land stations in black triangles). The position of the pipeline in S. Evoikos is marked by a black line.

## DATA ACQUISITION AND PROCESSING

Data acquisition was performed using the R/V-AEGAEO of HCMR for deep water operations (water depth more than 20m) while the shallow part of the survey, the microseismicity and the magnetic mapping were accomplished using the 8 m long M/B MAUD of GEOPRO. The active seismic experiment was held in February 2006. Microseismicity observations were performed in two different periods, from June to October 2003, and September to November 2006. Data processing and evaluation took place partly in GEOPRO GmbH – Hamburg and HCMR – Athens.

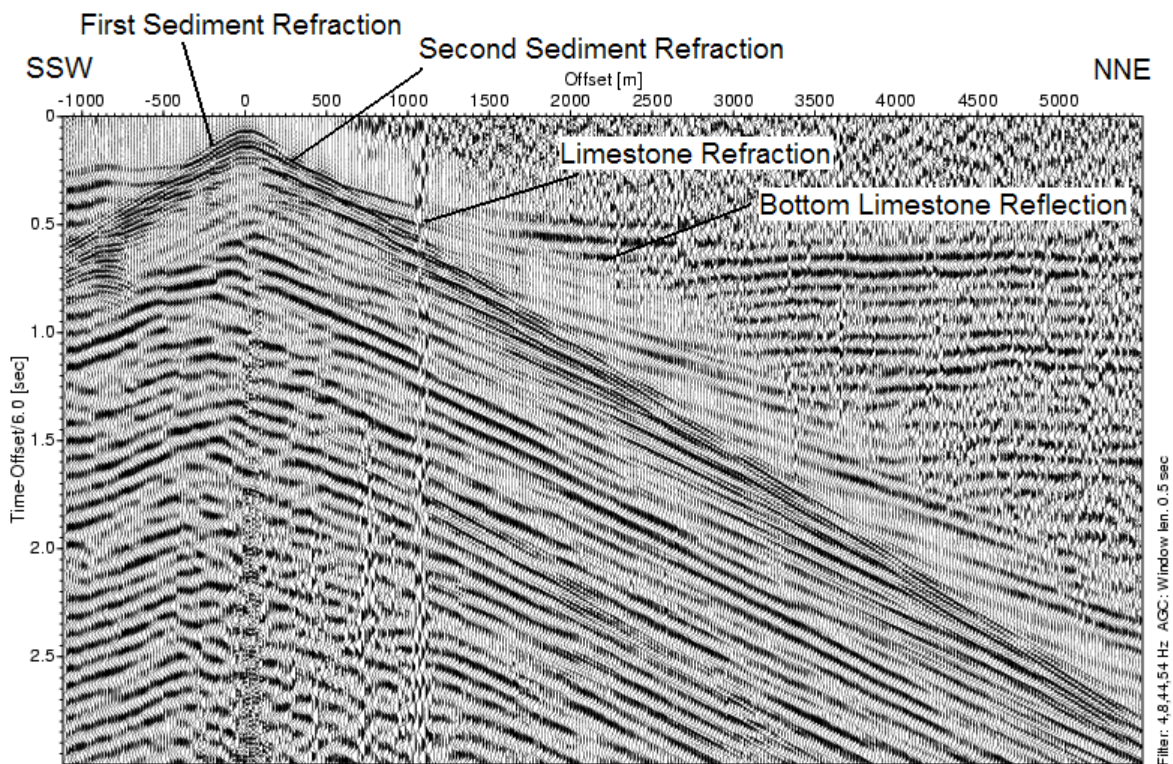
### The Ocean Bottom Seismograph (OBS) Observations - Velocity Modeling and Regional Geology

Since the geological development of the south Evoikos basin is not known and also the velocities of the geological units, required for depth migrating reflection seismic observations, have never been investigated, we observed one seismic line, by deploying 38 4C Ocean Bottom Seismographs (OBSs), spaced at 400 m intervals (see fig. 2) and recorded 38 Common Stations Gathers (travel time plots).



**Figure 2.** Pipeline route and OBS locations used for velocity modeling.

A single air gun of 0.89 l (54 cu.in.) was used as energy source. It was fired every 10 s, the R/V AEGAE0 traveling at 10 knots. Shots were therefore placed at 52 m spacing. OBS data were processed as Common Station Gathers (CSGs) and were plotted using a linear move out calculated by 6.0 Km/s velocity. We evaluated the CSGs using the wide-aperture reflection refraction modeling (WARRP) technique which exploits the wide-angle reflected energy, diving waves as well as normal incidence reflections (Makris and Thiessen, 1984; Dell'Aversana et al., 2000). This modeling approach is also referred to as "node modeling" and was developed for evaluating offshore seismic data recorded by Ocean Bottom Seismographs. Figure 3 presents one example of CSG at OBS location 4, close to Grammatiko side.



