

Evaluation of active faulting and earthquake secondary effects in Lefkada Island, Ionian Sea, Greece: an overview

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Abstract Based on neotectonic mapping, analysis of active deformation through tectonic data and the Coulomb stress changes caused by major earthquakes, the active faults in Lefkada Island were evaluated. Descriptions of historic and recent earthquakes were also taken into consideration as well as the seismotectonic data concerning the last strong seismic event of 2003. According to detailed field observations, among the active and neotectonic faults that have been identified, regarding seismic hazard, the most important can be considered the Athani fault. It is running parallel to and near the west coast and shows marked similarity with the northern branch of the offshore transform fault of Kefalonia-Lefkada. These two dextral strike-slip faults exhibit same structure and state of stress as well. Moreover, the Coulomb stress changes associated with the 2003 earthquake, well correlated with the spatial aftershock pattern, are positive in the area of the Athani fault. Attention has been also focused on the geologic hazard in relation to earthquake associated phenomena, such as surface rupturing, landslides and rockfalls, liquefaction and tsunamis. The fact that surface deformation is repeated in an identical way during past and recent earthquakes provides a great advantage for the seismic protection of the island.

Keywords Neotectonic mapping · Active faulting · Earthquake hazard · Lefkada earthquake · Athani fault

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1 Introduction: geological setting

The island of Lefkada in the central Ionian Sea presents a high seismicity and is characterized as Class III (the highest) according to the Seismic Hazard Map of Greece (EPPO 2003). The island's seismicity is due to the fact that Lefkada holds a key position in western Greece, where the Hellenic subduction in the South passes to the Adriatic collision in the North, through the right-lateral Kefalonia fault (also called Kefalonia-Lefkada Transform fault – KLTF). This fault runs a few kilometres offshore the west coast of Lefkada and is associated with most seismic events occurring in the area (Fig. 1). It consists of at least two segments: the northern (Lefkada segment), striking NNE-SSW, which is approximately 40 km long, and the southern (Kefalonia segment), striking NE-SW, 60 km long.

The dextral strike-slip character of KLTF was determined by Scordilis et al. (1983) on the basis of the fault plane solutions of the 1983 Kefalonia earthquake and confirmed by Kiratzi and Langston (1991) and Papadimitriou (1993). Papazachos et al. (1998) gave the mechanism for the Lefkada segment, with strike equal to 11° , dip 60° and rake 165° . Recent seismic and seismological marine surveys performed in the area of the KLTF (Kokinou et al. 2006) have shown that the segment west of Lefkada has a NNE-SSW direction, a steep eastern dip and the characteristics of a strike-slip fault. The same authors noted the presence of many faults with similar geometric characteristics and successive reactivations that exhibited either a normal or a reverse motion component. This differentiation to the convergent or divergent character of the fault movement has been also determined by the focal mechanism of the earthquakes. Indeed, the KLTF had a slight

