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LATE QUATERNARY AND HOLOCENE FAULTS OF THE NORTHERN GULF OF CORINTH RIFT, CENTRAL GREECE

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Abstract

New results for the recent tectonic activity in the northern part of the Gulf of Corinth rift are presented. Geological mapping and morphotectonic study re-populate the area of study with numerous active and possible active faults. The area is dominated by individual and segmented normal faults along with major structures like Marathias and Delphi-Arachova faults. The results are in accordance with recent studies that reveal a more complex and wider structure of Corinth Rift to the north.
Key words: *Active Tectonics, Seismic Hazard, Normal Faults, Extension, Delphi Fault*

Περίληψη

Νέα δεδομένα για την πρόσφατη τεκτονική δραστηριότητα στο βόρειο τμήμα του βυθίσματος του Κορινθιακού Κόλπου παρουσιάζονται. Με βάση γεωλογική χαρτογράφηση και λεπτομερή μορφοτεκτονική μελέτη, η περιοχή μελέτης εμπλουτίζεται με πολυάριθμα ενεργά και πιθανά ενεργά ρήγματα. Στην περιοχή επικρατούν μεμονωμένα και συνενωμένα κανονικά ρήγματα, καθώς και μεγάλες κύριες τεκτονικές δομές όπως τα ρήγματα Μαραθιά και Δελφών-Αράχωβας. Τα αποτελέσματα έρχονται σε συμφωνία με πρόσφατες μελέτες που αποκαλύπτουν μια περίπλοκη και πιο ευρεία δομή της τάφρου του Κορινθιακού στα βόρεια.
Λέξεις κλειδιά: *Ενεργός τεκτονική, Σεισμική Επικινδυνότητα, Κανονικά Ρήγματα, Εφελκυσμός, Ρήγμα Δελφών .*

1. Introduction

The Gulf of Corinth Rift is a rapidly expanding intra-continental extensional rift in a W-E setting, across the Alpine formations of the External Hellenides Geotectonic units of Pindos, Vardoussia, Parnassos and Beotia (Celet 1962, Doutsos et al. 1988, Ori 1989, Armijo et al. 1996). The initiation of the rift is estimated at the Late Pliocene (3.3 Ma – Leeder et al 2012) and is currently involving extension along segmented and individual normal fault of W-E to WNW – ESE strike in a broad zone from Patras Gulf to the west up to Beotia and Asopos rift to the east (McNeil et al. 2005, Tsodoulos et al. 2008, Taylor et al. 2011, Bernard et al. 2015). Evidence of the active deformation state and rate of the Corinth Rift are numerous and strong historical and recent earthquakes, intense microseismic activity and extension measured by GPS and surveys (Sebrier 1977, Ambraseys & Jackson 1990, Hatzfeld et al. 2000, Papadopoulos et al. 2000, Bell et al. 2009, Lambotte et al. 2014). Earlier interpretations of the Corinth Rift as an asymmetrical basin with fault activity concentrated on the southern north-dipping faults are being revised as a more complex basin structure is revealed from detailed offshore surveys. The scope of this study is to fill a gap of onshore fault activity in the northern part of the rift in order to assess seismic hazard in a poorly mapped area, further understand the structure of Corinth rift and document the transitional zone between the Gulf of Corinth and the northern active extensional basins of Kifissos, Evoikos Gulf and Spercheios Rift.