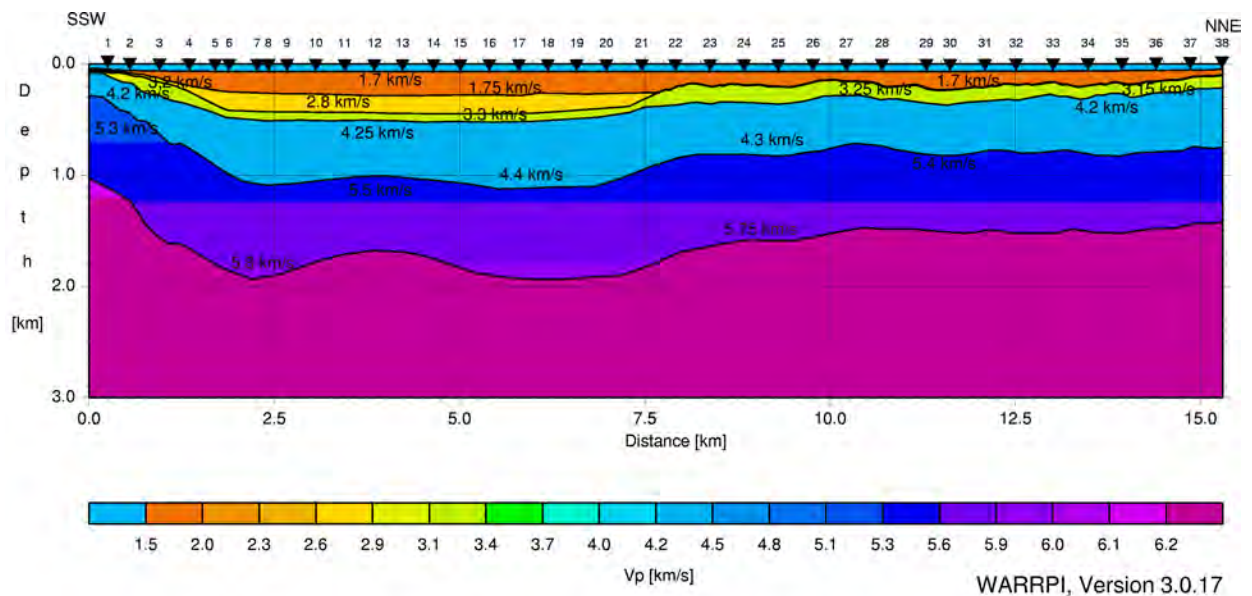
**Figure 3.** Common Station Gather 4 from the southwestern end of the profile (close to Grammatiko side). The CSG shows clear arrivals correlating with refracted and reflected waves of the P-wave field.

An initial P-wave speed model was developed by tomography inversion of the first-break travel time data. The model was subsequently refined by layered tomography, where reflections were also considered, and first order discontinuities introduced. The velocity definition within each layer permits vertical and lateral changes to be considered. Forward modeling by two-point ray tracing is used as a final stage in order to develop a well constrained and reliable wave speed-depth model.

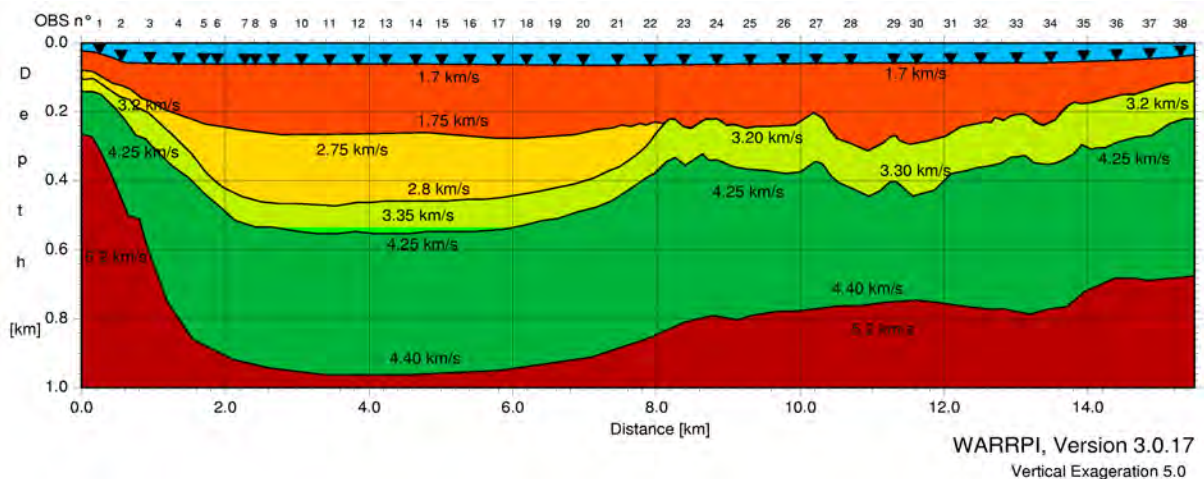
The final velocity model is presented in figure 4. It shows that depth to basement ranges from 1.9 Km at the southwestern part of the Basin, between OBS positions 6 and 21, and 1.5 Km at the northeastern part of it, between OBS positions 26 to 37. Five different sedimentary

