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D. MOORE

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O. HUNGR

*The University of British Columbia, Department of Earth and Ocean Sciences, Vancouver,
British Columbia, Canada*

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Deformation structures at Gulf of Corinth, Greece induced by the Egean earthquake of 1995

I. Mariolakos, I. Fountoulis, D. Mariolakos

Div. Dynamic Tectonic Applied Geology, Dept. of Geology, University of Athens, Greece.

ABSTRACT: On 13-6-1995 an earthquake of $M_s=6.1$ R struck the northwestern (Eratini area) and the southwestern (Egean area) coasts of the Gulf of Corinth (Greece). The epicenters of the main shock as well as the aftershock were located at the northwestern coast of the Gulf very close to Eratini village. Many geodynamic phenomena were observed during the seismic activity as: seismic fractures, liquefaction phenomena, submarine landslides, shoreline displacement and tsunami. Our interest is focused at the Eratini area in which between the already mentioned phenomena, pop-up like deformation structures observed. The study was based mainly on their trend, and shape. The whole deformation has been interpreted taking into account (i) the active faults of the bottom of the Gulf of Corinth, (ii) the data of the last seismic event, and (iii) the geodetic data (GPS) after the earthquake. Pop-ups like structures most probably are related to a kind of transpressional deformation.

RESUME: Le 13-6-1995 un seisme de magn.= 6.1R, frappa la cote nordouest, (region de Eratini) et la cote sudouest, (region de Aegion), du Golfe de Corinthe, (Grece). Les epicentres du seisme principal, ainsi que ceux des metaseismes, sont localises a la cote nordouest du golfe, tres pres du village de Eratini. Plusieurs phenomenes geodynamiques ont ete observes durant l'activite seismique comme: fractures seismiques, phenomenes de solifluction, Glissements de terrain sous-marins, deplacements des lignes de cote et tsunami. Notre interet est focalise a la region de Eratini a laquelle, parmi les phenomenes deja mentionnes, nous avons observe des structures de deformation du type "pop-up". L' etude a ete basee principalement a leur direction et a leur forme. Toute la deformation a ete interpretee en tenant cmpte: (i) les failles actives du fond du golfe de Corinthe,(ii) des elements du dernier evenement seismique et (iii) les elements geodetiques,(GPS), apres le seisme. Les structures du type pop-up doivent probablement etre liees a une espece de deformation de type "transpressional".

1 INTRODUCTION

On 13-6-1995 at 03:16 local time (00:16 Greenwich time) an earthquake of $M_s=6.1$ R struck the northwestern (Eratini area) and the southwestern (Aegion area) coasts of the Gulf of Corinth. Sixteen minutes later (03:32 local time) an aftershock of $M_s=5.6$ R followed. The epicenters of the main shock and the aftershock were located at the northwestern coast of the Gulf very close to Eratini village (Fig. 1) (NOA, 1995, Bernard *et al.*, 1997). According to the fault plane solution given by the NOA 1995, the seismogenic fault is a normal fault with a dextral horizontal component of movement, striking E-W (NOA, 1995).

The seismic activity caused many damages at Egean area (N. Peloponnessos) and some damages at Eratini area (Southern Sterea Hellas), while twenty nine people lost their lives due to the collapse of two buildings, one in Egean and another in Valimitika village, eastern of Aegion.

Many geodynamic phenomena were observed during the seismic activity as: seismic fractures, liquefaction structures, submarine landslides, shoreline displacement and tsunami. The above mentioned geodynamic phenomena were observed mainly at the coastal area around Aegion to the south and Eratini to the north, and resulted the amplification of the damages. In this paper we focus our interest at the Eratini area in which between the

already mentioned phenomena, pop-up like deformation structures observed.

2. GEOLOGY

The formations occurring at the Eratini major area can be distinguished into two major categories, alpine and post-alpine.

