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EGIO EARTHQUAKE (15 JUNE 1995): AN EPISODE IN THE NEOTECTONIC EVOLUTION OF CORINTHIAKOS GULF

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Abstract—Egio earthquake (15 June 1995) produced a series of destructive geological surficial effects in northern Peloponnessos and southern Sterea Hellas. After a brief review on the current opinions on the tectonic regime of the area has been made, we give a description of these effects, focusing mainly on the fractures along the Egio fault. Then, we present a model to interpret the earthquake activity of 15 June 1995; finally a discussion concerning the extensional tectonic regime of the area is made based on seismic data, the geometry of onshore and the recently described offshore faults.

INTRODUCTION

Central-Western Greece was hit by an Ms = 6.1 (National Observatory of Athens, 1995) earthquake on 15 June 1995, at 03:16 local time (Fig. 1). The shock was named 'Egio earthquake'. The strongest aftershock (Ms = 5.4) came 15 minutes later, while the whole aftershock activity lasted for some days (Stavrakakis and Chouliaras, 1996; Tselentis *et al.*, 1996). Extensive damage was caused in and around the seaside town of Egio, along the northern coast of the Peloponnessos and to a lesser extent, in Erateini in southern Sterea Hellas. Twenty-six people were buried and killed under the debris of two multi-story buildings, an apartment block in Egio and a hotel in Valimitika, a few kilometers east of the town.

A series of earthquake related surficial effects were produced by the shock (Fig. 2); liquefaction, submarine slides, coastline change (mainly retreat) and seismic fractures and/or ground fissures (the distinction between the last two is that the former are directly related to the seismic movement and may be surficial expression of the seismogenic fault). All these aggravated the damage and caused significant problems along the coastal zone of Egio and at the opposite side of the Gulf, in Eratini.

From various historical reports we learn that the region has repeatedly paid the toll to *Engelados* (the ancient Greek deity responsible for earthquakes) (Xinopoulos, 1912;