layers were identified having Vp velocities of: 1.7, 2.8, 3.25, 4.25 and 5.75 Km/s. The Basin started subsiding first at the southwestern part of it, where the 2.8 Km/s layer was deposited and then the complete Basin followed developing its northeastern part. To the SSW end of the Basin the basement is strongly uplifted and is partly exposed onshore Attica. For a better resolution of the upper part of the sediments structure the velocity model of the upper 1000 m of the Basin is presented in figure 5.

The results will be further discussed in conjunction with the other geophysical observations that will be presented below.



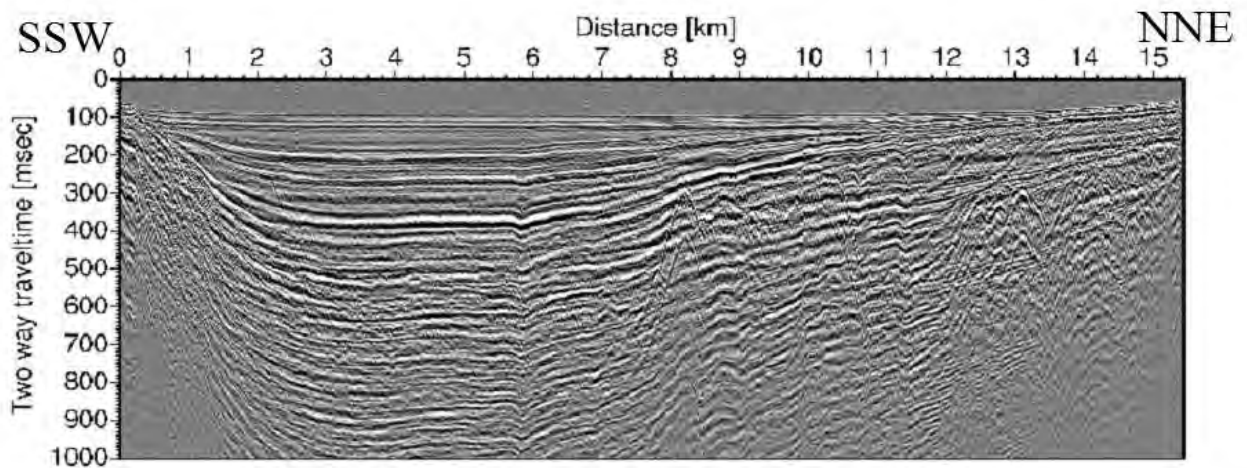
**Figure 4.** P-wave Velocity/Depth Model for the Natural Gas Pipeline Profile. OBS positions are marked along the profile (triangles 1 to 38).



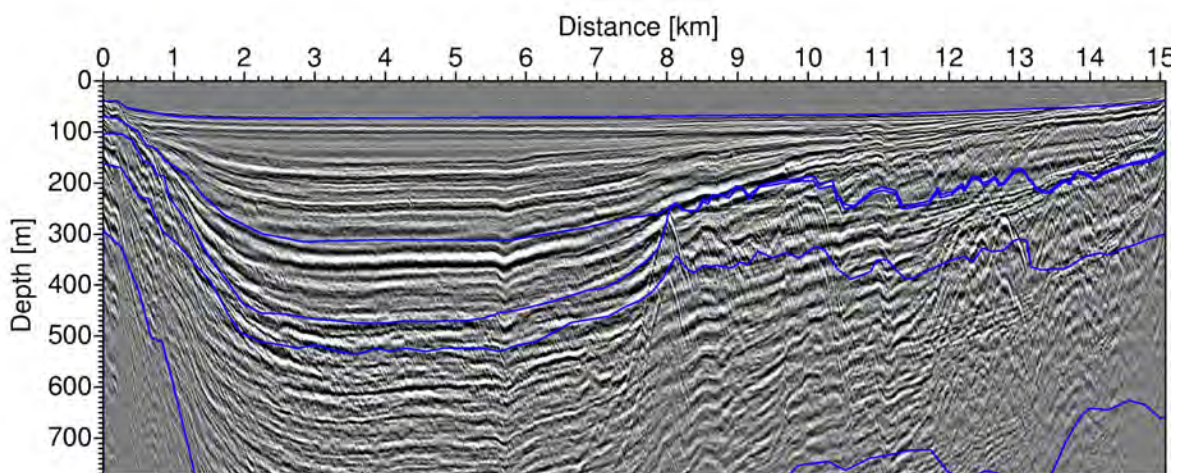
**Figure 5.** P-wave Velocity/Depth Model for the Natural Gas Pipeline Profile – Upper part.