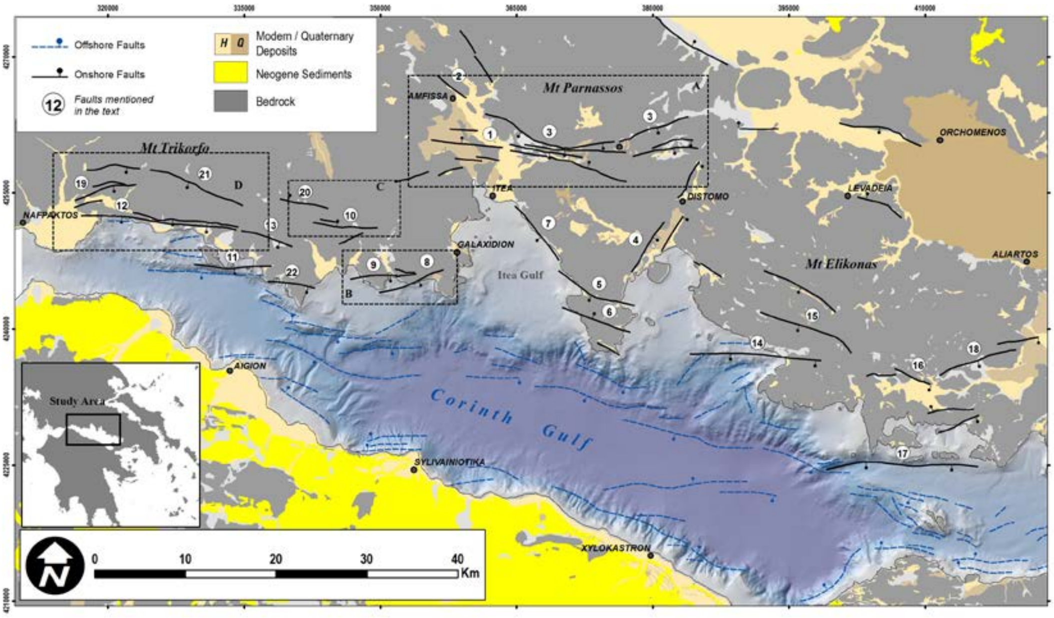

Figure 1 – Active and possible active faults of the northern Gulf of Corinth. Fault numbers are in accordance with Table 1. Bedrock formations with dark grey color and post-alpine sediments with light grey colors. Index boxes A, B and C show location of Figures 2 and 3. Seafloor topography of Corinth Gulf is shown with shaded relief. Grey fault lines denote off-shore faults from Stefatos et al. (2002), McNeil et al. (2005) and Bell et al. (2009).

2. Active Faults of the Area

2.1. Delphi – Arachova Fault Zone

The Delphi – Arachova fault zone is a large active extensional structure north of the central part of the Gulf of Corinth that defines the southern slope of Parnassos Mountain (Péchoux 1977, de Boer & Hale 2000, Piccardi 2000). The main Delphi – Arachova fault consists of two normal fault segments dipping south, with a length of about 10 km each (Figure 1 & 2). The Delphi fault to the west is clearly defined by a large morphological scarp from the Amfissa-Itea plain to the east of Delphi archaeological site with a trend of NW-SE to W-E. The Arachova fault to the east, is less accurately defined and mapped due to the large slope debris and avalances and the erosivity of the flysch basement formation. Fault measurements and morphotectonic features show a complex normal fault zone with an oblique slip (fault lineations 60^0 to the west). Overal morphological scarp reaches up to 500 meters in the Plistos Valley, with a post-glacial striated fault scarp of up to 10 meters. The fault zone is distributed with multiple parallel fault scarps along strike (Figure 3) converging at a depth to the main Delphi fault surface, as is evident in the area of the Delphi Oracle (Piccardi 2000, Valkaniotis et al. 2011). The Delphi Oracle site complex is situated inside the fault zone on the hanging wall and is disrupted by at least two historical surface ruptures in 373 BC and 1870 (de Boer & Hale 2000, Piccardi et al. 2008). The most recent activation of the fault zone was in the 31 July/1 August 1870 earthquake cluster with the main event having a possible magnitude of M=6.7, one of the strongest historical earthquakes in the central Greece (Ambraseys & Pantelopoulos 1989, Papadopoulos et al. 2000, Ambraseys 2009).

The western limit of Delphi-Arachova fault zone is defined by the southern limit of entrenching of the meander of Skitsa River. There were found no evidence of propagation and linkage of the fault zone to the Amfissa active fault to the north-west. To the east, the limit of the fault zone is obscure, with the probability of the NE-SW propagation through Parnassos Mt. The Plistos watershed is propagating to the east, capturing drainage that previously flowed to the east (Figure 3). This is explained to be a result of the deepening of the basin in the central and western parts of the basin due to the subsidence in the hangingwall section of the fault.