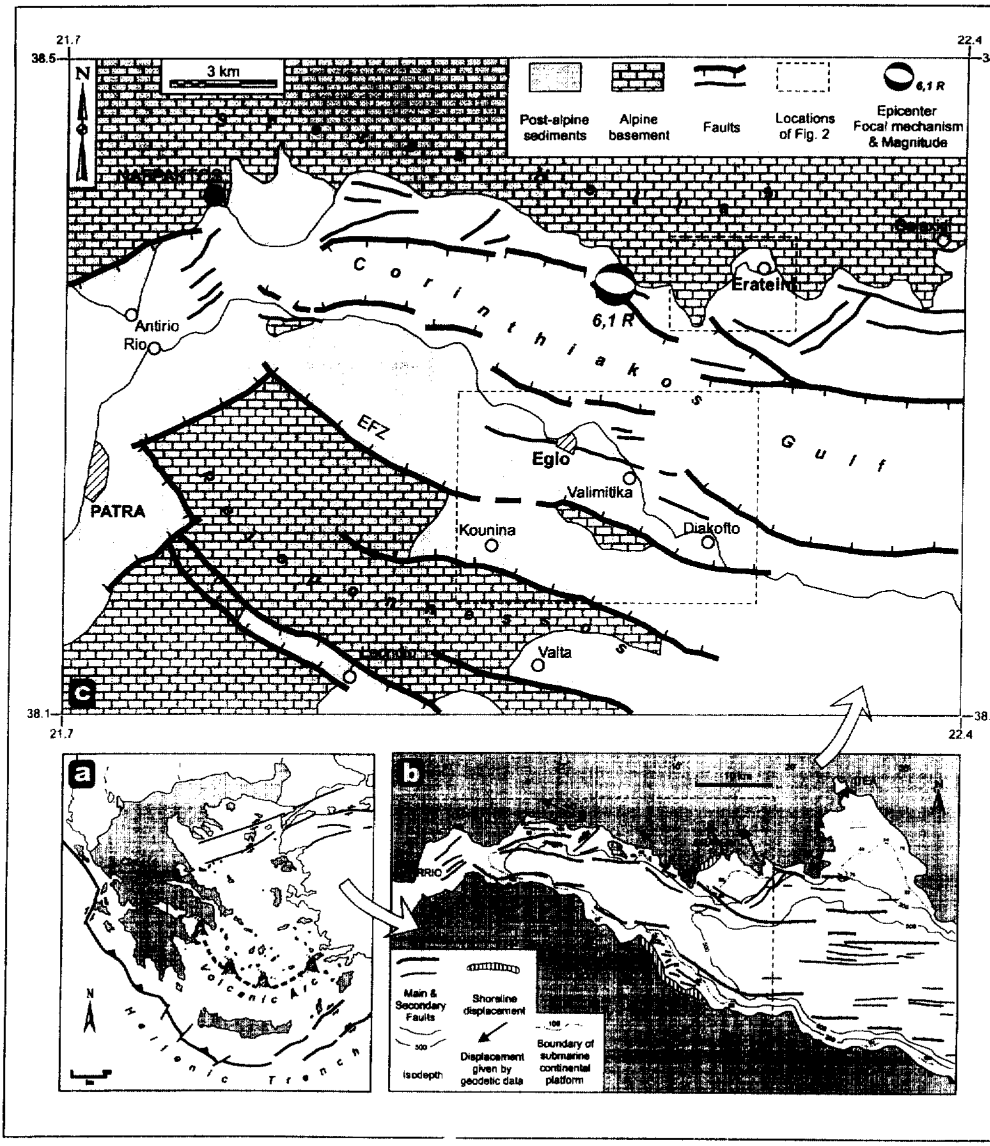

Fig. 1. (a) location map; (b) regional map of western Corinthiakos Gulf. GPS data are form Bernard *et al.* (in press), offshore faults from Chronis *et al.* (1997) and shoreline displacements from Lekkas *et al.* (1996a); (c) Geological sketch map to show major faults, fault zones and generalized geologic structure.

Stavropoulos, 1954; Papazachos and Papazachos, 1989). One of these cases was the destruction of ancient *Eliki*, a town 7 km east of Egio) in 373 BC (Mougiaris, 1987; Mougiaris *et al.*, 1992). Reference is also made to the earthquakes of 1746 and 1817 (Xinopoulos, 1912; Stavropoulos, 1954), when Egio was razed, from the combined activity of the shocks and tsunami. Schmidt (1875) gave not only a detailed account of the 1861 earthquake activity, but also provided information on related effects, as ground fissures and liquefaction. In his