The alpine formations belong to Pindos geotectonic unit and they consist mainly of Early Cretaceous chert and limestone alternating with red shales, Late Cretaceous thin-bedded pelagic limestones and flysch formation (sandstones, marls, etc.) and to Vardussia geotectonic unit consisting of pelagic carbonates and clastic sediments (Celet, 1976), (Fig. 2).

The post alpine formations consist of Quaternary continental deposits in the form of talus, scree, and coastal deposits. The basement of the post alpine deposits at the Eratini area is flysch formation, while at the area western of Eratini (Agios Nikolaos, Agios Spyridon) consists of thin-bedded pelagic limestones.

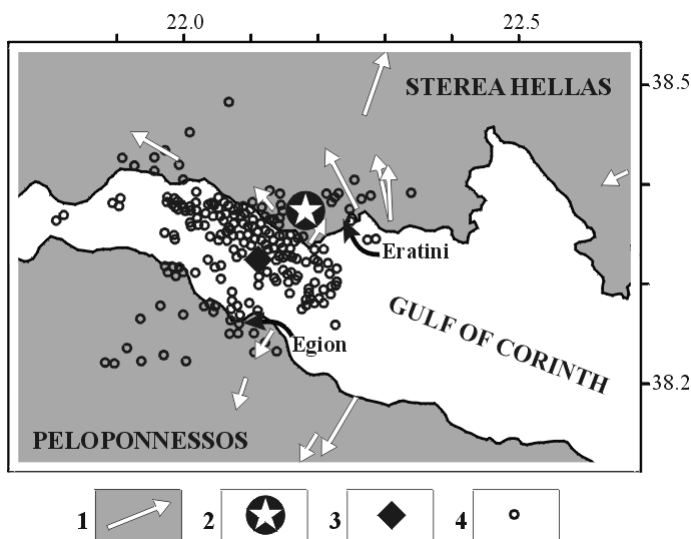


Figure 1 Earthquake activity for the period 15-6-1995 to 17-7-1995 in Western Gulf of Corinth (Modified from NOA, 1995) and the observed horizontal displacement for the 15-6-1995 Egion earthquake (Modified from Bernard *et al.*, 1997). 1:horizontal displacement, 2:epicenter of the main shock, 3:epicenter of the aftershock, 4:epicenter of aftershock.

TECTONICS - NEOTECTONICS

In the study area two geotectonic units occur. The Vardussia unit overthrusts the Pindos unit. The mean strike of the thrust is NW-SE. Furthermore, the fold axes occurring in the limestones as well as in the flysch formation of the Pindos unit strike also NW-

SE. Only in Agios Spyridon area, the fold axes strike N-S (Fig. 2). The thrusts or reverse faults occurring within Pindos unit strike in the same direction with the fold axes (NW-SE), while the axial planes of the folds are dipping towards NE. All these structures were created mainly in pre Late Miocene times.

Concerning the neotectonics of the major area, the Gulf of Corinth is a narrow strip of sea that separates Peloponnessos from the rest of continental Greece (Fig. 2). It constitutes a typical post-alpine basin trending WNW-ESE, that is perpendicular to the geometry of the alpine geotectonic units and the Hellenic trench system as well. According to most researchers (Heezen *et al.*, 1966, Brooks & Ferentinos, 1984) the Gulf of Corinth constitutes an asymmetrical tectonic trough, the formation time of which is unknown exactly; however it must be between Late Miocene and Early Pliocene. The evolution of the basin is controlled by faults of normal character. These faults caused uplift of the Pleistocene marine deposits for more than 1.000m in Northern Peloponnessos, while in Southern Sterea Hellas there is no sign of Plio-Quaternary marine deposits, and only continental deposits of small thickness occur. This is an indication that Sterea Hellas is continuously under a subsiding regime and for this reason no post alpine marine deposits occur along the northern coast of the Gulf of Corinth. Consequently, there is a migration of the Gulf of Corinth northwards, most likely since Early Pleistocene, with a synchronous uplifting of northern Peloponnessos. Worth to mention is that the uplifting rate of the northern Peloponnessos is different from east to west, that means that it increases from Corinthos city (east) as far as the area of Diakofto (center), whereas decreases towards west as far as Patra (west).