## High Resolution Reflection Seismics

Reflectivity was mapped by a single channel streamer of 60 m length. Seismic energy was generated by a single air gun of 0.16 l (9.75 cu.in.) that was fired at 3 s intervals at a ship's speed of 4 knots. Thus, shooting spacing was every 6.3 m. Two additional reflection lines were observed at the Grammatiko and Aliveri ends of the profile, in order to obtain a better coverage at both ends of the line. It is obvious that the areas where the gas Pipeline enters into the sea are very sensitive and have to be particularly well protected from geohazards. Data were processed in the time domain by applying band filtering only (see fig. 6). The quality of the records was very good and no additional processing was necessary. By combining the velocity model from the OBS data with the single channel reflection information we migrated the time domain reflectivity in depth (see fig. 7). In this figure we also plotted the first order discontinuities (in blue) mapped by the OBS velocity/wide angle reflection modeling.



**Figure 6.** Single channel reflection seismic section.

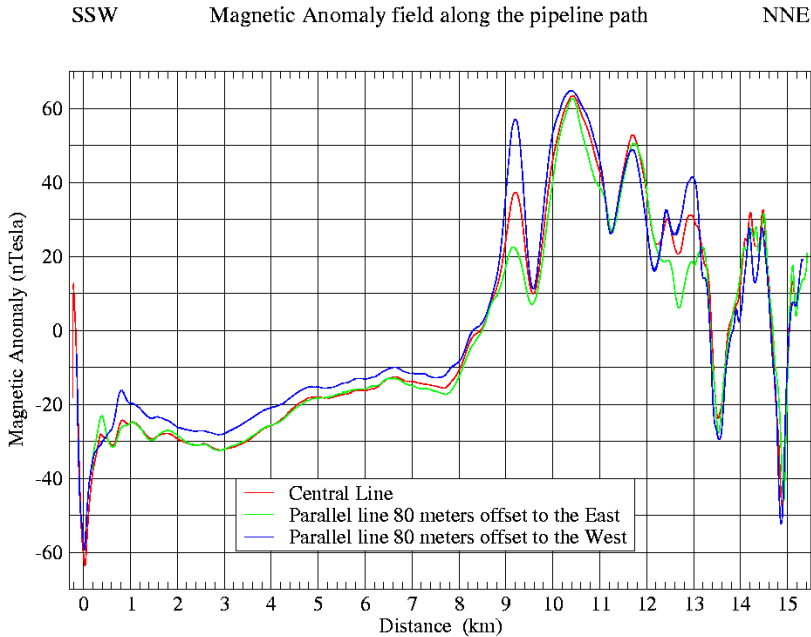


**Figure 7.** Depth Migrated Reflection seismic section with overlapped interfaces from Velocity model.

The single channel reflectivity mapping showed a well-structured basin consisting of two sub basins. The southwestern one, extending from Km 1 to 8, has a thick soft sediment sequence and was the first part of the Basin developed by the extensional processes that stretched the area between Evia and Attica. The flanks of this subbasin are clearly defined by faults that were activated during the different extensional phases that shaped the present day Basin. At the central part of the basin, around km 8, these faults do not seem to be active today. They have no surface expression, and do not propagate through the soft sediments (1.75 Km/s) that build the recent infill. The situation is however different at the southwestern limit of the Basin, towards Grammatiko. Faults, defining the termination of the Basin to the SSW, truncate the complete sedimentary section and have been active from the early phases of its development to present. As we will see later, they are also seismically active. The same is the case to the NNE termination of the Basin. The main faults are however onshore, also correlating with microseismicity observations.

