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SEISMOGENIC SOURCES AND RELATED ACTIVE FAULTS IN THE GULF OF CORINTH; A COMBINED APPROACH

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Abstract

The neotectonic graben of Corinth gulf forms an interesting case study from the geodynamical and seismological point of view, since specific characteristics met on the fault zones around the gulf and the adjacent seismological data pose several questions related with the overall modern activity across a number of neotectonic faults. Indexing active fault zones with structural, seismological and sedimentological criteria leads to thorough understanding of the evolution and modern activity and provide researchers useful tools in order to evaluate the degree of present day activity of the broader area. The combined approach proposed here, with joint use of both, seismogenic sources and structural evidence, contributes to the re-evaluation of the earthquake potential by assessing the role of active features in the already complex geodynamic environment of the Corinthian gulf.
Key words: *neotectonic, earthquake fault, Greece.*

Περίληψη

Το νεοτεκτονικό βύθισμα του Κορινθιακού κόλπου αποτελεί μία ιδιαίτερη περίπτωση από γεωδυναμικής και σεισμολογικής άποψης, καθώς τα ιδιαίτερα χαρακτηριστικά των ρηξιγενών επιφανειών και τα σεισμολογικά δεδομένα θέτουν ερωτήματα σχετικά με την σύγχρονη δραστηριότητα ορισμένων ενεργών ρηγμάτων. Η συνδυασμένη χρήση σεισμικών πηγών και νεοτεκτονικών δεδομένων βοηθά στην εκτίμηση του σεισμικού δυναμικού αναδεικνύοντας το ρόλο των προαναφερθέντων στο ήδη πολύπλοκο γεωδυναμικό περιβάλλον.
Λέξεις κλειδιά: *νεοτεκτονικό βύθισμα, ενεργά ρήγματα, σεισμικότητα, Ελλάδα.*

1. Introduction

The Gulf of Corinth is located in the mainland of Greece, as shown in Figure 1, and is considered to be a neotectonic graben cross cutting the Alpine Orogenetic Belt of the Hellenides in back arc location. The main direction of the gulf is 110°N but the width is not as stable, reaching 10km near Aigio whereas at the Eastern Gulf of Corinth it is more than 40 km.

The overall extension is expressed by the activity of normal faults trending E-W with a nucleation depth within the upper crust (Rigo *et al.* 1996). Typical length for these fault zones are few tens of kilometres and their dips can be distributed in two groups; the first one with dips 50°-60° and a second group ranging between 60°-80°. These fault zones are segmented, with a segment length varying from few km up to 12 km (Koukouvelas and Doutsos 1996). Since the Plio-Pleistocene different sedimentary phases had been developed around the fault-controlled basin leading to the distinction of several sub-basins (Ghisetti *et al.* 2004).

Earthquakes expressing the fore mentioned deformation state have been observed hypocentral depths reaching 30 km and corresponding fault plane solutions whereas events with greater hypocentral depths are considered to express the ongoing subduction of the African plate. Geophysical data supports diminishing crust thickness reaching 40 km at the western part of the gulf whereas at eastern gulf of Corinth drops at 32 km (Clement *et al.* 2004).The modern stress field, as inferred from fault plane solutions of small magnitude earthquakes, supports extension in N-S direction the above is in agreement with fault plane solutions derived from greater earthquakes and field observations of both, historical and modern earthquakes (Louvari 1996).

