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Liquefaction, ground fissures and coastline change during the Egio earthquake (15 June 1995; Central-Western Greece)

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ABSTRACT

The destructive earthquake (Ms = 6.1 R) that hit the town of Egio and the surrounding area of the Northern Peloponnessos (Greece) generated extensive liquefaction, ground fissuring and coastline changes. Historical data indicate that the same region has experienced episodic earthquake damage, with some seismogenic phenomena having re-occurred at the same locations. In conclusion, it is confirmed that this is a high seismic risk region, where proper building design and planning can reduce the potential danger if the geodynamic setting is properly taken into account.

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INTRODUCTION

On 15 June 1995 (0316 local time) an earthquake of magnitude Ms = 6.1 R (N.O.A., 1995) hit the region around Egio (Northern Peloponnessos, Southern Sterea Hellas). The epicentre lay offshore, in the Gulf of Korinthos (Fig. 1) between Erateini and Egio (38.26°N, 22.15°E). The toll of the earthquake included the loss of 26 human lives, from the collapse of two multi-storey buildings, an apartment block in the town and a hotel at Valimitika, to the East. In addition, about 2000 houses suffered severe damage, or were rendered demolishable, 2300 buildings suffered significant damage, while the destruction was of smaller intensity for 10,000 more (Carydis *et al.*, 1995).

A large part of the damage is attributed to the concomitant surficial phenomena directly or indirectly connected with the shock: ground fissures, liquefaction and coastline change. These phenomena occurred mainly along the coastal areas of Egio (Northern Peloponnessos) and Erateini (Southern Sterea Hellas).

The shock was the latest in a series of destructive events that have hit the region. According to historical references, the region has repeatedly suffered by the blows of *Engelados*, the ancient Greek deity responsible for the earthquakes (see historical data).

GEODYNAMIC SETTING — NEOTECTONIC STRUCTURE

The study area belongs in the neotectonic macrostructure of the Gulf of Korinthos, which separates Peloponnessos from mainland Greece (Fig. 1). Its western extremity lies next to the Hellenic Trench and its eastern end is near the volcanic arc.

The Gulf of Korinthos, since its probable formations towards the end of the Miocene (Kelletat *et al.*, 1976), has been controlled mainly by N–S extension (McKenzie, 1978; Jackson *et al.*, 1982; Doutsos *et al.*, 1988; Leeder and Jacskon, 1993). Graben-fill sediments exposed in the uplifted southern part of the graben can be distinguished in three lithostratigraphic units (Rozos, 1991; Poulimenos *et al.*, 1993). The lowermost comprises marls, clays and sands of late Pliocene to early Pleistocene age; their depositional environment is lacustrine to lagoonal. The middle unit, of late Pleistocene age, is composed mainly of conglomerates and sandstones, characterized by high primary dips, internal discontinuities and lateral transitions, typical of deltaic and fan deposits. Finally, the uppermost units consist of Holocene formations, comprising sandy marls, loose conglomerates and sands, which are of almost horizontal deltaic and fluvial depositional environments. The topmost units are coastal sediments that occur along the present coasts of the Gulf.

In contrast, in southern Sterea Hellas, i.e. at the northern margin of the Gulf, the post-Alpine sediments are of very limited extent and thickness. They are mainly represented by recent deltaic deposits and coastal sediments, as is the case at Erateini.

The asymmetry in the outcrop pattern of the post-alpine sediments is due to the geometry of the Korinthos basin, a half-graben controlled by a master faults system (the Gulf of Korinthos fault) (Jackson *et al.*, 1982; Brooks and Ferentinos, 1984) which forms a 500-m high submarine escarpment, and has a listric geometry accompanied by antithetic tilting of the layers in the downthrown block (Brooks and Ferentinos, 1984).