The study of the Quaternary deformation of the area around the Gulf of Corinth revealed that the faulting as well as the morphology of the coast is the result of rotation phenomena (Freyberg, 1973, Mariolakos, 1976, Mariolakos *et al.*, 1985, Mariolakos & Papanikolaou, 1987). Furthermore Kelettat *et al.*, 1976, 1978, Mariolakos *et al.*, 1989, 1991, 1994, suggest that certain blocks have been subjected to rotation at the southern Peloponnessos as well.

The western part of Gulf of Corinth graben is controlled by two major fault zones that are located along the southern and northern continental shelf of the Gulf. These fault zones strike ESE-WNW, and consist of faults striking E-W in an echelon arrangement. The vertical displacement along the

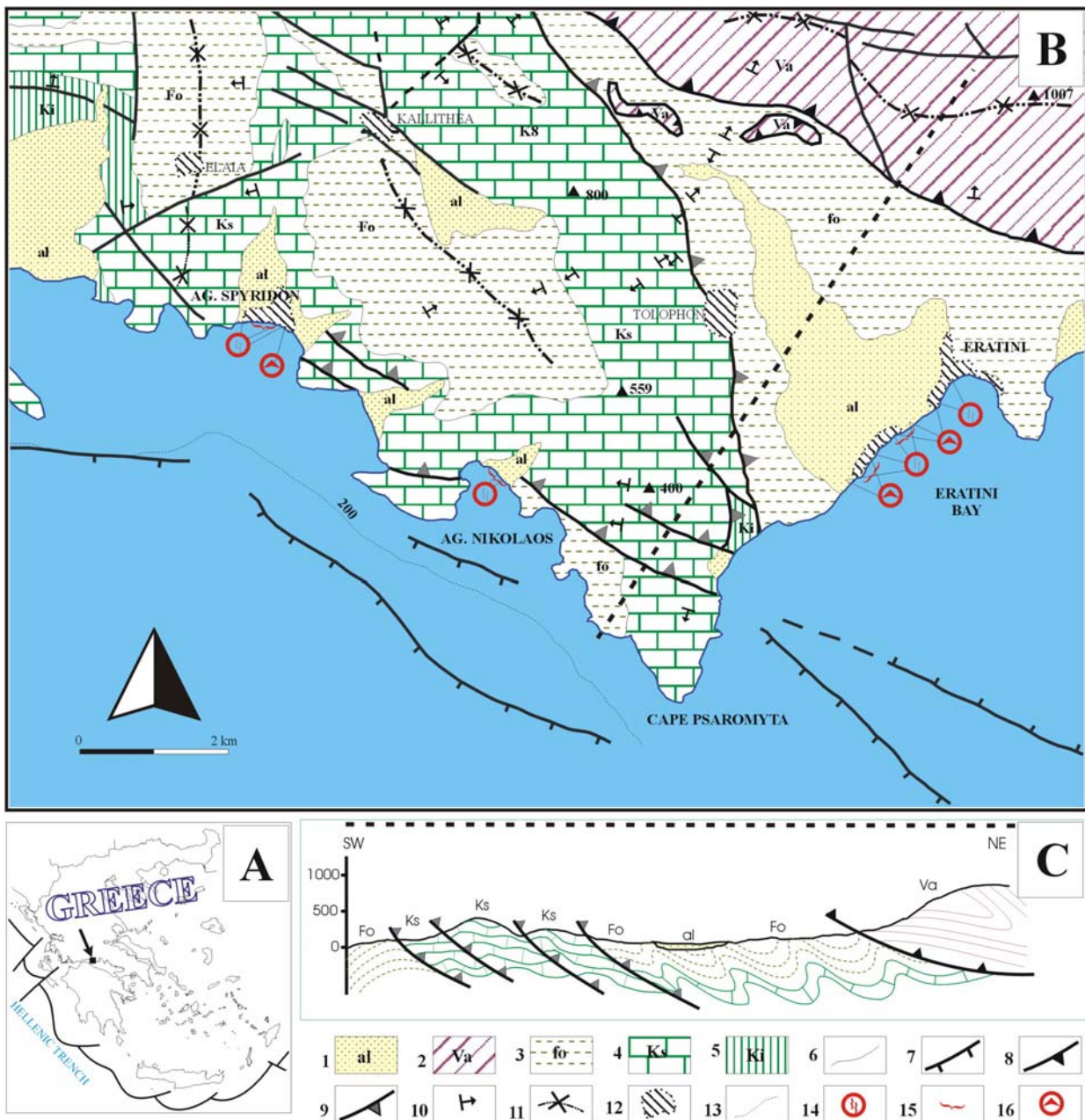


Figure 2 The study area (A), Geological and Structural sketch map (B) (modified from Paraschoudis, 1977). 1:Holocene deposits, 2:Vardousia unit, 3,4,5:Pindos unit (3:flysch, 4:thinbedded limestones, 5:alternations of cherts, limestones and red shales), 6:geological boundary, 7:submarine active faults (modified from Papanikolaou et al., 1997), 8:overthrust, 9:thrust, 10:strike and dip of strata, 11:fold axis, 12:urban area, 13:isobath contour, 14:seismic fracture, 15:shoreline displacement, 16:pop-up like structure

fault zones is small at the western part of the Gulf and increases towards east in more than 500m.. The eastwards increasing of the vertical displacement along the submarine fault zones coincides with the increasing of the Gulf depth and the thickness of the Plio(?) – Quaternary deposits (Papanikolaou *et al.*, 1997). The en echelon arrangement of the faults consisting the fault zones is observed in both submarine and continental areas (Papanikolaou *et al.*, 1997).

3. MACROSEISMIC OBSERVATIONS – GEODYNAMIC PHENOMENA

At the northern coasts of the Gulf, the geodynamic phenomena were restricted in a very narrow zone along the coast of Eratini, Agios Nikolaos and Agios Spyridon villages. The observed geodynamic phenomena were seismic fractures, shoreline displacements (mainly subsidence of the coasts), landslides, and liquefaction phenomena.