Destructive eartquakes with magnitude greater than 6.0 have occurred mostly on the southern shore, like the seismic event that devastated the ancient town of Heliki on 373 B.C. and the town of Voura near by. As Pausanias mentions in his famous work, Ahaika, Heliki was washed off by a tsunami having occurred just after the earthquake. The broader area of Aigio suffered losses from great earthquakes at 23A.D., 1402, 1748, 1817, 1888, 1889. The latter was followed by a tsunami as well (Papazachos and Papazachou 2002). At the eastern part of the gulf, the city of Corinth has been destructed thirty-three times since the ancient times; some of the earthquakes are well documented like in 303 B.C. 74 A.D. at Roman times, 521, 543, 580, 1300. Few earthquakes like the one of 1402 near the town of Xylokastro which brought damages at Aigio as well as a tsunami, the 1742 when the village of Evrostini suffered great damages and a tsunami occurrence and the 1775 earthquakes, should be pointed out (Papazachos and Papazachou 2002). After the event of 1858 the town of Corinth was placed at its modern position near the sea. Several earthquakes have taken place at the broader area, at 1887 near Xylokastro, 1928 near Loutraki with the occurrence of great damages, at 1962 and 1972 as well. However there are several earthquakes with epicenters near the north coast, likes the ones occurred at 1600 at Galaxidi and at Eratini, at 1769 and 1965 (Papazachos and Papazachou 2002).

The use of seismogenic sources in the present study provides the tool jointly evaluate structural evidence and seismological data. Seismogenic sources frequently used over the last decades represent areas where earthquakes randomly occur. However, it is significant to point out that in this case study seismogenic sources do not represent distinct areas where different rates of activity are observed. The latter could not be validated as the seismic potential of each seismogenic source cannot be evaluated, partly because of seismological catalogues' incompleteness and the geographical location uncertainties involved. The effort in the present study is focused on the use of seismogenic sources constrained mostly by the morphological expression of the fault zone(s) accepting the remark that there is no physical limit to the rupture.

2. Methodology

Through this paragraph tectonic evidence and seismological data are presented for the different sub-basins that can be distinguished along the southern margin of the Gulf of Corinth. The distinction of each sub-basin under the names; Aigio, Akrata-Xylokastro, Kiato and Corinth, meets structural and sedimentological criteria. Among the sedimentological criteria that have been set are phase homogeneity and lateral continuity. Through the geodynamical evolution of the gulf different paleogeographical environments have given distinct sedimentological phases such as lacustrine-lagoonal phases, with lignitic horizons and slumping phenomena, Gilbert type fan deltas in the Aigio and Akrata-Xylokastro sub-basin, deposited either in lagoonal or in marine environment, like in the Kiato sub-basin, terrestrial deposits found mostly in the Corinth sub-basin, both Quaternary and Holocene in age.

Indexing active fault zones with structural, seismological and sedimentological criteria is a concept developed over the last decades by many researchers (Machette 2000, Trifonov and Machette 1993, Haller *et al.* 1993, Tondi 1998, Pierdomici *et al.* 2005) and organizations (USGS, NRC) bringing studies of fault reactivation and earthquake risk closer together.

As far as structural criteria related to the surface expression of the fault zone, four parameters can be taken into acconnt; the existence of a great scale morphological discontinuity of tectonic origin, a remnant or polished fault scarp with kinematic indicators such as striations can be observed, or the existence of other fault related structures or fabrics. Seismological evidence have been assessed by four parameters; whether the specific fault zone has been related, by field work or observations, with a particular earthquake, whether the fault zone is included in a seismogenic source and finally if well defined epicenters of historical or instrumental era earthquakes, expressing the gulf's present deformation are located in close proximity to tbe fault zone.

For every parameter taken into consideration a certain number of degrees is attributed (Table 1), from which in the next step a total number of degrees, from both the structural and seismological parameters, is calculated. Placing fault zones into distinct categories, by using the final number of degrees assigned, is the proposed indexing method.

A special category of fanlts, attributed only one degree in the evaluation of structural geology, are the inferred faults. Sedimentological evidence, and sometimes seismological data, provides only a hint about the trace of the fault zone, but dnring field work no clearly expressed tectonic line has been observed.