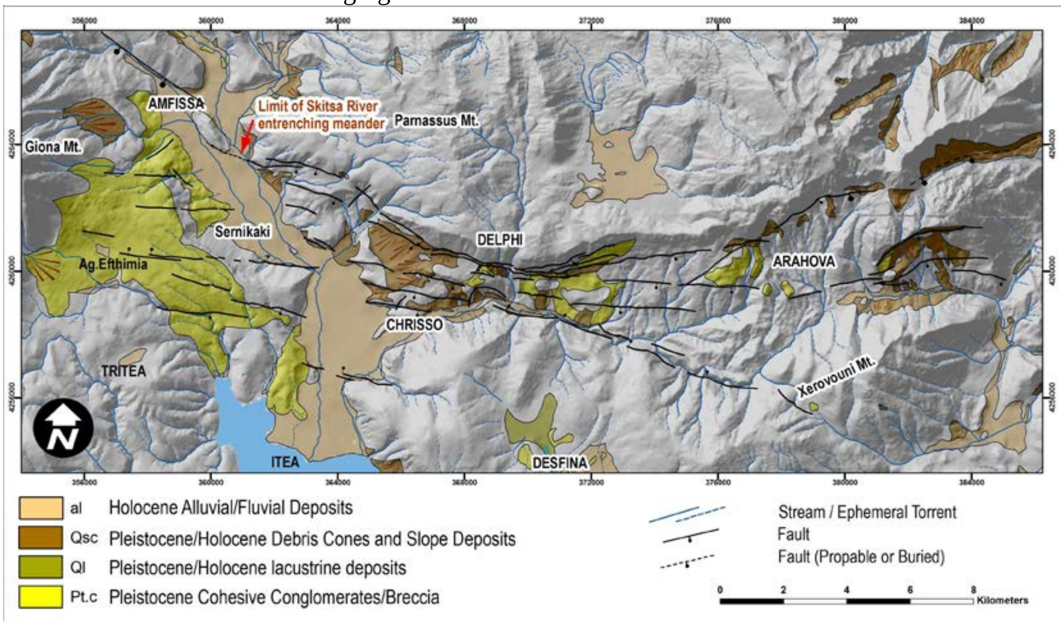

Figure 2 – The Delphi – Arachova Fault zone. Neogene and Quaternary sediments from this study and IGME Geological Maps.

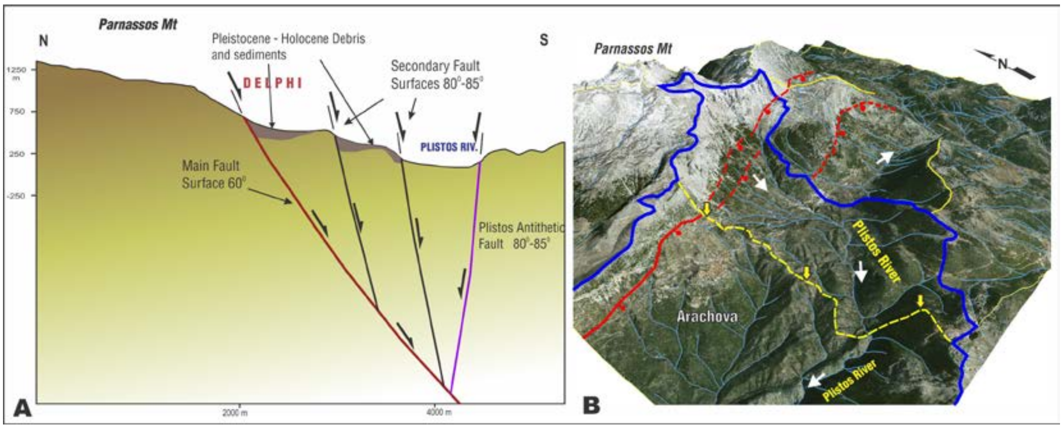

Figure 3 – A) Interpretive section with the tectonic model of the Delphi-Arachova Fault Zone. B) The eastern half of Plistos valley. Plistos basin (blue line) is expanding eastwards, capturing drainage that previously flowed to the east (yellow dotted line). Arachova fault and possible extensions with red line.

A complex array of normal and strike-slip faults with a W-E/WNW-ESE strike and north-dipping was mapped displacing Quaternary sediments in the Agia Efthimia plateau. The relation of this fault complex with the Delphi-Arachova Fault Zone is unkown, with a probable interpretation as an antithetic western extension. Agia Efthimia fault is believed to be a candidate for the 1580 historical earthquake (Papadopoulos et al. 2000, Ambraseys 2009).