3.1 Seismic fractures – pop up like structures

a) Agios Spyridon

Many seismic fractures were observed at Agios Spyridon striking parallel and perpendicular to shoreline, that is (E-W and N-S correspondingly). The seismic fractures that strike parallel to the coastline (E-W) were observed mainly at the central coastal part of the village on the asphalt track. They were open and they contributed to the loss of the coast for a length of more than 100m.

The seismic fractures, which strike perpendicular to the coastline (N-S), were observed at the western entrance and the central part of the village. These fractures cut the asphalt track as well as the cemented mole. At the western part they have a length of 5m and in some cases they cut also the gravel particles inside the asphalt track.

At the central part of the village a very impressive phenomenon was observed: there were two PVC pipes of about 15cm diameter inside the cemented mole. One of them was striking parallel to the coastline (E-W), whereas the other one perpendicular (N-S). The first one had been deformed to a «fold» (Fig. 3) in other words the pipe was curved forming an «anticline» that means shortening in an E-W direction (Fig. 4). The pipe of N-S direction has been deformed in a ductile way so that its circular shape was deformed to an ellipse, with the big axis vertical and the small axis

horizontal, striking E-W. In the same time the floor-stone couplets which covered the cemented mole and at the area above the deformed pipes had overthrust each other or had been dislocated in a pop-up like way. All these give us the sense that in this site the deformation took place under a compressional stress field in an E-W direction. At this point we have to mention that the fold axis of Pindos unit strike approximately N-S at the area located western-northwestern of Agios Spyridon village.