**Magnetic survey**

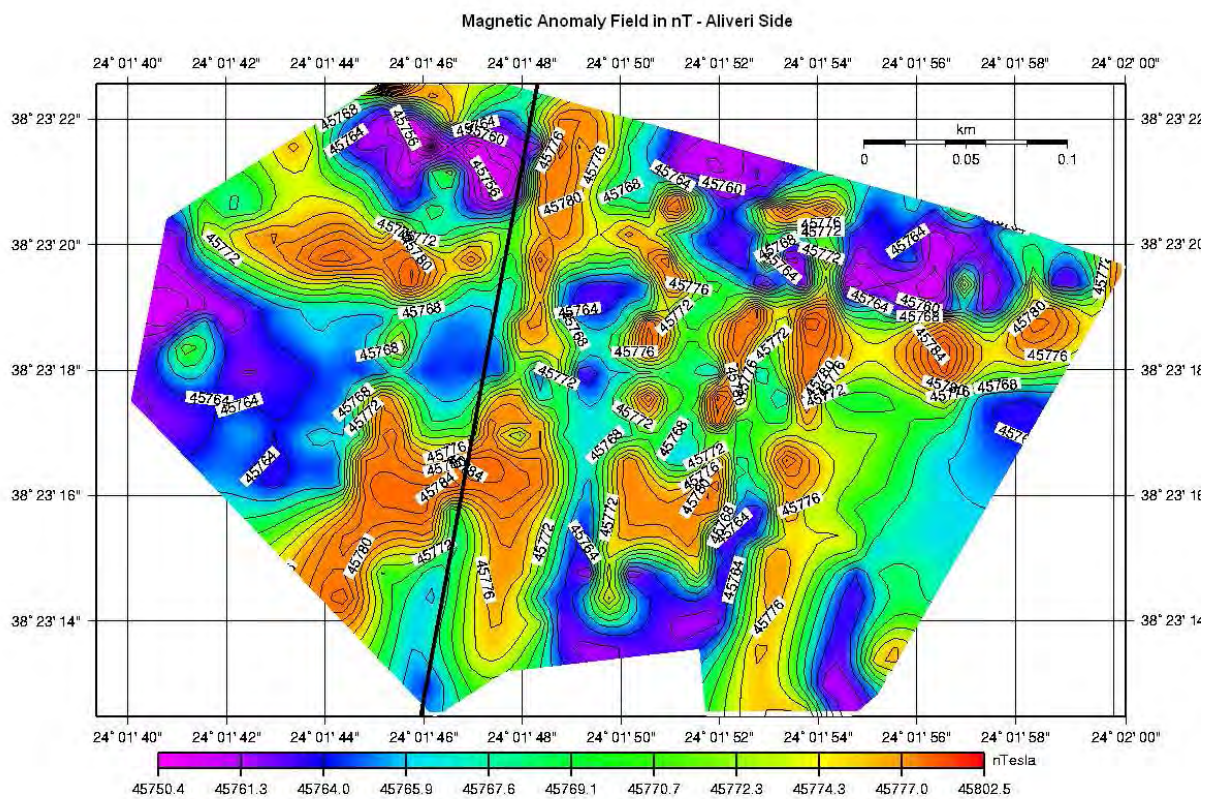
Magnetic anomalies were mapped and used to reconstruct the geological evolution of the Basin and compare it with the geological structures onshore. The total magnetic field was observed by a Geometrics Cesium Marine Magnetometer, model G882, of high sensitivity (0.01 nT). Repeated measurements were performed to estimate daily magnetic field variations, and appropriate corrections were applied to the magnetic data. The total magnetic field was mapped along three parallel profiles to the pipeline path separated by 80 m spacing. They all showed similar magnetic features, nearly identical after subtraction of the daily variations of the total intensity (fig. 8).



**Figure 8.** Magnetic anomaly curves of the total intensity along the pipeline path and two lines placed in 80 m offset to the east and west, parallel to the central line. All three lines have mapped the same magnetic sources and differences in amplitudes are only due to changes of distance between the sensor and the magnetic bodies

The strong magnetic effect marking the termination of the Basin to the NNE is obviously generated by the steep uplift of the metamorphic basement and the 3.25 Km/s layer, which is probably magnetically contaminated by rock inclusions of high susceptibility. The magnetic field to the SSW, between Km 1 and 8, is very smooth along all three lines. It is in good correlation with the early development of the southwestern subbasin that displaced the basement for several hundred meters. To the NNE, between Km 8.5 and 15 (end of the deep water line) the magnetic field becomes very irregular. A series of high frequency, large amplitude magnetic anomalies characterize this part of the section. They also correlate with strong reflections in the high resolution reflection seismic profile and the area where the 3.75 Km/s layer is in high position. Both the magnetic field (small half-width anomalies with high amplitudes) and the high frequency irregular reflectivity indicate that the 3.25Km/s layer contains inclusions of rocks with high susceptibility. Such rocks can either be parts of ophiolitic fragments or highly metamorphic basement, transported during the last glaciation period from Evia to the SSW.

In order to map man made environmental hazards close to the coastal zone, we mapped magnetically a much wider area at the sides of Grammatiko and Aliveri. The magnetic map showed particularly interesting anomalies in the Aliveri region (fig. 9). These anomalies have to be verified by sampling the magnetic bodies causing them in order to secure the pipeline construction and will not be further discussed here.