2.2. Western Corinth Gulf

In the western part of the area studied, multiple onshore and coastal en-echelon normal faults were mapped (Figures 1 and 4). The largest structures are the Marathias and Trizonia fault zones, dipping to the south in the western rim of the Gulf of Corinth. Marathias fault has an evident morphological scarp trending W-E along the coast.

The Kokkinovrachos fault (Figure 4) south of Lidoriki, is a north-dipping normal fault antithetic to the general fault setting (Valkaniotis 2009). It is interpreted as an inherited structure, re-activated in the current stress regime, with evidence of Late Quaternary-Holocene activity (recent colluvial sediments and a possibly post-glacial fault scarp).

Along the northern coast, the coastal fault zones of Agioi Pantes and Galaxidi are found to the east of Eratini (Figure 4). The Galaxidi fault has a WSW-ENE strike and terminated onshore to the east of Galaxidi town. A continuous post-glacial striated fault scarp along the limestone bedrock is evident for a recent (Holocene) activation of the fault. Parallel to the Galaxidi fault is the Agioi Pantes fault, dipping also south, and both forming an overlap zone (ramp structure in Figure 4).

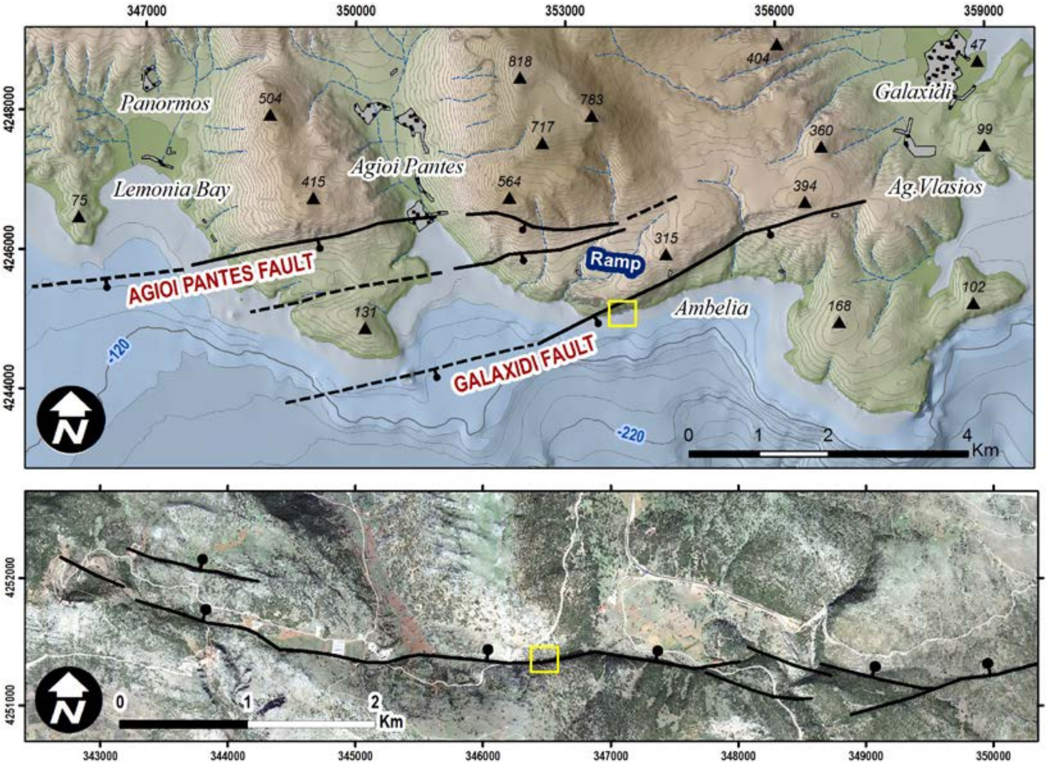

Figure 4 – Above: The Agioi Pantes and Galaxidi Fault Zone. A ramp structure is formed in the overlap area between the two faults. Elevation and bathymetry contour interval is 20m. Below: Kokkinovrachos Fault. Normal Fault scarps mapped with thick black lines and dot on downthrown side.