Table 1 – Parameters of indexing active faults used in the present study

Structural Geology		Seismology	
Parameter	**Degrees attributed**	**Seismology**	**Degrees attributed**
Existence of great morphological discontinuity	2	Vicinity of historical epicenters	2
Existence of remnant fault scarp	3	Vicinity of well defined epicentres from the instrumental era	3
Existence of striations	4	Included in a seismogenic source	4
Existence of polished fault scarp with adjacent kinematic indicators and structures	5	Correlation with a particular earthquake	5
$2<N_1<5$		$2<N_2<5$	
$2 < N_1 + N_2 < 10$			

Offshore faults have been noted as a result of many research studies over the last decades (Heezen 1966, Lyberis *et al.* 1998, Papathedorou and Ferentinos 1993, Perissoratis 2000, Lykousis *et al.* 1998, Perissoratis 1986, Sakellariou 1998, Bernard *et al.* 2004, Stefatos *et al.* 2002). In the effort of indexing all active fault zones and in order to avoid overestimates concerning offshore faults at the stage of assessing only for structural geology parameters, the latter have been attributed by two degrees only, based on the fact that their original identification was made possible from the observation of a great scale morphological discontinuity.

2.1. Description of sub-basins on the south coast of the gulf

Analytical description of each sub-basin is given below; structural and sedimentological data combined with seismological evidence have lead to a thorough geodynamic analysis of the broader area. The formation of tectonic grabens in a smaller scale in marine or terrestrial environment can be considered as a result of the activity of boundary fault zones under study.

2.1.1. Aigio sub-basin

In Aigio sub-basin three major fault zones were studied, Pirgaki – Mamousia Fault Zone (Fault No. 30, 31, 41), Heliki Fault Zone divided in Western Heliki F.Z. (Fault No. 22, 23, 26) and Eastern Heliki F.Z. (Fault No. 18, 19, 20, 21) and Aigio Fault Zone in WNW-ESE direction (Fault No. 32). The existence of transversal faults between the first two zones has been pointed out not only based on seismological evidence (Lyon-Caen *et al.* 2004) but from field work as well. The fault zone's geometry at Aigio sub-basin is an example of complex normal fault growth forming a neotectonic basin; the migration of activity at the hanging wall of the fault zone has been adequately expressed here. Segmented fault zones, with segment lengths reaching 4km, appear to have a more pronounced active character further north from Pirgaki – Mamousia Fault Zone. At the north part of the sub-basin the segments of Western Heliki Fault Zone and Aigio Fault Zone appear to overlap while a step-over is observed between Eastern and Western Heliki F.Z with 500m meters lateral difference creating a more complex fault geometry. Fault scarps where additional structural data was collected can be found at Heliki F.Z. and Pirgaki – Mamousia F.Z. where the outcrops can be found in pre-neogene basement rocks, mainly Mesozoic limestones.

The Plio-Quaternary sediments found in the hanging wall belong to two distinct rift stages (Ori 1989, Doutsos and Piper 1990). The first stage is related with a shallow water basin of lacustrine to lagoonal phase expressed with marls, bearing oxidized and pebbly horizons and mass flow near the west edge of Western Heliki F.Z. whereas the second phase is expressed with Gilbert type fan deposits. Foreset and topset beds are best expressed near the village of Mamousia, where the thickeness of the depositional series exceeding 600m supports the notion tbat the major activity of the near by Pirgaki-Mamousia F.Z. controls the deposition of the fore mentioned formation.

In Aigio sub-basin there are four known seismogenic sources, most of them related to prior seismic events; the seismogenic source related with the surface expression of the Eastern Heliki F.Z. with strong evidence of reactivation during the earthquake of 1861, a second source related with the Western Heliki F.Z, the Aigio seismogenic source with doubtful reactivation at the 1995 destructive earthquake and the seismogenic source near the town of Aigio related with 1888 earthquake, that might have reactivated the western segment of Heliki F.Z. (Valensise *et al.* 2001).