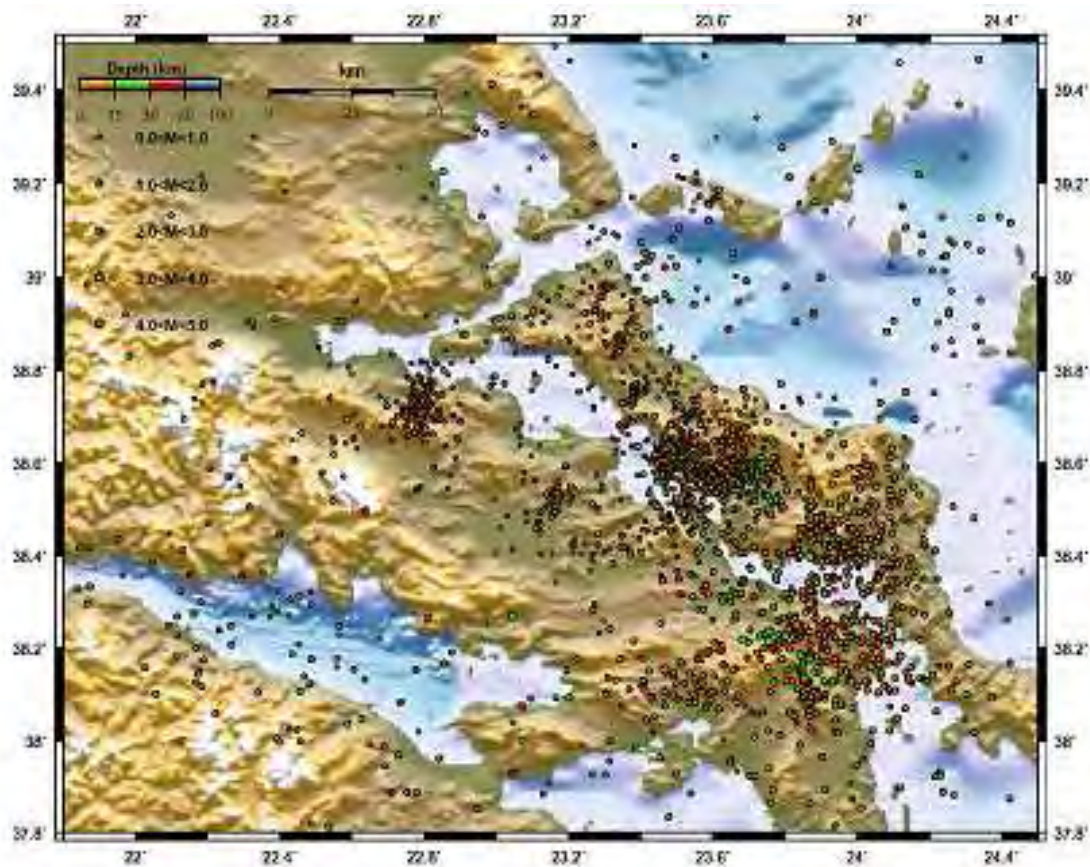


**Figure 9.** Magnetic anomalies at the northeastern part of the pipeline path – Aliveri side. Pipeline path is denoted in black.

## Microseismicity observations

Microseismicity has been observed in two different campaigns. The first one lasted from June 30 to October 24, 2003, and the array consisted of 7 OBSs and 23 stations on land, and it was located in the north Evoikos basin area (Papoulia et al., 2006). The second field period lasted from September 23 to November 26, 2006, and the array consisted of 5 OBSs and 20 land stations, and was located at the south Evoikos basin area (see fig. 1). The data were evaluated using state of the art techniques and the velocity model was additionally constrained by local velocity data published by Makris et al. (2001). The accuracy obtained for the epicenter locations within the array are  $\pm 1$  Km for the shallow recorded seismicity.