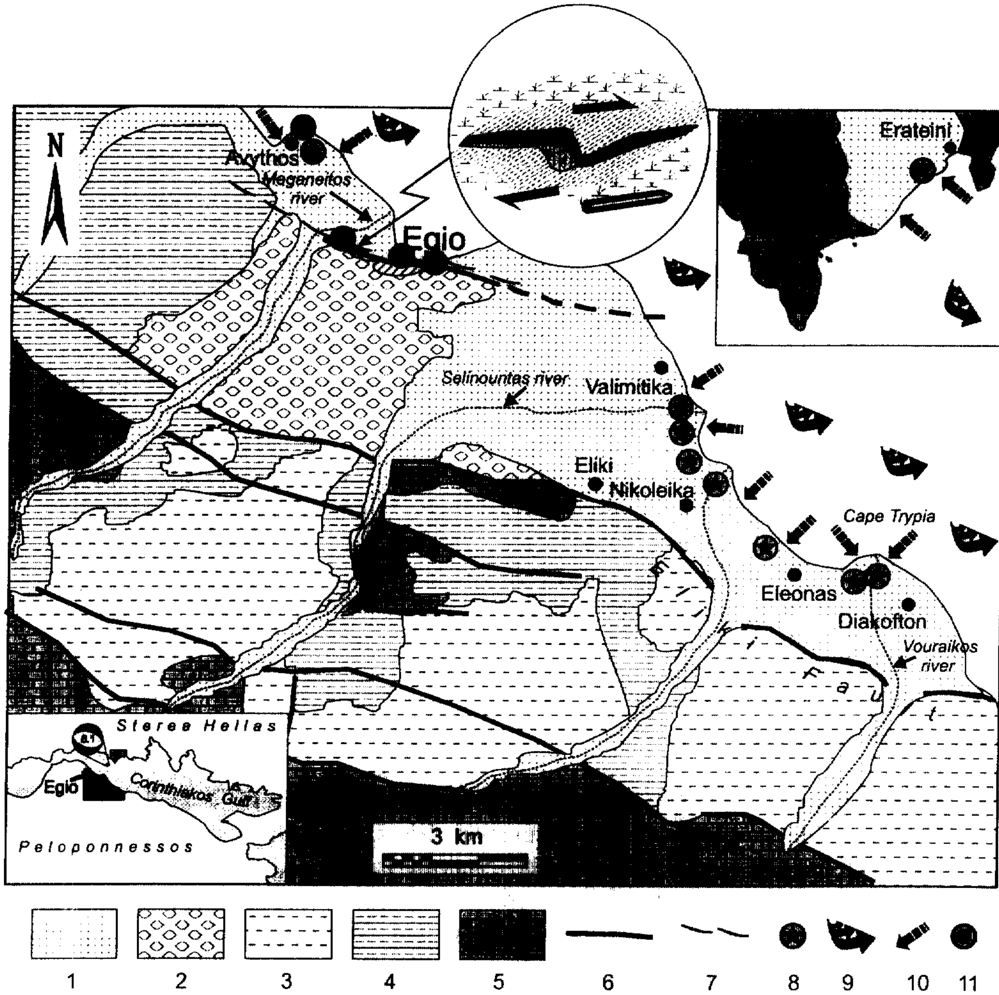

Fig. 2. Geological map and earthquake related surficial effects in the vicinities of Egio and Erateini (see Fig. 1c for locations). 1: Alluvial coastal and fan delta deposits, 2: M. Pleistocene-Holocene alluvial fan deposits, 3. M. Pleistocene fandelta deposits, 4. L. Pleistocene lacustrine-lagoonal deposits, 5. Alpine basement, 6. Fault, 7. Seismic fracture, 8. Liquefaction, 9. Submarine slide, 10. Coastline retreat, 11. Settlement. Geology modified after Poulimenos (1991). Earthquake effects after Lekkas *et al.* (1996a).

map are displayed fissures of ESE–WNW trend, which, according to Mougiaris *et al.* (1992) delineate the trace of Eliki fault (EF) and are related to its reactivation. Finally, for the area of Erateini phenomena as ground fissures, coastline retreat and submarine slides were described by Tataris (1965) for the 1965 (Ms = 6.4) earthquake. In the following paragraphs, and after we make a brief review of the current opinions on the tectonic regime of the area during the Quaternary, we shall describe in short the related earthquake surficial effects produced by the shock of 15 June 1995. We shall then attempt to approach their causes, mainly focusing on the generation of seismic fractures. Finally, a model to explain the earthquake activity and deformation pattern will be presented and discussed upon.

TECTONIC REGIME

Corinthiakos Gulf is characterized as one of the most active extending regions in the Eastern Mediterranean (Jackson *et al.*, 1982; King *et al.*, 1985 and many others). It is the central-eastern portion of the Corinthos-Patra 'graben' system, develops oblique to the Hellenic Arc (Fig. 1a), and separates the Alpine basement of Continental Greece from that of Peloponnessos (Doutsos *et al.*, 1988). Since its formation, possibly during the Miocene (Kelettat *et al.*, 1976) it is under extension, a result of back-arc rifting (Le Pichon and Angelier, 1979). This extension, according to numerous geological studies (Jackson *et al.*, 1982; King *et al.*, 1985; Higgs, 1988; Doutsos *et al.*, 1988) and focal mechanism solutions (McKenzie, 1978; Rigo *et al.*, 1996), has a N–S direction and is accompanied by a 1 mm yr^{-1} downward movement of the northern part of the Gulf, relative to the southern one (Tselentis and Makropoulos, 1986). Quaternary extension rate has been measured to 10–18% (Doutsos and Piper, 1990).

The graben of Corinthos was been extensively studied, both inland and offshore. The part covered by the sea is an asymmetrical graben, with a maximum depth of 900 m. and its southern edge coincides with a major normal fault-the Gulf of Corinth fault (Jackson *et al.*, 1982; Brooks and Ferentinos, 1984), while antithetic faults occur in the north (Doutsos and Piper, 1990). The onshore part of the graben in northern Peloponnessos comprises a 25 km. long zone that has been uplifted for at least 1800 m. since the Late Pleistocene (Philippson, 1892; Mariolakos, 1975). This uplift was connected to normal, north-dipping fault activity (Jackson *et al.*, 1982; King *et al.*, 1985; Doutsos *et al.*, 1988), while N to NNE trending transfer faults have strongly influenced the drainage system (Poulimenos *et al.*, 1989). This deformation created certain morphological features typical of active basin margins, as drainage diversions (Dufaure, 1977) and scarps (Vita-Finzi and King, 1985). Higgs (1988) supported that there is a general reduction in the size of the graben with time, as deformation migrates towards more 'interior' faults. According to the same author, fault-block rotation can be described with the terms *planar graben* and *half graben geometry*. On the contrary, Doutsos *et al.* (1988) consider the faults that occur inland as of listric character; the same has been supported by Brooks and Ferentinos (1984) for the offshore faults of the Corinthiakos Gulf, after seismic surveying.