2.1.2. Akrata-Xylokastro sub-basin

In Akrata-Xylokastro sub-basin the most important fault zone is tbe Xylokastro Fault Zone (Fault No. 2, 3) treuding WNW-ESE, reaching 9km in length but it is interesting to point out the existence of Valimi F.Z. trending NE-SW with a length of 4km. Marine data and adjacent marine terraces of recent age observed on the Xylokastro Fault Zone's trace, strongly support the hypothesis that the central part of the gulf is more active. Based on the latter, the existence of a submarine seismogenic source, parallel to Xylokastro F.Z, can be supported as well. Valimi F.Z., at the southern part of the sub-basin, is probably one of the boundary fault zones for this sub-basin, probably older than Xylokastro F.Z., characterized as a remnant fault zone by the use of structural evidence.

The sediments in the Akrata-Xylokastro F.Z. can be divided into three distinct phases, the older of them belonging to a basal conglomerate of Upper Pliocene age, discordant on the pre-neogene basement, an intermediate formation of lagoonal to lacustrine phase marls, expanding to Kiato basin as well, and a younger formation of conglomerates; which belongs to a younger Gilbert type fan delta. Is interesting that south of Xylokastro F.Z. the overall character of a non well defined formation, probably of lacustrine phase marls, is more prominent. Horizons of lignites and paleosoils give the impression of a more lacustrine character; maybe representing a lake in front of a contemporary Gilbert fan delta.

The geometry of the fault zones in Akrata-Xylokastro sub-basin is different than that in Aigio sub-basin; parallel fault zones have been replaced by one major fault zone controlling the coastline and the riverbed of Krathis river near Akrata village at the western part of the basin. In the former area there are alpine basement outcrops trending NE-SW forming the southern edge of Krathis structural high.

The seismogenic sources in Akrata-Xylokastro sub-basin is Xylokastro seismogenic source reactivated during the 1887 earthquake, combining the offshore fault zone as well and Derveni seismogenic source.

2.1.3. Kiato sub-basin

Kiato sub-basin has more peculiar character; structural evidence are obscured by the great thickness of sediments observed whereas the small number of faults identified have been characterized as inactive, which is thought to be the reason for the absence of epicenters in the broader region.

Sediments found in Kiato sub-basin belong in four formations; the lower one being marls of lacustrine phase of Upper Pliocene age discordant to the pre-neogene basement, the second formation of Gilbert type fan delta deposits, the third formation of marls with more marine character than the former and an upper formation of Gilbert type fan delta of Pleistocene age. The development of this sequence is rather extensive in the horizontal and not the vertical direction as in fan deltas observed by the authors in Aigio and Akrata-Xylokastro sub-basins. A possible explanation for the above observation could be the more subtle character of activity; since the deposition of Gilbert fan delta formation in the sub-basin of Aigio and Akrata-Xylokastro occurred iu front of an upward moving footwall with great rates of activity.

2.1.4. Corinthos sub-basin

The overall structural character of deformation in the Corinthos sub-basin is quite different. Major and minor fault zones trend E-W, with the exception of the northernmost fault zone located at the tectonic horst of Mapsos (Fault No. 70, 71). Fault zones are several km in length; only the major fault zones in Perachora peninsula exceed 7km. The active boundary identified by the epicenter distribution and structural characteristics coincides with the Xylokerisa Fault Zone (Fault No. 70, 71).

The Plio-Pleistocene sediments identified in the Corinthos sub-basin correspond to four formations, the lower one consisting of marls of lacustrine to lagoonal phase. Terrestrial sediments have been deposited discordant on top of them overlaid by marls of lacustrine phase of Plio-Pleistocene age. This lacustrine to lagoonal phase marl formation and the upper formation, belonging to a younger Gilbert type fau delta; extend eastwards iuto the Kiato sub-basin. It has been suggested that the boundary between the two sub-basins is of tectonic origin, an inferred sinistral strike slip fault observed from satellite images and the transpose of the two upper formations.