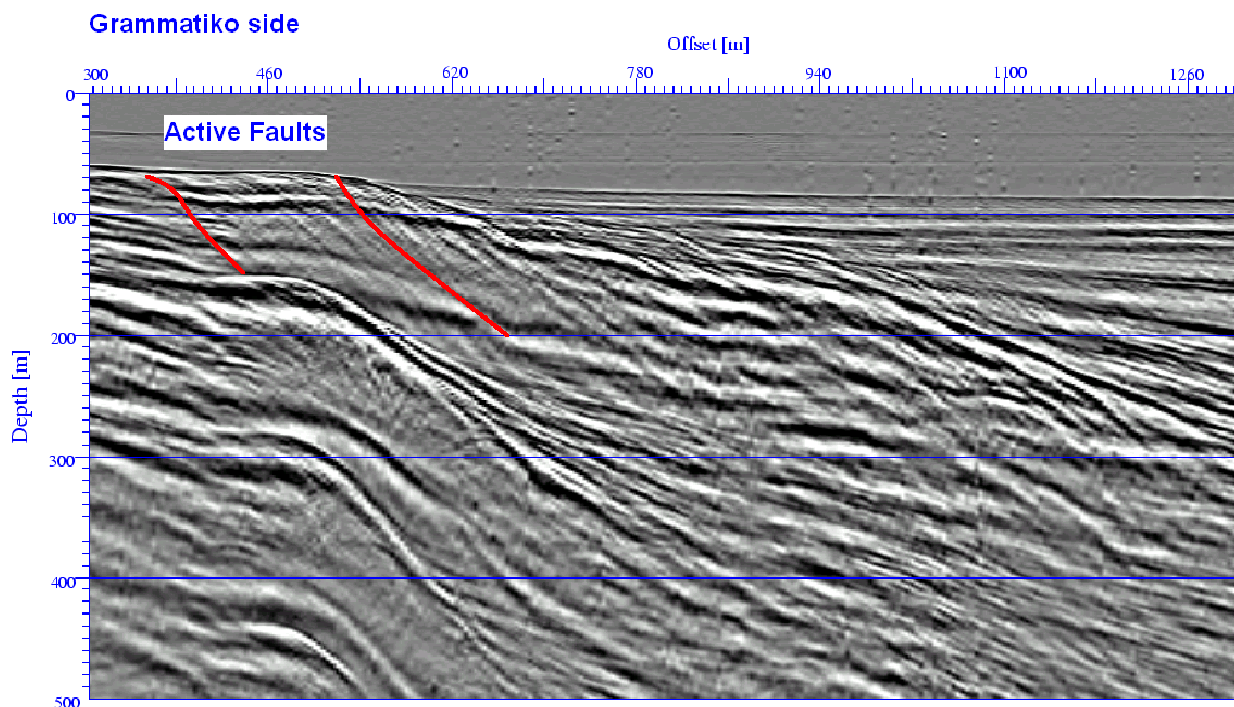
The results presented by combining both microseismicity studies are presented in figure 10. The relatively high seismicity that was recorded at both coastal regions is crucial for the gas Pipeline study. Particularly the Aliveri area and the onshore faults presented in publications of the Institute of Geological and Mineralogical Studies (IGME) – Athens (see fig. 1) are seismically very active. Significant seismicity is associated with the Grammatiko area, and is well correlated with offshore mapped active faults, as will be discussed below, considering all the geophysical findings.



**Figure 10.** Micro-earthquake distribution in south Evoikos basin and surrounding area recorded from local onshore/offshore seismic arrays. Period of observation: June 30 to October 24, 2003, and September 23 to November 26, 2006.