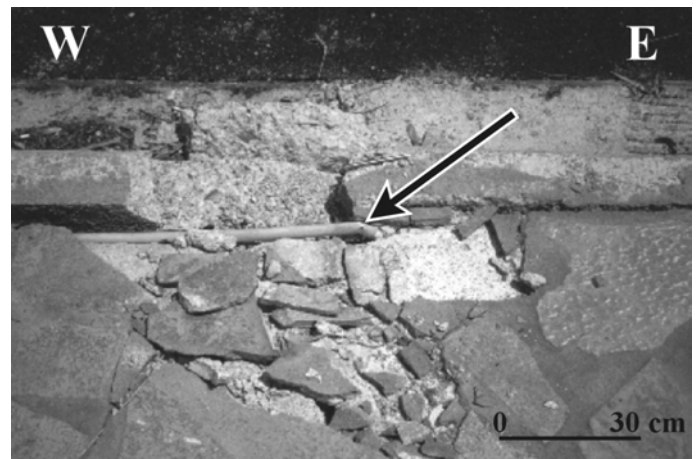


Figure 3 PVC pipe within the cemented groundwork deformed like an «anticline» in Agios Spyridon



Figure 4 The original circular shape of a PVC pipe deformed to an ellipse.

In Agios Nicholaos village the fractures were restricted in the coastal area and especially at the harbor. Most of them were open, parallel to the mole and caused damages to the nearby old or new buildings.

b) Eratini

Along the seaside from Tolophon area to Eratini village many seismic fractures parallel (NE-SW) and perpendicular (NW-SE) to the coastline were

observed. The seismic fractures that strike parallel to the coastline (NNE-SSW) were observed mainly on the asphalt track as well as on the cemented mole. They were open and they contributed to the shoreline loss for a length of more than 150m.

The seismic fractures that strike perpendicular to the coastline (NW-SE) cut the cemented mole. More specifically, squared floor-stone couplets were placed on the top of thick cemented mole that has been founded on loose coastal and deltaic deposits. The cemented groundwork was fractured during the earthquake and in many cases the upper part moved southwards resulting the dislocation of many floor-stone couplets in pop-up like structure (Fig. 5). In the same time a large pipe (50cm in diameter) was crushed and squeezed and finally shortened in an almost NE-SW direction (Fig 6). The seismic fractures have the same strike with the fold axes and the upthrusts occurring in the area.



Figure 5 Pop up like structure due to 15-6-1995 earthquake in Eratini.

3.2 Shoreline displacements - landslides

The shoreline displacement was not uniform along the whole length of the coastal area, but it changed from place to place. In several sites the sea has transgressed the land only for some meters due to sinking off the ground.

In Eratini area the transgression of the sea was not more than two or three meters in sites where river and coastal deposits occur (Fig. 7). In this point it should be stressed that shoreline displacement was also observed in coastal areas where alpine rocks occur. At this point it should be stressed that Bernard *et al.*, 1997 mention that a subsidence of 144mm has been measured using GPS in the affected by the earthquake area at cape Psaromyta.

This subsidence is referred for time period between 1991-1995 (after the earthquake).

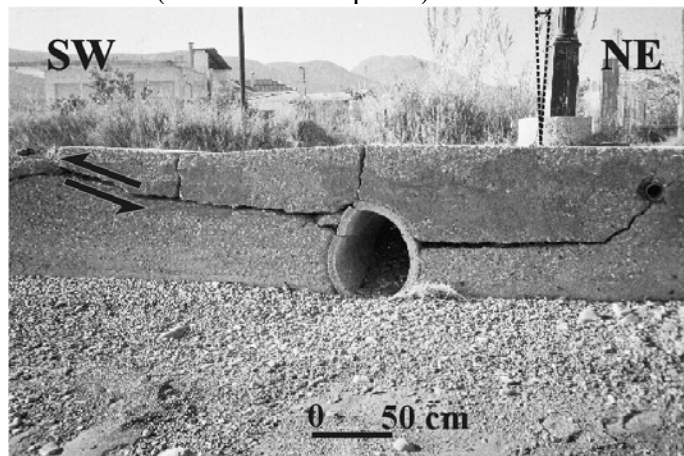


Figure 6 Fracturing of the cemented mole. The large pipe was squeezed and shortened in NE-SW direction.