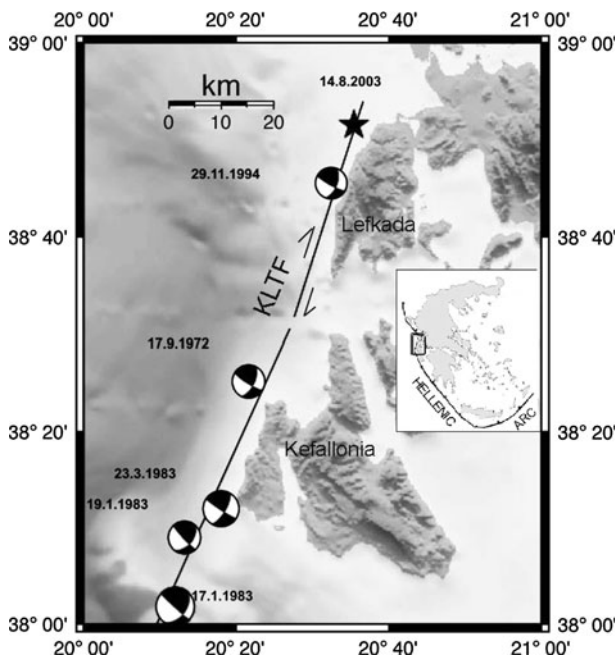
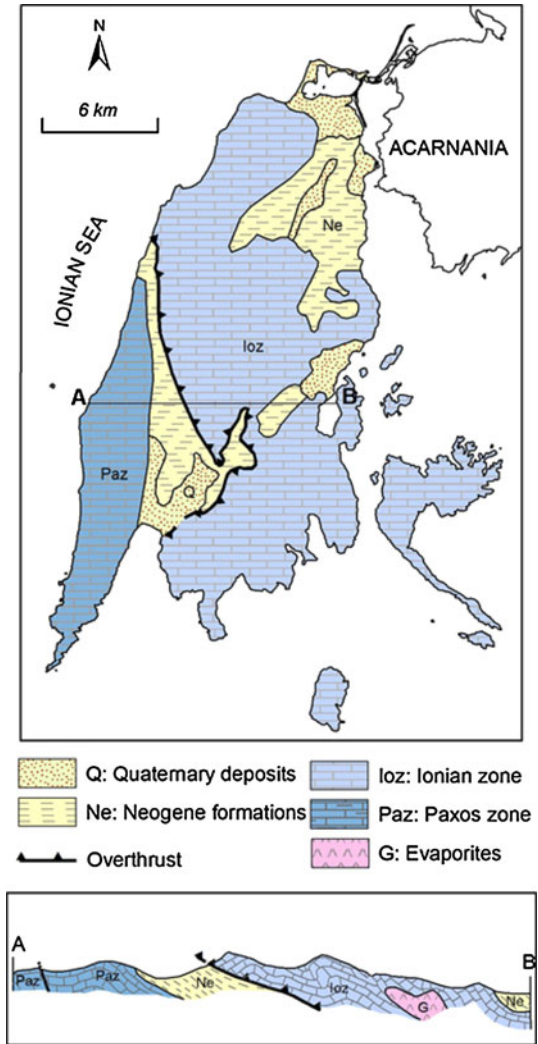


Fig. 1 The Kefalonia-Lefkada Transform Fault (KLTF) and the focal mechanisms of large earthquakes since 1970 (after Papadimitriou et al. 2006, slightly modified). *Inset* the Hellenic arc is illustrated, and the map area is indicated by the *small rectangle*

Fig. 2 Simplified geological map and geological cross-section (AB) of Lefkada island



reverse component during the 1983 earthquake and a slight normal component during the 2003 earthquake.

The wider area has undergone multiple tectonic processes that have led to a steep relief and a complex geological structure (Bornovas 1964; I.G.R.S.-I.F.P. 1966; B.P. 1971; Underhill 1988). Additionally, the deformation style is amplified by the presence of evaporites. Morphologically, Stavrota mountain (1,140 m) dominates the central part of the island and Skaroi (673 m) the eastern part. From a geotectonic point of view, the largest part of the island of Lefkada belongs to the Ionian zone, while its western part belongs to the Paxos (or Preapulian) zone (Fig. 2). This zone is characterized by limestones and dolomites covered by neogene clastic sediments, mainly marls and sandstones. The Ionian zone starts with evaporites, followed by dolomites, limestones and siliceous schists partly covered by flysch of Oligocene-Middle Miocene age. The neogene sediments consist of conglomerates, sandstones, marls and marly limestones. Quaternary sediments

outcrop to a very limited extent, a characteristic difference compared with the other Ionian Islands, where pleistocene marine and lacustrine deposits have a great extent. Recent geological formations are, however, worth noticed, because of the serious instability problems they often cause. Extended deposits of talus scree crop out mainly in the western and southern part of the island, where rockfall and landslide phenomena are very frequent, particularly triggered by strong earthquakes.