Papanikolaou *et al.* (1991), studying the eastern portion of the southern margin showed that during the initial development stages of the graben the faults had a significant horizontal component of movement while later they acquire a normal-oblique (Mariolakos and Papanikolaou, 1987) character. Combining this observation with the deformation of the alpine structures in continental Greece and the Peloponnessos, they presented the model of a proto-Corinthian tectonic structure, perpendicular to the Hellenic Arc, analogous to other, normal to the Hellenides and Deinarides structures, for the origins of which Aubouin and Dercourt (1975) had suggested old transform faults.

According to Ori (1989) the development of the graben took place in two phases. During the first the sediments that filled it were of terrestrial or shallow-marine origin. In the second phase, the connection with the Ionian Sea was established and Gilbert-delta and deep phacies dominate. According to Poulimenos (1991) and Dart *et al.* (1994) three litho-stratigraphical units can be distinguished in the vicinity of Egio (Fig. 2). The lower one is of Early Pleistocene age and consists of clays, marls and sands directly overlying the alpine substratum. The middle unit comprises typical deltaic and alluvial fan deposits, mostly conglomerates and sands, unconformably overlying the previous unit. The topmost unit is characterized by alluvial fan deposits, upon which the town of Egio has been founded. The last two units, according to Poulimenos (1991) are of M. Pleistocene-Holocene age. Holocene and recent deltaic and fluvial deposits (loose conglomerates, sandy marls and sands) cover unconformably all the rest.

The active faults in the study area occur along the coast and offshore. Large, mainly E–W (and WNW–ESE) faults have been recognized by older oceanographic surveys (Ferentinos *et al.*, 1985) and by recent ones (Chronis *et al.*, 1997) (Fig. 1b). Along the onshore margin of northern Peloponnessos, the active Eliki fault occurs, which, according to Mougiaris *et al.* (1992) was responsible for the 1861 earthquake. This fault zone extends from Diakofto, passing two kilometres south of Egio until the Rio-Antirio strait. More to the south there are two or three fault zones parallel to EFZ, passing from the villages of Kounina, Vlata, Leontio, etc. (Doutsos and Poulimenos, 1990; Poulimenos, 1991) (Fig. 1c). Also, smaller order longitudinal structures can be recognized, as the 9 km. long Egio fault that crosses the town of Egio, creating a distinct (?)footwall escarpment. This fault is believed to have been reactivated during the 15 June 1995 earthquake.

The northern margin of the Gulf is characterized by the almost total absence of post-alpine formations (Mariolakos, 1975) (Fig. 1c). There are only minor local outcrops of small thickness, mostly fluvial, alluvial and coastal deposits. The region seems to be subsiding (Tselentis and Makropoulos, 1986); thus the distance between the north and southern coasts of the Gulf increases about 1 cm yr^{-1} (Billiris *et al.*, 1991). This process is accomplished through the activity of large offshore faults along the northern margin, located after oceanographic surveying (Chronis *et al.*, 1997) (Fig. 1b).

EARTHQUAKE RELATED SURFICIAL EFFECTS

Detailed investigation soon after the 15 June 1995 shock on the surficial effects caused showed that in northern Peloponnessos most of them were located within a 12 by 3 km zone, from Selianitika, west of Egio to Cape Trypias, to the east; on the contrary, in Sterea Hellas, the occurrence of such effects was quite limited, within a 1000 by 100 m. zone, along the coast of Erateini (Fig. 2).

Seismic fractures

The seismic fractures that occurred in the vicinity of Egio are located within a zone that develops parallel to the escarpment of Egio (Fig. 2). This scarp seems to have been formed by the activity of a (?) normal fault, whose foot-wall consists of loose alluvial and fluvial deposits and its hangingwall comprises L. Pleistocene-Holocene consolidated conglomerates bearing sand and marl intercalations.