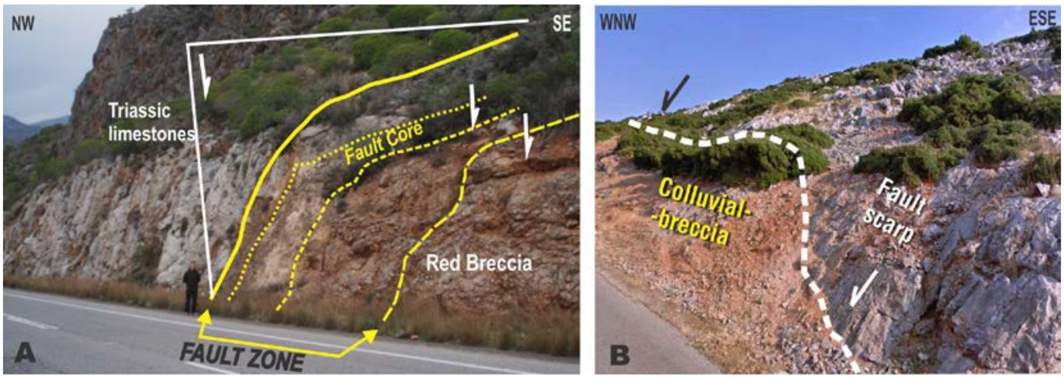

Figure 5 – A) Fault zone detail of the Galaxidi Fault. B) Fault scarp of Kokkinovrachos Fault. Site of images is shown in Figure 3.

The inland faults in the western area, like Kokkinovrachos, Amygdalea and less likely Kallithea Fault, could be the source of the 1909 M=6.3 Fokis earthquake, as the damages and macroseismic intensities correlate with a northern sited fault and possibly north-dipping (Ambraseys & Jackson 1990, Valkaniotis 2009).

Using the morphotectonic approach to study the faults in the area is a useful method to assess the activity of the faults. An example is shown in Figure 6, for the western part of the area, between Mornos fan and Eratini. The lesser order basins and drainage in Trikorfo mountain area were analysed. The hypsometrical integral values show a non-mature state of the basins (values > 0.5), and correlate with incision and erosion due to the higher deformation in the central part of the footwall of Marathias, Trizonia and Marathakia faults. SL-index values measured along the streams also indicate erosion and uplift in the footwall of these faults. A high value anomaly of the SL-index to the central part of the area, not correlated with lithological changes, hints to the presence and possible deformation in the Trikorfo fault zone.

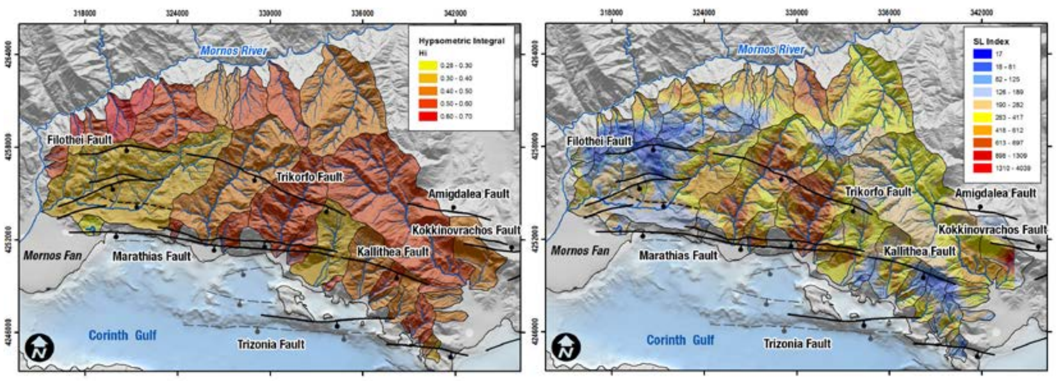

Figure 6 – A) Drainage basins in Trikorfo area, classified with hypsometric integral (Hi) values. Major faults are also shown. B) SL-index values in the same area. High values (red) indicate rapid uplift and erosion in the footwall drainage.