The entire southern part of the Korinthos rift has been uplifted since the early Pleistocene. Vertical movements associated with normal faults, many of

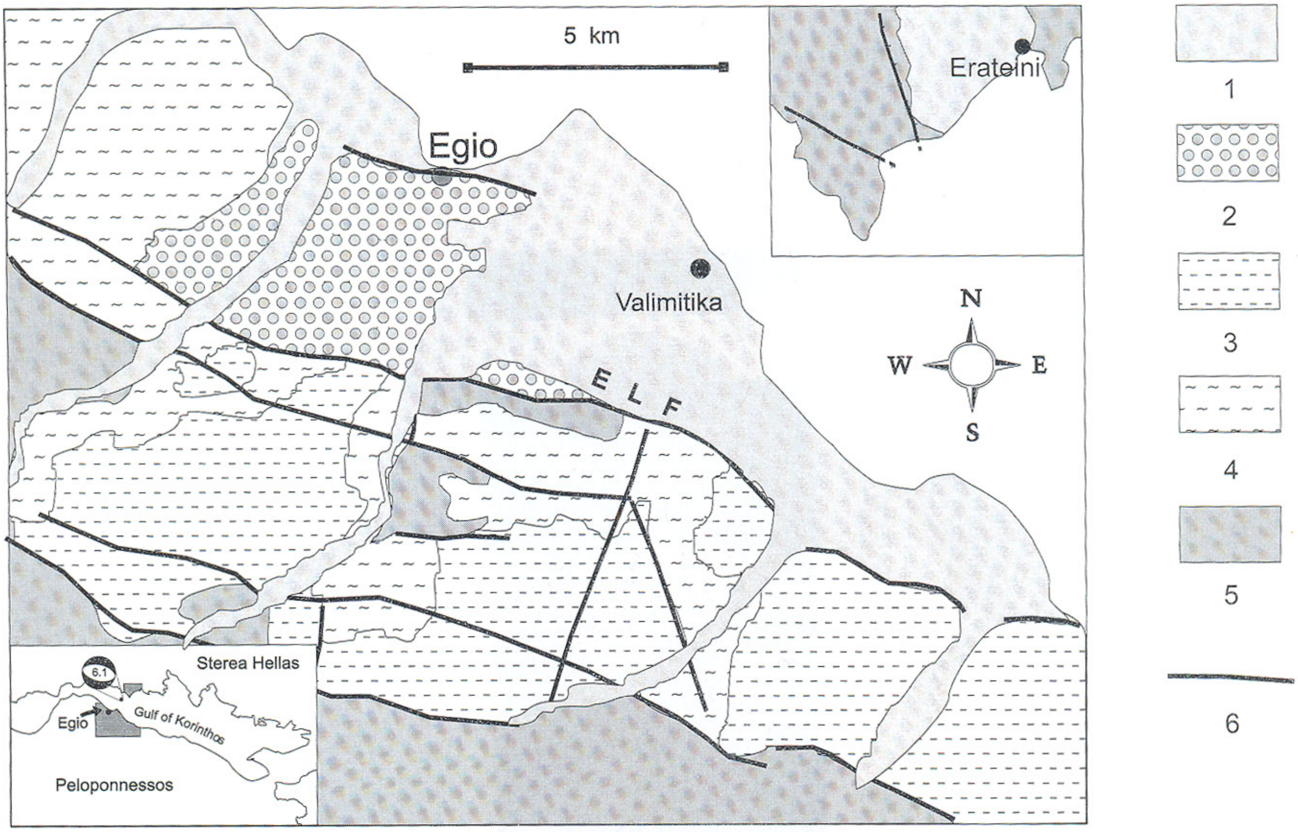

Fig. 1. *Modified geological sketch map after Poulimenos et al., (1993). 1. Alluvial coastal and fan delta deposits (Holocene), 2. M. Pleistocene-Holocene alluvial fan deposits, 3. M. Pleistocene fan delta deposits, 4. L. Pleistocene lacustrine–laggonal deposits, 5. Alpine basement, 6. Faults and fault zones. ELF:Eliki Fault.*