2.2. Offshore faults and seismogenic sources

The assessment of offshore faults in seismotectonic research is always a difficult task. Offshore faults are recognized as a morphological discontinuity but no structural evidence is usually available. Focal parameters are not well constrained in offshore earthquakes, so the proximity of epicentres derived from instrumental data is the more common seismological parameter taken into consideration. Seismogenic sources used in the present study represent a compilation derived from both the research program FAUST (Valensise *et al.* 2001) and the ones defined by the authors.

More specifically, the seismogenic source in the Loutraki area, the one containing the Perachora Offshore Fault and the one further east at the central part of the north coast are suggested by the authors. In some cases seismogenic sources are not well defined; whereas in other cases tectonic asymmetry implies that an additional seismogenic source, as the Perachora offshore F.Z., can be related with a specific type of deformation. Another example on the eastern part of the gulf is the south dipping Loutraki F.Z. with offshore and terrestrial fault components bounding the northern gulf of Lehaio, where the distinct homonymous seismogenic source can be correlated with the 1928 earthquake.

3. Results and Discussion

The original evaluation of the fault zones, during field work, has been based on the relevant age of the fault zones as the latter was assessed by the age of the formations cross cut by the fault zone.

After the original evaluation the fault zones under study have been divided into three groups following only geological criteria.

- Fault zones with footwall outcrops belonging to pre-neogene basement and hanging wall filled with Plio-Pleistocene deposits, which are considered as boundary fault zones from an early rift stage of the gulf. However, their present day activity is questionable.
- Fault zones cross cutting Plio-Pleistocene formations; often lack clear morphological expression. Thus, in the present study morphological expression was introduced as a parameter for indexing fault activity.
- Fault zones cross cutting Holocene formations, are considered to be active mainly due to their recent age but this definition suffers from lack of further geological evidence.

The classification of the above groups of fault zones are translated using geological parameters to the indexing proposed in the present study. Following the proposed methodology five categories of fault zones under study were derived.

The results of this proposed common approach are presented in the two figures below (Figs 1, 2), in order to assess the indexing criteria for the fault zone activity evaluation. In Figure 1 the assessment of fault zones using only the structural parameters is presented, whereas in Figure 2 seismological parameters have also been taken into account.

Following this combined approach three types of fanlt zone behaviour, discussed below, can be distinguished.

- Fault zones that were initially underestimated and have now been assigned a higher degree of activity. A typical example is the Aigio F.Z., for which there is evidence that it has been activated during 1995 seismic sequence and is also correlated with Aigio seismogenic source. In the same type of fault zone behaviour belong the Schinos and Pisia F.Z., in the Perachora peninsula, reactivated during the 1981 seismic sequence. It is noteworthy that some offshore faults follow the same behavioural pattern when seismological data come into play. An advantage of the proposed common approach is the possibility to evaluate individually different segments of a unique fault zone. Heliki F.Z. can be considered as an example, since its different segments are assessed independently from one another; as long as additional data exists. The Western and Eastern Heliki F.Z. in Aigio sub-basin activated during the historical 373 B.C. earthquake and reactivated in 1876. These earthquakes are attributed to two different seismogenic sources and the type of their morphological expression is also different.
- Fault zones that were initially overestimated, and have now have been assigned a lower degree of activity. Characteristic of this type of fault zone behaviour are, the Pirgaki-Mamousia F.Z., the 3rd order fault zones of Acrocorinthos, Mapsos and Mavri Ora