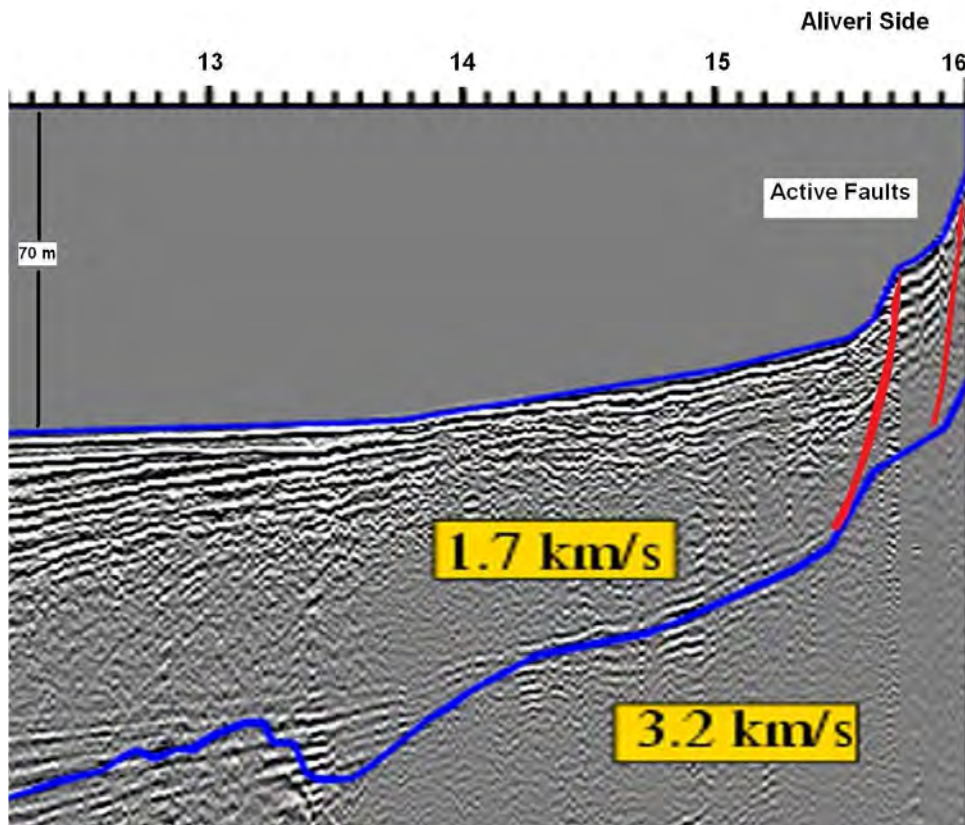
## Discussion and Conclusions

As we have seen, the combination of high resolution single channel reflection seismic observations together with velocity models developed from OBS seismic data and microseismicity studies from local amphibious arrays is a powerful approach in delineating geological structures, tectonics and active faults offshore. For the area between Grammatiko and Aliveri we have delineated the geophysical formations of the Basin above the metamorphic basement. From the geometry and thickness of the sediments it is obvious that the Basin started developing at the SSW part of it, between OBS position 4 and 21 and then the rest of the Basin subsided forming it as we see today. The vertical displacement of this recent tectonic activation is in the order of 400 m. Maximum depth of the Basin is 1900 m in the SSW depression and 1500 m in the NNE part of it. The 2.8 Km/s layer, which is deposited in the SSW section of the Basin only, represents the first phase of subsidence. After a subsidence of nearly 180 m the rest of the Basin followed and obtained the geometry as seen today. The subsidence is still ongoing as it is obvious from active faulting at the SSW end of the Basin, towards Grammatiko and the NNE part of it, in the onshore/offshore area of Aliveri. The maximum recent down throw is in the order of 50 m, located NNE of Grammatiko. Figures 11 and 12, from both ends of the Basin, provide a better resolution of the reflectivity and the faults at both sides can be better identified.



**Figure 11.** Depth migrated reflection seismic section at the SSW part of the south Evoikos basin (Grammatiko side). Main active faults are marked in red.

The microseismicity recorded by the two local arrays deployed in the area of Evia, show significant activity in the Aliveri region which is coinciding with a series of faults mapped onshore by IGME and offshore by Papanikolaou et al. (1988) (see fig. 1). In the Grammatiko side of the Basin (SSW coastal area) local seismicity was also recorded though not as intense as that of the Aliveri side.



**Figure 12.** Depth migrated reflection seismic line at Aliveri side indicating the two located active faults. The figure shows the last 4 Km of the profile (Km 12 to 16). Velocity interfaces (in blue) and velocity values (in yellow) from the velocity/depth model are included.

Finally, man-made pollution hazard was mapped at both ends of the surveyed area. Particularly in the Aliveri seaside a lot of local magnetic anomalies indicate significant contamination from metallic objects and waste from ships. The later have high susceptibility and are probably associated with the power generating plant of electricity at Aliveri.

In conclusion, in order to assess geohazard for local constructions and environmental protection, it is necessary to combine geophysical methods with oceanographic and sedimentological studies onshore and offshore, as was demonstrated by the present study.

#### ACKNOWLEDGMENTS

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## REFERENCES

- Dell'Aversana P., Ceragioli E., Morandi S. and Zollo A. (2000). "A simultaneous acquisition test of high density 'Global Offset' seismic in complex geological settings". *First Break*, 18, 87–96.
- Galavazi M., Wegerif J., Razak B.V., Cangali S. and Hamilton I. (2007). "Beating Caspian Geohazards, Block 1 Development, Turkmenistan, Extended Abstracts OTC Conference, Houston.
- Institute of Geology and Mineral Exploration (1989). "Geological Map of Greece (Scale 1:50000).
- Makris J. and Thiessen, J. (1984). "Wide-angle reflections: A tool to penetrate horizons with high acoustic impedance contrasts". *Expanded Abstracts*, 54<sup>th</sup> Annual International SEG Meeting, Atlanta.
- Makris J., Papoulia J., Papanikolaou D., Stavrakakis G., (2001). "Thinned continental crust below northern Evoikos gulf, central Greece, detected from deep seismic soundings", *TECTONOPHYSICS*, 341, 225-236.
- Papanikolaou D., V. Lykousis, G. Chronis and P. Pavlakis, (1988). "A comparative study of neotectonic basins across the Hellenic arc: the Messiniakos, Argolikos, Saronikos and Southern Evoikos Gulfs", *Basin Research* 1, pp. 167–176.
- Papoulia J., Makris J., & Drakopoulou V. (2006). "Local seismic array observations at north Evoikos, central Greece, delineate crustal deformation between the North Aegean Trough and Corinthiakos Rift" *Tectonophysics* , 421, 1, 97-106.