3. Central Part – Antikira Gulf

In contrast to the southern part of Corinth Rift, the northern part is characterised by a complex and variable fault structure, possibly related to the influence of inherited bedrock structures and older stress regimes. A fault structure irregular to the general setting of the Corinth Rift is the Antikira fault in the western rim of the Antikira Bay, in the central part of Corinth Gulf. The Antikira normal fault has a NE-SW strike and dips to the east. It forms a steep morphological scarp of 100-300 meters height. The fault has been mapped and described earlier by Sebrier (1977), but erroneously was recognised as a reverse structure (Figure 7B). Field investigation in this study, along the fault and in the original site that Sebrier describes reveal a normal fault, that possibly has been recentrly re-activated in the present stress regime. A sketch of the site (near the road Desfina - Antikira) is shown in Figure 7. The local curvature of the fault plane that is exposed at the specific site leads to a flipping of the fault surface to the west and measurements taken there show a reverse component. No evidence for a reverse fault zone was found elsewhere along the fault. Measurements in striated fault surfaces show at least one older phase with horizontal dextral striations, and the recent normal-oblique striations. The last phase of striations (NNE-SSW direction of extension – fit to present state of extension), Late Quaternary and Holocene sediments on the hangingwall, and the morphology of the fault scarp lead to a characterization of the fault as possible active, with at least Late Quaternary activity.

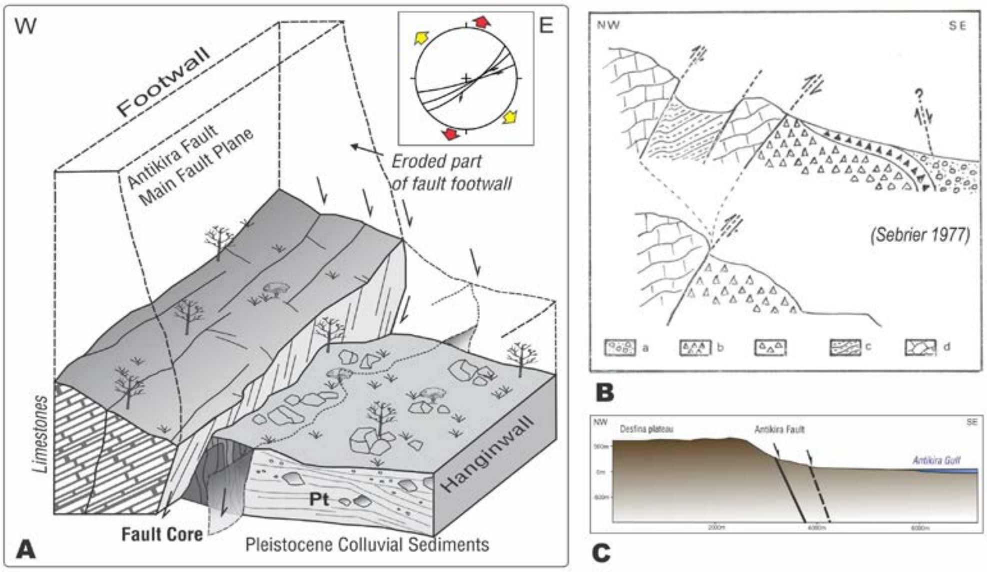

Figure 7 – A) Scetch based on field observations, explaining the mis-labeling of Antikira fault as reverse by Sebrier (1977). The curvature of the fault surface B) Original sections at Antikira fault from Sebrier (1977). C) Profile of central section of Antikira Fault.

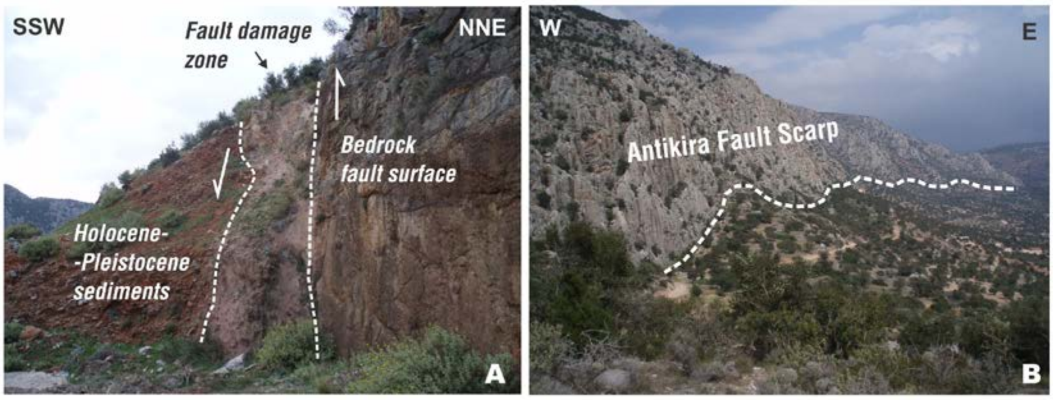

Figure 8 – Examples of normal faulting in the northern Gulf of Corinth Rift. A) Excavation outcrop of Amfissa Fault to the north-west of the city of Amfissa. B) The Antikira Fault scarp in the western side of Antikira Gulf.