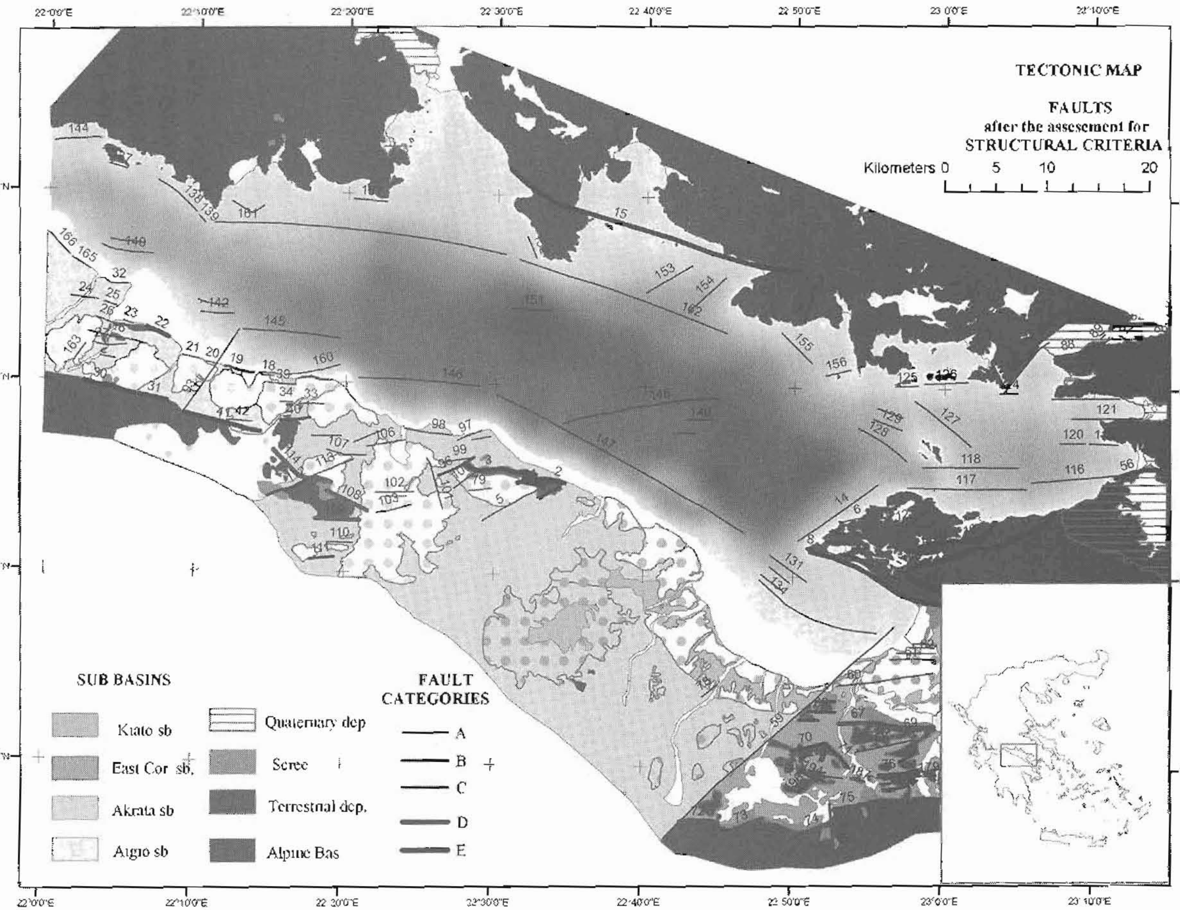

Figure 1 - Structural map. Faults are evaluated only with structural criteria. At each sub-basin lagoonal phase deposits are represented with uniform fill whereas dotted symbolism corresponds to Gilbert fan delta deposits