which are of listric character with NNE-dipping fault surfaces (Doutsos and Piper, 1990). A good example of such faults is the Eliki fault (ELF in Fig. 1) that strikes ESE–WSW and has created a distinct scarp, visible for 2 km south of Egio. The footwall of ELF consists of Pleistocene sediments overlying the alpine bedrock, while its hanging wall comprises Holocene fan deposits. Its vertical throw has been estimated at 450 m and has had an average uplift movement rate of 0.25 mm yr^{-1} (Doutsos and Poulimenos, 1992). Although this fault is thought to have been reactivated in the 1861 earthquake (Schmidt, 1875), it remained inactive during the 15 June 1995 shock.

DESCRIPTION OF EFFECTS

Soon after the 15 June 1995, earthquake detailed recording and analysis of observed surficial phenomena (namely liquefaction, ground fissures and coastline changes) was carried out (Fig. 3). These effects were located within a 2-km-wide zone along the northern coast of Peloponnessos. This zone extends from Selianitika and Cape Trypia, to the west and east of Egio, respectively. However, at the southern coast of Sterea Hellas comparable phenomena were limited to a 50 m by 1 km-wide zone at Erateini.

Along the coast of northern Peloponnessos the outcrops comprise coastal sediments, and recent deltaic deposits. The former are highly heterogeneous, consisting of clay-silts, loam, sands and more rarely fine gravel. According to Rozos (1991) their mechanical and physical characteristics are very poor, with internal friction angle $\varphi = 10–40^\circ$ and cohesion coefficient $c = 0.30–1.1$ kg cm^{-2}. The deltaic deposits show similar properties; they consist of gravel and pebbles in sand matrix and have $\varphi = 15–40^\circ$ and $c = 0.0–1.0$ kg cm^{-2} (Rozos, 1991). The fluvial and coastal deposits that occur at the opposite coast of Erateini are of similar sedimentological and mechanical character.

Ground fissures

The main shock created a large number of fissures that damaged roads, open recreational spaces, tourist facilities and light constructions.

The fissures at northern Peloponnessos were located along an 8-km long coastal zone, between the mouths of rivers Selinountas and Vouraikos, along the coast between river Meganeitos and Cape Gyftissa, and along the coast of Avythos, at the west of Egio (Fig. 3). At the opposite coast of southern Sterea Hellas, fissuring was limited to a few surface cracks in thin, localized outcrops of coastal and fluvial deltaic deposits at Erateini (Fig. 6); these fissures did not propagate into the Alpine basement.