At first, seismic fractures were observed at the western outskirts of the town and developed mainly in the premises of two factories, the Hellenic Weapon Industry and Kouniniotis. They were a few to some tens of m. away from the escarpment and could be followed for a distance of 2 km. At the western edge of their occurrence (Rododafni) they cut formations corresponding to those of the footwall and their trend was WSW–ENE, while heading eastwards, they cut the recent deposits of Meganeitos river; their trend had shifted to E–W. The fractures cut various constructions founded on these formations, as road paving, supporting walls, embankments and fences. At places, one could observe a small, 2–3 cm. offset (northern-side-down), while locally they were *en echelon* arranged (Fig. 2); the same has been mentioned by Roberts and Koukouvelas (1996). Further investigation showed that these fractures continued through the town and further to the east (Fig. 2). In Egio they could be seen cutting streets surfaces, floors, etc.

Outside the town limits, the fractures had E–W trends (measured on a paved road surface), without any visible offset, while in Stafidalona, some open ones of the same trend were located.

The total length of their occurrence is somewhat more than 6.5 km (according to Koukouvelas and Doutsos (1996) it is 7.2 km). Maps presented by various researchers (Bernard *et al.*, 1996; Koukouvelas and Doutsos, 1996; Lekkas *et al.*, 1996a) show some discrepancy in the distribution of fractures, mostly for the eastern ones. Two could be the reasons for this disagreement: (i) that each research group mapped fractures that the others failed to notice, and/or (ii) that in the eastern part confusion was caused by the multitude of fractures that could have been formed by other causes, as land settlement.

Note also that along the zone of seismic fractures the damage caused to constructions was significantly increased; the maximum intensity values were linearly arranged along this zone (Lekkas *et al.*, 1996a).

Ground fissures

They were located along the coastal zone and caused damage to road works, open recreational sites and other light constructions. The affected formations were unconsolidated coastal and recent (?Holocene) deltaic deposits.

In the vicinity of Egio, fissures were located along the coastal zone between the mouths of Selinountas and Vouraikos rivers, east of the town and from the delta of Meganeitos to Cape Gyftissa, west of Egio; other occurrences were around Avythos (Lekkas *et al.*, 1996b) Along the opposite coast ground fissures were significantly fewer, cutting the thin coastal and fluvial deposits and not extending down into the substratum of Erateini.

Their length varied between a few cm and some tens of m., their aperture was from a few mm up to 40 cm and they extended for a maximum depth of 60 cm. At cases, some of them could have been deeper, but they were filled with debris or liquefied material. Their trends were not uniform but mostly followed the direction of the coastline or riverbeds. Systematic study on their trends (Lekkas *et al.*, 1996b) showed that these cracks were the result of either differential settlement of the loose soil, or lateral instability of ground masses close to river banks and the coast, or finally due to liquefaction in the underlying strata or nearby formations. Therefore, these ground fissures are not directly elated to sub-surface fault-slip but have formed because of ground shaking.

Coastline changes

The event of 15 June 1995 was accompanied by intense coastline changes along the coastal area between the mouths of the Selinountas and Vouraikos rivers in the northern Peloponnessos and along the coast of Erateini, in southern Sterea Hellas.

This change was not uniform throughout the zone. Thus, at places the coast had subsided, and land was inundated for a few metres from the shore (as at Nikolaika), while at other locations the magnitude of coastal retreat was quite higher, reaching some tens of metres, as at Cape Trypias (Fig. 2).

In Erateini, the sea advanced inland for 2–3 m., in areas covered by fluvial and coastal deposits; no such a case was observed where alpine rock outcropped.

The small magnitude of 'dip-slip' movement observed in the seismic fractures developing parallel to Egio fault does not in itself justify the extent of coastline retreat. Also, coastline retreat in northern Peloponnessos occurred both at the downthrown (Avythos, Egio) and the upthrown (Selianitika, Nikoleika) block of Egio fault. Thus, the phenomenon should be related to the compaction of recent (?Holocene) sands and gravels, to successive submarine micro-slides and liquefaction, as indicated by Lekkas *et al.* (1996b) and proven by Papatheodorou and Ferentinos (in press). Note also that, no coastline retreat occurred in outcrops of the alpine basement or compact Pleistocene-Holocene formations.

Landslides

No significant onshore landslides were observed, save a few scattered rockfalls (fallen blocks up to 1 m^3 in volume) along the road network around Erateini. On Eliki fault or the other ones to the south in northern Peloponnessos no slides or rockfalls took place, either.