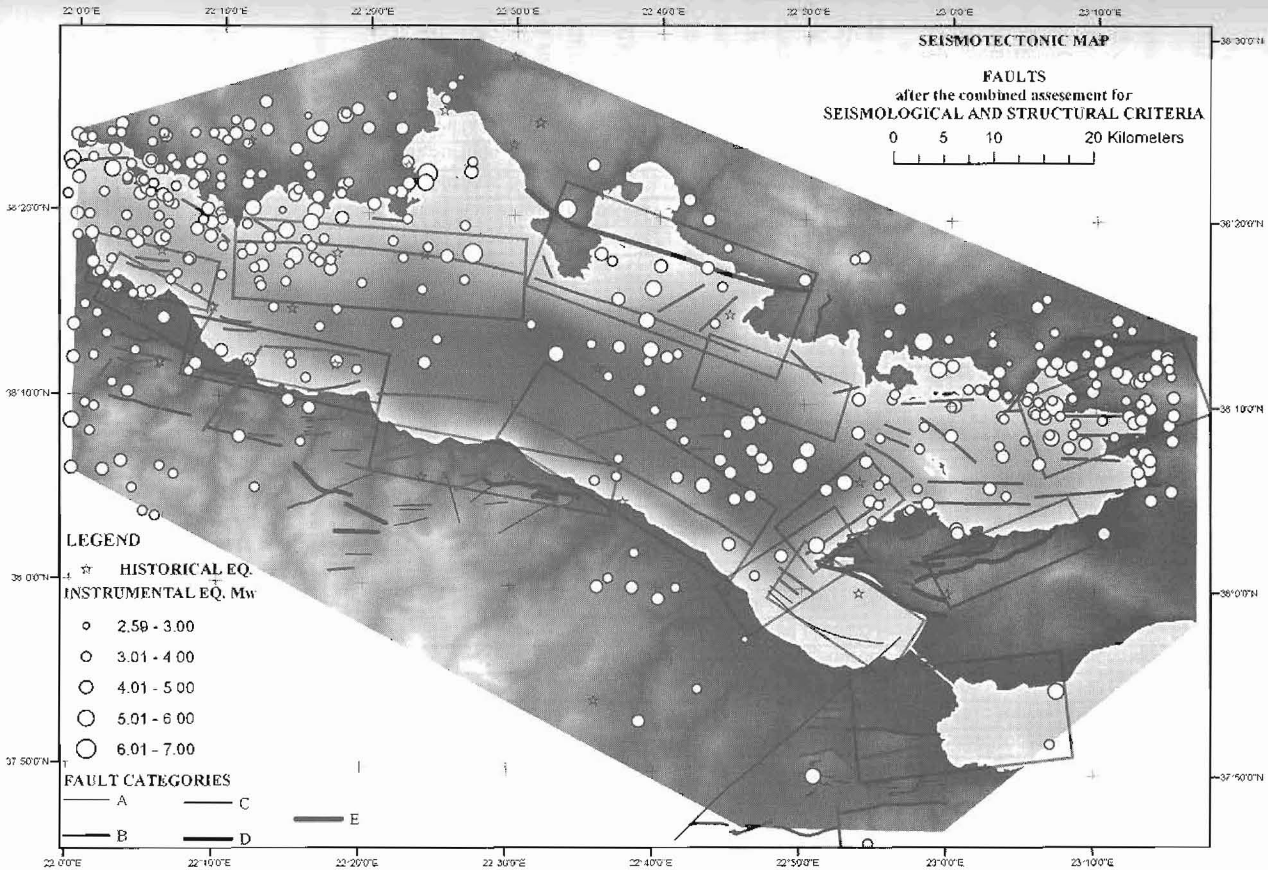

Figure 2 – Seismotectonic map. Fault evaluation based on both seismological and structural parameters. Rectangle areas represent seismogenic sources