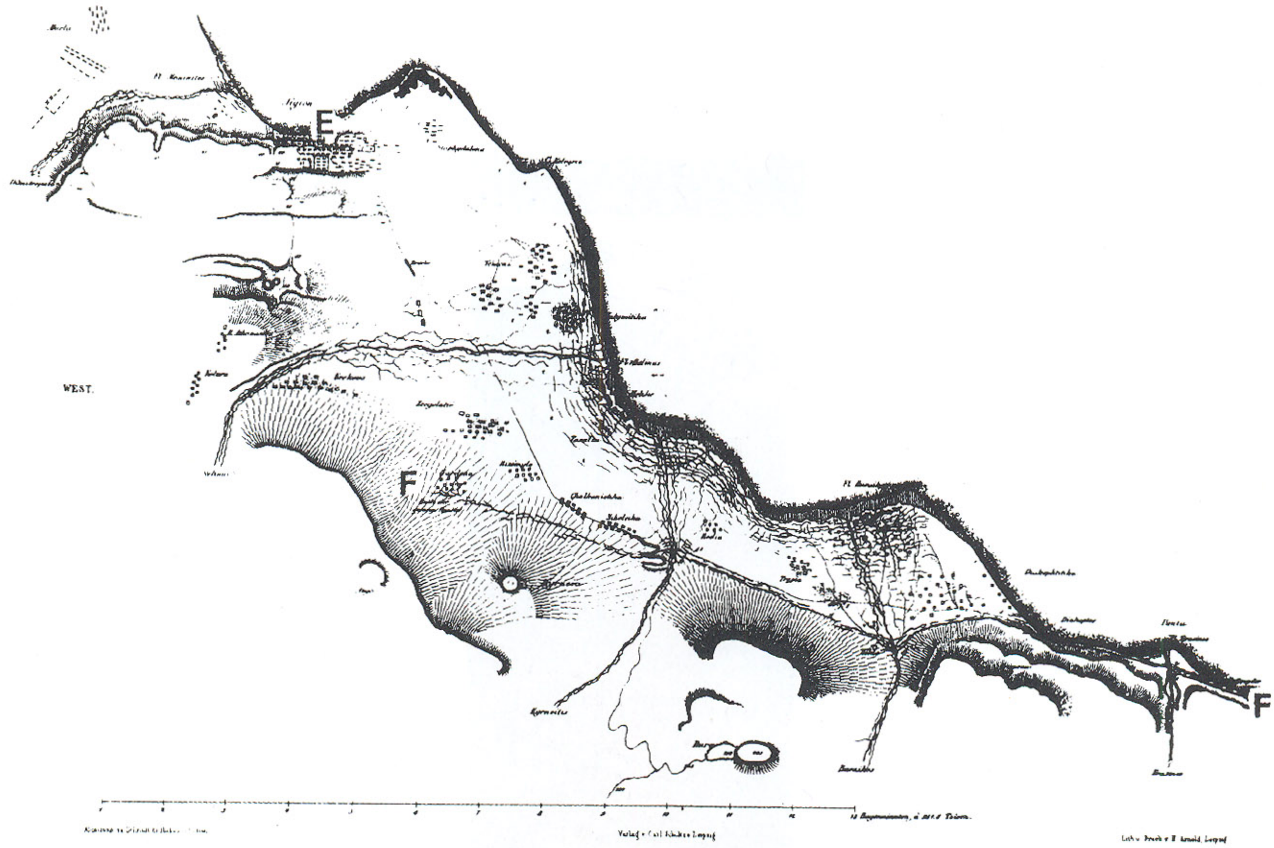

Fig. 2. *The map of the concomitant to the 1861 earthquake phenomena, after Mougiaris et al., 1992 reporting Schmidt, 1875. FF: the postulated fault break; E: Egio.*

The length of fissures varied from a few tens of cm to some tens of m. The cracks were mostly linear, slightly divergent or curved and in some cases *en échelon* arranged. Their width was from a few mm to 40 cm and their visible depth reached 60 cm. In some cases the depth must have been greater, but the open cracks were filled with rubble from the collapsed walls, or with emergent liquefied material. In certain fissures, or segments of them, a minor vertical offset was observed, accompanied by a small dextral or sinistral offset, of few mm or cm.

Systematic study of the trends of the fissures at Egio showed that there were two prevailing sets, one parallel to the coast and one normal to it. Besides, at the cracks located in the river deposits and along the levees, the pattern was similar; however, in this case, the primary set ran parallel to the river bed and the secondary normal to it. No definite geometrical pattern occurred amongst the fissures in the deltaic deposits, but it was relevant either to the one along the coast or at the riversides. In contrast, fissures at Erateini run almost exclusively parallel to the seashore.

In conclusion, the fissures that developed over a large area bore no kinematic affinity with the fault deformation that either directly or indirectly participated in the seismic activity. Instead, they were a by-product of the seismic shaking and their occurrence appears likely to be controlled exclusively by the differential compaction of the loose formations, the lateral instability of the ground masses at the coastal or riverside area, and the differential seismic response of the various unconsolidated phases of the formations.