However, indications of large slides along the coasts of Egio and Erateini were provided mainly by coastline retreat, turbidization of seawater and change in the sea bottom relief (the latter was maintained by local fishermen). Proof to this came later by oceanographic surveys by Papatheodorou and Ferentinos (in press) and Chronis *et al.* (1997). The former in particular studied extensively the submarine slides and gave detailed descriptions of the phenomenon, providing comprehensive analysis of their types and mechanisms. All submarine slides were located next to areas of coastline retreat and basic factors for their generation were liquefaction and reduction in shear strength of non-lithified sediments. Note that similar effects had effects had been described for the 1965 shock in Erateini (Tataris, 1965).

Liquefaction

Extensive liquefaction was induced by the main shock, causing considerable damage not only to various constructions such as road but also to cultivated land (Fig. 2).

Liquefaction phenomena were located along the coastal region, over an area of 10 km^2, between the mouth Selinountas river and cape Trypias, where the Vouraikos discharges into the Gulf and at the coastal zone at the west of Egio, at Avithos. Along the northern coast of the Gulf, these phenomena were sparse and occurred only in the vicinity of Erateini.

Field study and geologic data showed that in the areas affected by liquefaction the outcropping formations are coastal, alluvial and fluvial deposits. The outflow of liquefied material resulted in the deposition of mainly fine material (sand) and more rarely, coarser material (Lekkas, *et al.*, 1996b). As results from the sedimentological study by Schwartz and Tziavos (1979) in the area east of Egio, the liquefied stratum must lie at a depth between 4.3 and 7.5 m.

DISCUSSION AND COMMENTS

The occurrence of seismic fractures, mainly at the west of Egio and their prolongation into and to the east of the town (Fig. 2) became a controversial subject. The fact is that although there were numerous cracks along the Egio fault, the offset in most of them was too small to be discernible. During the survey after the earthquake we observed along the western portion of the fault an offset in the cracks of 3 cm (Bernard *et al.* (in press) talk about 5), while at places an *en echelon* pattern was found (Fig. 2).

No matter what the case is, the offset is of the order of a few centimetres (compare the measured offsets during the Alkyonides earthquake, (Mariolakos *et al.*, 1982; Jackson *et* *al.*, 1982; King *et al.*, 1985)) and the question that arise is: can a fault with visible offset of 3 (or 5) cm produce a 6.1 earthquake?

There are three basic opinions expressed so far. Koukouvelas and Doutsos (1996) and Roberts and Koukouvelas (1996) attempting to interpret this observation suggested that the Egio fault was not reactivated in the main shock, but during the aftershock sequence; they narrow down their estimate by saying that the fractures were caused by the largest aftershock. Bernard *et al.* (in press) support that the earthquake was produced by an offshore fault and believe that the fractures in Egio were caused by slide in shallow depth, within the loose conglomerates and because of high acceleration values in the town. Finally, Carydis *et al.* (1995), Papanastassiou *et al.* (1995), Bernard *et al.* (1996) suggested that the earthquake was produced by slip of Egio fault.

The fact that the main shock occurred at 03:15 and the main aftershock just 15′ apart made it difficult to distinguish which of the two shocks was responsible for the fractures. However, the people who were working nightshift at HWI assured us that the majority of damage was caused by the main shock. A detailed study on damage distribution (Lekkas *et al.*, 1996a) proved that damage and fractures were tightly interrelated. Based on these we can assume that the fractures were caused by the main shock. Certainly this assumption does not rule out the possibility the fractures continued to develop during the aftershock sequence, as was proven by Koukouvelas and Doutsos (1996). The suggestion by Bernard *et al.* (in press) should be abandoned, as a. the fissures in Rododafni cut marls and consolidated conglomerates, and not only the outcropping loose conglomerates, as is the case further to the east; b. the intensity of damage cannot be related to 3–5 cm slip, c. the trends of the fissures were systematically arranged along the trace of Egio fault, while along the coast, where the cracks were caused by slide, liquefaction, etc., their trends were random (Lekkas *et al.*, 1996a), and d. in the area between the coast and Egio fault, no cracks were found.