Evidence of NE-SW faults were also found to the north, along the narrow valley corridors that pas s through Distomo, up to the east of Delphi-Arachova fault zone, without any large fault structure t o be evident. This is interpreted as an older tectonic structure or a lower crust anomaly.

4. Discussion -Results

Recent studies and new data from the present research reveal a complex structure of the northern part of the Gulf of Corinth rift and populate the poorly mapped region with numerous and new faults. A summary of the main active and possible active fault for the area of research is shown in the Table 1. Faults are classified with categories according the last evident activation, based on seismicity, historical earthquakes, geological data and morphotectonic features. As Holocene category, we classify faults that exhibit post-glacial activation (post-glacial striated fault surfaces, hanging wall colluvial sediments or modern seismicity) an age which corresponds to 18.000 years BP for the Aegean. Slip rate data are scarce and those that can be measured (fault scarps) show a mostly low to very low slip rate of 0.1-0.2 mm/yr and a large repeat time (Valkaniotis 2009), in accordance with active faults of mainland Greece. Marathias and Trizonia to the west, Delphi-Arachova and some coastal major fault zones have possibly a larger slip rate, as is evident in the seismological and geological data. The area of the northern Gulf of Corinth Rift is comprised of individual and en-echelon normal faults with a low slip-rate and evident of a lesser extensional activity. The fault structure seems to deviate from the previous understanding of a general uniform subsidence and inactivity of the area, although there are not enough evidence to assign the tectonic deformation of the area to the Corinth Rift extension or the general back-arc extension of the Aegean area.

The new data reveal a more complex setting for Seismic Hazard since most of the area was considered as a lower hazard in relation with the southern and the major offshore faults. Estimated maximum credible earthquake magnitude for the faults presented in this study is M=6-7, according to empirical relationships between fault length and magnitude in the Aegean area (Wells & Coppersmith 1994, Pavlides & Caputo 2004). Results from the current study of active faults in the northern Gulf od Corinth were incorporated in the Greek Database of Seismogenic Sources (GreDaSS) in the form of fault models and seismogenic sources (Caputo et al. 2012). More data from paleoseismological studies, fault trenching and dating of geomorpholic surfaces are crucial to the better understanding of the deformation rate and earthquake cycle in the area. More detailed mapping in the inland mountainous area of Fokis to the west and Beotia to the east is necessary to reveal and document poorly mapped or unkown active structures.

Table 1 - Summary of the main Active and Possible Active Faults of the Northern Gulf of Corinth Rift. Fault numbers correspond to Figure 1. Category classifies faults according to the last evident activation of the fault zone.

No - Name	Length (Km)	Category	No - Name	Length (Km)	Category
1 – Agia Efthimia	7	Historical? (1580?)	12 – Marathias	16	Holocene
2 – Amfissa	5	Late Quater-nary	13 – Kallithea	5	Late Quaternary
3 – Delphi - Arachova	20-30	Historical - 1870	14 – Zaltsa	14	Late Quaternary
4 – Antikira	6	Late Quater-nary	15 – Elikonas	10	Middle-Late Quaternary
5 – Sikia	8	Late Quater-nary	16 – Thisvi	5	Holocene

No - Name	Length (Km)	Category	No - Name	Length (Km)	Category
6 – Kourmoutsi	8	Late Quater-nary	17 – Domvrena	15	Late Quaternary
7 – Makrigialos	7	Late Quater-nary	18 – Neochori	11	Holocene
8 – Galaxidi	6	Holocene	19 – Efpalio - Drosato	5-6	Late Quaternary e
9 – Agioi Pantes	6	Late Quater-nary	20 – Amigdalea	6	Middle-Late Quaternary
10 – Kokkinovrachos	7	Late Quater-nary	21 – Trikorfo - Filo-thei	12	Late Quaternary
11 – Trizonia	9	Holocene	22 – Marathakia	5	Late Quaternary

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