Liquefaction

The main shock caused widespread liquefaction and extensive areas (10^3 m^2) were covered by the emergent quicksand, causing considerable damage to open recreational spaces, roads, crops, pumping wells and tourist facilities (Fig. 5).

The liquefaction occurred in zones along the coastal area of Egio, and for a width of 400 m, while there were additional liquefaction sites located inland, on terraces 20–100 m high. Liquefaction occurred primarily in the area between the mouths of Selinountas river and Cape Trypia, where Vouraikos discharges, and the coastal zone to the west of Egio (Avythos). In places, too, liquefaction occurred in association with earthquake fractures, as for example at the premises of the Hellenic weapon industry (HWI in Fig. 3). The total liquefaction area amounts to 1 km^2.

In contrast, liquefaction was more limited at the northern coast of the Gulf, at Erateini (Fig. 6). The total area of liquefaction here did not exceed 0.5 km^2.

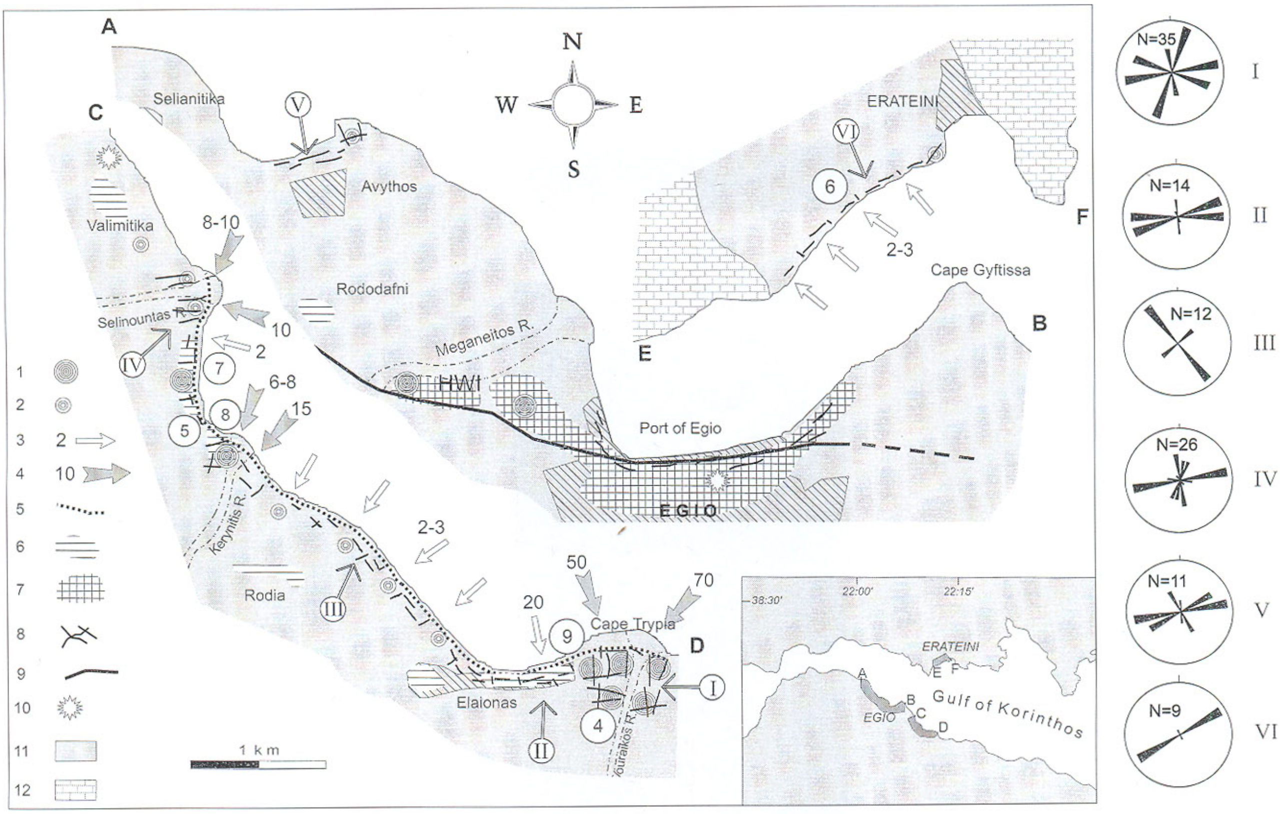

Fig. 3. *Regional map with the occurrences of the earthquake-related surficial effects. 1. Liquefaction (large), 2. Liquefaction (small), 3. coastline retreat (small magnitude) and retreat estimate, 4. coastline retreat (large magnitude) and retreat estimate in metres, 5. post-earthquake shoreline, 6. minor damage areas, 7. major damage areas, 8. ground fissures, 9. earthquake fracture, 10. building collapse, 11. post-Alpine sediments, 12. Alpine basement. HWI: Hellenic Weapon Industry. Latin numerals denote the locations of the rose diagrams of fissures. Numbers in circles indicate approximate locations of figures 4–9.*

The field study confirmed that liquefaction took place at areas consisting of recent formations of coastal, alluvial and fluvial deposits. Quicksand was ejected through: (i) craters, measuring less than 30 cm in diameter, lying along fissures; (ii) craters that lay on the intersection between two or more fissures (their diameter in these cases was up to 50 cm); (iii) the fissures (or parts of them), creating sand ridges, and more scarcely; and (iv) isolated craters up to 50 cm in diameter. It was also reported by farmers that boreholes served as