Focal mechanism solutions of the main shock (see Table 1 in Bernard *et al.* (in press)) showed that it was caused by an E–W trending fault, dipping 20–25°N. Analyzing the seismic data, Bernard *et al.* (in press) proposed a break that propagated upwards through a steeper rupture surface, emerging offshore, NE of Egio. Chronis *et al.* (1997) reporting the results of the three oceanographic surveys performed between October 1995 and January 1996, seem to confirm the suggestion by Bernard *et al.* (in press) and confirm both the occurrence of a number of submarine slides and a series of mostly E–W trending faults that bore signs of recent activity. Chronis *et al.* (1997) suggest that these are gravity faults that create distinct escarpments on the shallow platform of the Gulf. Thus, attempting to account for active deformation in the area we need to take the following into account:

(1) The occurrence for earthquake-related surficial effects is capable of providing factual evidence for earthquake activity, and in particular:

Liquefaction, coastline change, slides and ground fissures are the result mainly of ground shaking and differential mechanical behavior of loose sediments. Especially for the case of coastline retreat, if we combine our observations with GPS data (Bernard *et al.* (in press)) we can see that it occurred in area where the displacement vectors were normal to the coast (Fig. 1), with direction away from it, while no coastline retreat took place where the displacement vector magnitude was significant, but its direction was parallel to the coast (e.g. point M in Fig. 1). The mapped ground fissures (see Lekkas *et al.*, 1996b) bore no relationship to any possibly active tectonic structures.

(2) Earthquake fractures seem to have been formed in the main shock and not during the largest aftershock. Their occurrence could serve as a guide for the fault activity in the area.
(3) The combination of earthquake data, GPS and SAR (Bernard *et al.* (in press) suggests that the shock was caused by a low-angle detachment fault beneath the Gulf. The fault surface proposed by the same authors, seems to correspond the zone suggested by Rigo *et al.* (1996) for the western part of the Gulf and, formerly, by King *et al.* (1985) for the eastern part. A similar solution was provided by Pham *et al.* (1996), with the difference that they suggested the zone had a 'syncline' form.
(4) Recent comprehensive work by Armijo *et al.* (1996) suggests for the whole of the Corinthiakos Gulf that it forms an element in the possible southwestern extension of the North Anatolian fault, taking into account, among others, paleomagnetic rotation, seismicity and GPS and SLR data.
(5) Among the 148 events analyzed by Rigo *et al.* (1996), about 30% of them corresponded to oblique-slip (strike-slip percentage more than 35%), another 37% contained 10–30% strike-slip, and 'pure' dip-slip (s.s less than 10%) accounted for 33% of the whole.
(6) The same authors report a N 0° to N 10°E trending T axis for the area of western Corinthiakos, while Bernard *et al.* (in press) give for the 15 June 1995 event a T axis azimuth of N 10°W. These two options may provide adequate explanation for individual faulting, but seem to fail to account for the overall fault and deformation pattern in and around the Gulf, where the dominant trend of active faults is E–W, them being arranged in a right-stepping *en echelon* pattern, both along the northern and the southern margins of the Gulf (Chronis *et al.*, 1997) (Fig. 1b).

The model of low-angle detachment zone seems to be have a sound basis. However, we suggest that for the 15 June 1995 event, fault slip propagated towards the surface via two steeper, parallel to each other, E–W trending faults, that merged with the detachment zone in depth. The first one may have accommodated the higher amount of released energy and develops offshore (most probably fault FF in Fig. 3), just north of Cape Gyftissa. The second corresponds to Egio fault, along and/or parallel to which the earthquake fractures were formed and the highest intensity values were recorded (Lekkas *et al.*, 1996a)

The suggestion of two (or more?) activated faults connected to a low-angle detachment in depth, coupled with the right-stepping *en echelon* pattern of active faults, and the percentage of oblique-slip focal mechanism solutions (Rigo *et al.*, 1996; Mariolakos and Papanikolaou, 1987), guide us to the thought that the overall tectonic regime is other than that or pure extension. Similar point of view was recently expressed by Armijo *et al.* (1996), but they connected this to extension of the North Anatolian Fault, which, in our opinion, is not yet clearly substantiated.

On the other hand, participation of oblique-slip (and, for a 15% of the events analyzed by Rigo *et al.*, 1996 strike-slip) faulting is significant and the active fault pattern suggest a transtensional stress field. The activation of two (or more?) faults as we suggested conforms to experiments and observations on extensional-strike-slip environments (e.g. Tronn and Brunn, 1991; Richard *et al.*, 1995).