Table 2. Evaluation data process

Fault No.	Structural evidence	Seismological data
1	Morphological Discontinuity, Polished Surface, Striae	Seismogenic source
2	Morphological Discontinuity, Polished Surface, Striae	Seismogenic source
3	Morphological Discontinuity, Polished Surface, Striae	Seismogenic source
4	Morphological Discontinuity, Polished Surface, Striae	Seismogenic source
8	Morphological Discontinuity, Polished Surface, Striae	Vicinity of modern epicenters
9	Morphological Discontinuity, Polished Surface, Striae	EQ related (1981), Seismogenic source, Vicinity of modern epicenters
10	Morphological Discontinuity, Polished Surface, Striae, Kinematic Indicators	EQ related (1981), Seismogenic source, Vicinity of modern epicenters
11	Morphological Discontinuity, Polished Surface, Striae, Kinematic Indicators	EQ related (1981), Seismogenic source, Vicinity of modern epicenters
13	Morphological Discontinuity, Polished Surface, Striae	Seismogenic source
15	Morphological Discontinuity, Polished Surface, Striae	Seismogenic source, Vicinity of modern epicenters
19	Morphological Discontinuity, Remnant Surface	EQ related (1861), Seismogenic source
22	Morphological Discontinuity, Polished Surface, Striae	EQ related (373 B.C.), Seismogenic source, Vicinity of modern epicenters
30	Great Scale Morphological Discontinuity, Polished Surface, Striae	Vicinity of modern epicenters
31	Great Scale Morphological Discontinuity, Polished Surface, Striae	Vicinity of modern epicenters
45	Morphological Discontinuity, Polished Surface, Striae	Seismogenic source, Vicinity of modern epicenters
46	Morphological Discontinuity, Polished Surface, Striae	EQ related (1981), Seismogenic source, Vicinity of modern epicenters
47	Morphological Discontinuity, Remnant Surface	Vicinity of modern epicenters
55	Morphological Discontinuity, Polished Surface, Striae	EQ related (1981), Seismogenic source, Vicinity of modern epicenters
56	Morphological Discontinuity, Polished Surface, Striae	Vicinity of modern epicenters
67	Morphological Discontinuity, Remnant Surface, Kinematic Indicators	Seismogenic source
72	Morphological Discontinuity, Remnant Surface	Vicinity of modern epicenters
73	Morphological Discontinuity, Remnant Surface	Vicinity of modern epicenters
74	Morphological Discontinuity, Remnant Surface	Vicinity of modern epicenters
75	Morphological Discontinuity, Remnant Surface	Vicinity of modern epicenters
82	Morphological Discontinuity, Polished Surface, Striae, Kinematic Indicators	Seismogenic source, Vicinity of modern epicenters
92	Morphological Discontinuity, Polished Surface, Striae, Kinematic Indicators	EQ related (1981), Seismogenic source, Vicinity of modern epicenters
108	Great Scale Morphological Discontinuity, Remnant Surface, Striae	No seismological data
109	Great Scale Morphological Discontinuity, Remnant Surface, Striae	No seismological data
114	Great Scale Morphological Discontinuity, Remnant Surface, Striae	No seismological data

structural high, and the Agios Vasilios F.Z. These fault zones are not correlated with any seismogenic source and adjacent seismic activity. Similar behaviour is exhibited by the two NE-SW trending fault zones, in both edges of Xylokastro F.Z., and smaller faults observed at the broader area of Vouliagmeni Lake, at Perachora peninsula. Boundary fault zones corresponding to an early rift stage of the gulf tend to belong to this type of fault zone behaviour.

- Fault zones that appear to be almost at the same category of activity, among which some offshore faults and inland fault zones in areas with low seismic activity.

Additional advantages of following the proposed methodology for indexing active faults are pointed out below. Firstly, both structural and seismological parameters are taken into account in order to evaluate a single fault zone. Secondly, each segment of the fault zone can be assessed separately by use of additional structural evidence and seismological data. Another main advantage is that by the use of seismogenic sources the problem of correlating a specific event with a single fault zone, an approach than in most of the cases has turned out to be problematic, is avoided. The degree of fault activity is also ranked; the fault zone under study is evaluated separately by many distinct parameters such as the morphological expression, the nature of the fault's surface, the structural characteristics of the fault zone and kinematic indicators (striations breccia trails, fractures etc.). The degree of earthquake activity is evaluated with the use of both, historical references and instrumental seismological data, and is always focused in the study of a specific seismogenic source containing, in most cases, more than one active fault zones. Through this combined approach different degrees of activity are attributed to the fault belonging to a specific seismogenic source. The proposed methodology can be updated for seismological data and structural evidence separately and by different researchers every time since it is based on distinct structural and seismological parameters.

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