funnels for the upward movement of the quicksand. Mainly fine material (sand and silt) was ejected and more rarely coarser material (fine gravel). In other cases no surficial outflow was noticed, but the liquefied material caused loss of support of the overlying formations which in turn were deformed. Hand-augered cores and sampling showed that the quicksand consisted of sandy clays and clayish sands, that develop from 0.5 to 6 m deep, where augering stopped.

Coastline changes

The shock was accompanied by intense coastline change, with significant coastal retreat in the coastal area between the mouths of rivers Selinountas and Vouraikos, and at the coast of Erateini, causing damage to a few minor harbour constructions, tourist facilities and roads (Figs 7, 8).

The extent of coastline retreat varied throughout the zone. Thus, at Nikoleika (Fig. 8) the sea advanced a few metres, while at the delta of Vouraikos this same change was up to some tens of metres. The most impressive change took place at the coast east of Eleonas, up to Cape Trypia, where the recent deltaic deposits of Vouraikos river and coastal deposits occur. At this place, the sea advanced inland for about 50 m at the east of the hamlet and the total width of the land inundated by the sea is more than 70 m at Cape Trypia (Fig. 9). As a result, large parts of the shore do not exist any more. This change gradually becomes smaller heading to the west of Eleonas, being less than 10 m at the mouth of Selinountas, and finally becoming negligible at Valimitika.

On the north coast of the gulf at Erateini the sea progressed for about 3–4 m where recent fluvial deposits occur, while where the Alpine basement crops out no such change was observed.

The observations along the northern and the southern coasts of the Gulf showed that no generalized subsidence occurred. The coastline changes were due either to rearrangement of the packing in the Holocene formations because of seismic shaking, or to small-scale submarine slumping with simultaneous loss of lateral support. That is why the magnitude of coastal retreat at the river mouths was higher, where sediments of very low cohesion factor (c = 0.0–1.0 kg cm^{-2}) occur.