Two more points need to be stressed out. First, to what extent has 'antithetic' faulting participated in the whole earthquake activity of Egio? The gently, north-dipping nodal plane chosen to represent the causative fault is not too clearly constrained, in our opinion,

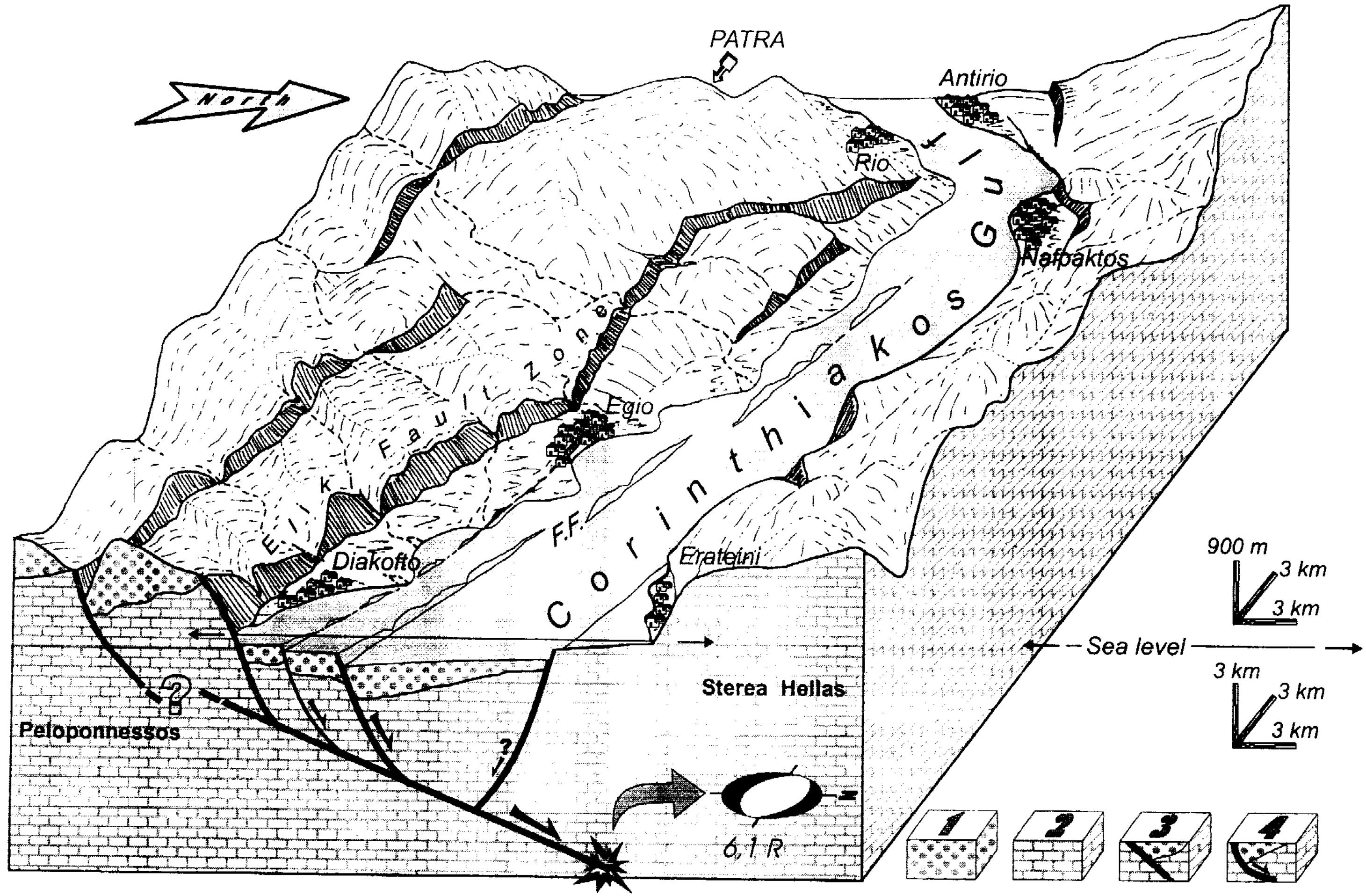

Fig. 3. Block diagram of central and western Corinthiakos Gulf, to show the proposed model of fault reactivation for the 15 June 1995 earthquake. 1 (?) Miocene–Present sediment fill of the Gulf, 2. Alpine basement, 3, Fault, 4. Fault possibly activated by the earthquake.

judging from the hypocenter distribution (see Fig. 12 in Bernard *et al.* (in press)). Second, but perhaps equally important, is the role of plastic deformation in the area, which may explain observations and facts as the small amount of slip observed in fractures, especially along the Egio fault and the extent and magnitude of coastline retreat.

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