Taking into account the described shoreline displacements, it is believed that there is no any general submerge of the coasts that caused the transgression of the sea in land. These shoreline displacements were mainly caused due to several submarine landslides very close to the coast, as well as due to liquefaction phenomena.

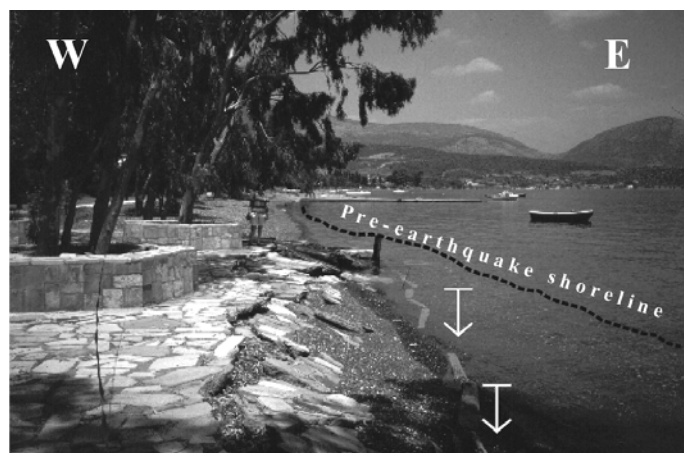


Figure 7 Shoreline displacement of the Eratini coast due to the 15-6-95 earthquake activity.

The earthquake has not caused any remarkable landslide at the major area. Only few small landslides, as well as rock falls were observed only in artificial road-slopes. The landslides and the rockfalls didn't have any systematic geographical distribution.

On the other hand, many submarine landslides were observed and mapped by submarine geophysical survey. The most of them are located close to the coastal areas where shoreline displacement occurred. Submarine landslides during

an earthquake, have been described at Aegion harbor and Eratini in older times (Tataris, 1965).

4 DISCUSSION - CONCLUSIONS

In order to comprehend the ongoing geodynamic procedures in the area, we need to bear in mind the following remarks:

1. Mainly alpine sediments as well as structures occur in the study area.
2. No neotectonic fault zones forming grabens or horsts occur at the study area.
3. No sign of fault reactivation was observed.
4. The described pop up like structures in Eratini and Agios Spyridon villages have the same strike (geometry) with the existing tectonic features (fold axes, thrusts, overthrust).
5. Most of the epicenters of the aftershocks were located western of the epicenter of the main shock forming zones more or less parallel to the coast-line between Cape Psaromyta and Agios Spyridon to the upthrusts strike and to the submarine fault zones (Fig. 1). The aftershocks define a zone about 20km WNW-ESE and 10km NNE-SSW, north-east of Egion (Eratini area) and they are mostly clustered between 5 and 9km in depth (Bernard *et al.*, 1997).
6. The shoreline displacements occurred in young loose deposits should be caused due to differential compaction of the loose material, to liquefaction phenomena, or to sub-marine landslides (Papanikolaou, *et al.*, 1997). On the contrary, the measured with GPS subsidence of the Cape Psaromyta, in which only thin-bedded limestones occur, can be explained by the tectonic deformation of the area.
7. According to Bernard *et al.*, 1997, the seismogenic fault is a low angle fault striking E-W and dipping towards north. The focal mechanism indicates fault of normal character with a horizontal component of movement.
8. Furthermore, the measured horizontal displacement using GPS is very clear in N-S direction but in the same time there is a serious horizontal displacement in NW-SE direction (Fig. 1).

Taking all these into account it is believed that the reactivated fault most likely occurs at the submarine area, southern of Eratini, representing an old thrust surface which now is active in an opposite way that is a fault surface of normal character due to a more composite regional stress field. Within this stress field local transpressional and transtensional

stress fields can be produced. Due to such a local transpressional stress field pop up like structures as well as compressional structures can be produced. Nevertheless, taking into account the observations have been made for the affected area, no fault reactivation was observed offshore at the southern margin of the Gulf of Korinthos.

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