HISTORICAL DATA

The region around Egio has repeatedly suffered the devastating effects of earthquakes. One of those cases was the event of 373 BC during which the town of ancient *Eliki* that lay about 7 km to the east of the modern city, was practically razed. According to the ancient historians Pausanias and Strabo, the devastation was augmented by the sudden subsidence that took place – possibly connected with liquefaction – and the creation of large tidal waves (Mougiaris, 1987; Mougiaris *et al.*, 1992). It should also be noted that 150 years after the earthquake of 373 BC, temples and statues lay at the sea bottom (Xinopoulos, 1912; Stavropoulos, 1954). Historical reference is also made to the earthquakes of 1746 and 1817 when Egio was destroyed by the shocks and the ensuing tidal waves, though no evidence of fissuring, liquefaction or coastal changes are documented for these events.

Finally, as for the earthquake that hit Egio in 1861, there are not only written reports on the destruction, but also comprehensive mapping of the earthquake-related surficial effects, by Schmidt (1875) (Fig. 2). In that map, ESE–WNW trending fractures have been depicted, coinciding possibly with the trace of the Eliki fault zone (Mougiaris *et al.*, 1992). Schmidt's study confirms the seismogenic reactivation of the fault zone during that event (Figs 1, 2). Furthermore, coastline change, ground fissuring and liquefaction took place. The phenomena that occurred in the 1861 earthquake were located at the same zones as observed in the 1995 earthquake (Figs 2,3).

As far as Erateini is concerned, the same phenomena, coastline retreat and ground fissures, occurred during the

Fig. 4. *Ground fissures along the road, to the east of Egio. The prevailing trends are directly related to the direction of the nearby river bed of Vouraikos.*

Fig. 5. *Liquefaction at the east of Egio, inside a tourist facility.*

Fig. 6. *Liquefaction and ground fissures at the coast of Erateini. The aquifer at this site was saline, a fact that led to the deposition of thin salt layers (after the evaporation) together with the quicksand.*

1965 (M = 6.4 R) earthquake. According to Tataris (1965) a 350 m-long fissure occurred along the coast of the town. This fissure did not propagate into the Alpine basement and was attributed to ground shaking; besides, the magnitude of coastline retreat was up to 25 m, caused by local slumping.

DISCUSSION AND CONCLUSIONS

The area around Egio has repeatedly paid the toll of earthquake activity in the western Gulf of Korinthos, at least since the ancient times. The recent event of 15 June 1995, measuring M = 6.1 R in the surface Richter magnitude scale (Ms), caused the death of many people and produced extensive damage both inside the town of Egio and in the broader area of Northern Peloponnessos – Southern Sterea Hellas. A large proportion of the damage caused in the region was due to the occurrence of earthquake-related surficial effects, such as liquefaction, ground fissures and coastline change. The shock destroyed mainly roads, recreation areas, tourist and agricultural facilities, and other small-scale constructions.

The earthquake-related surficial effects occurred where deltaic and coastal formations outcrop, mainly along the coastal zone to the east and west of Egio. The fact that the earthquake of 1861 led to similar phenomena at approximately the same locations confirms the crucial impact of the sedimentological characteristics on the spatial distribution of ground deformation. It is also noteworthy that no such association was observed in the areas where other (non-surficial) geological formations crop out. Besides, the effects seem to have been located at the hangingwall of the then reactivated ELF; however, according to Lykoussis *et al.* (1995), the seismogenic fault of the 15 June 1995 earthquake was an offshore one.

Comparable phenomena at Erateini were significantly limited, which is attributed to the smaller outcrops of the post-alpine formations there.

The correlation between the outcrops of certain geological formations and the selective occurrence of the earthquake-related surficial effects may constitute a

Fig. 7. *Submerged jetty due to coastline retreat (east of Egio).*

Fig. 8. *Damage at a seaside road, caused by coastline retreat (Nikoleika, east of Egio).*

Fig. 9. *Photograph taken a few days before the June 15 earthquake, at Elaionas, east of Egio. The dashed line shows the post-earthquake shoreline. The retreat is as much as 50 m.*

guide for urban planning and land use, not so much in the aspect of the restriction of development of certain activities, as construction and tourist development, but from the viewpoint of the adaptation of these activities in the geodynamic singularities of the area.

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