The geodynamic evolution of the area was associated, for the largest part of its geological history, with the dominant compressive stresses expressed in the formation of numerous folds and thrusts. The axial distribution of synclines and anticlines discloses the role of evaporites in the tectonic detachment of sedimentary rocks. The largest compressive structure created during the neotectonic stage is the overthrust of the Ionian zone onto the Preapulian zone (Ionian overthrust) (Figs 2, 3). This is a structure presently considered inactive, as the compression front is identified further to the west, in the offshore area (Sorel 1989). From offshore sections compiled in the region of the central Ionian Sea, a number of important tectonic structures were also identified, such as the Ionian overthrust, backthrusts within the crust, diapirism and normal faults (Sorel et al. 1976; Le Pichon and Angelier 1979; Monopolis and Bruneton 1982; Mascle et al. 1984; Poulos et al. 1999; Clement et al. 2000). Regarding the interpretation of the region's geodynamics, Cushing (1985) and Sorel (1989) have attributed the island's recent deformation to NE-SW striking compressive stresses that have been associated with the evolution of the KLTF and have created the island's updoming, while normal faults have been interpreted as structures created by local stresses at the crest of this updoming.

The present work is based on geologic investigation aiming to identify the nature of faulting, to determine and characterize the active faults and to evaluate their future seismic behaviour. Additionally, historic and recent earthquake data were taken into account, and the Coulomb stress changes produced after seismic fault rupture were calculated. Special emphasis was given on the mapping and studying of the Athani fault, because of: (1) the similarity of its geometric and dynamic characteristics to those of the offshore KLTF, (2) the elevated seismic intensities noted in its proximity during most strong earthquakes and (3) the calculated Coulomb stress changes suggest that the 2003 earthquake may encourage future rupturing on this fault.

2 Methodology

The identification of active faults was based on geological, geomorphic and tectonic data. Factors contributing to assessing the age of the latest fault activity were: the tectonic displacement of late quaternary deposits, the landforms and the geomorphic indications of the region and the freshness of the faults' surfaces, as well as their dynamic characteristics. For the processing of the tectonic striations measured on the fault surfaces, the GEOLDYSOFT software (Carey and Mercier 1987) was used. Further information was provided by historic data about the island's seismic damages as well as by new seismotectonic data after the 2003 event.

For the Coulomb stress changes after each seismic rupture, the Coulomb 3.1 software of the U.S. Geological Survey was used (King et al. 1994; Toda et al. 1998). The Coulomb 3 is designed to investigate Coulomb stress changes on mapped faults and earthquake nodal planes and to estimate how an earthquake promotes or inhibits failure on nearby faults. Calculations are made in an elastic halfspace with uniform isotropic elastic properties, following Okada (1992). When an earthquake reduces the average value of the shear stress

on the fault that slipped, shear stress rises at sites in addition to the fault tips. The Coulomb failure stress change, D_{sf} is defined as:

$$D_{sf} = D_t + m(DP + D_{sn})$$

where D_t is the shear stress change on a fault (reckoned positive in the direction of fault slip), D_{sn} is the normal stress change (positive if the fault is unclamped), DP is the pore pressure change in the fault zone (positive in compression) and m is the friction coefficient (with range 0–1). Failure is encouraged if D_{sf} is positive and discouraged if negative; both increased shear and unclamping of faults promote failure.

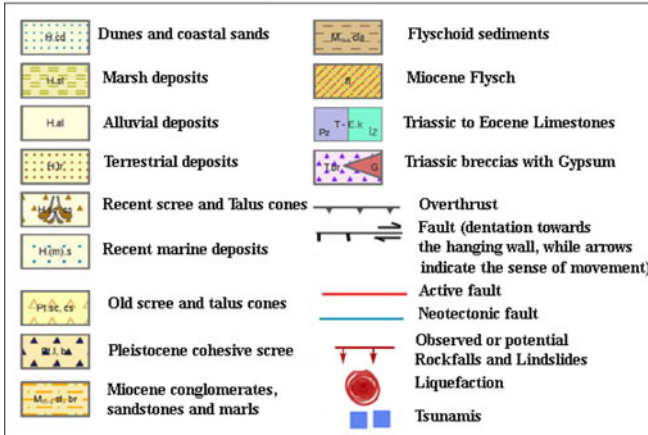
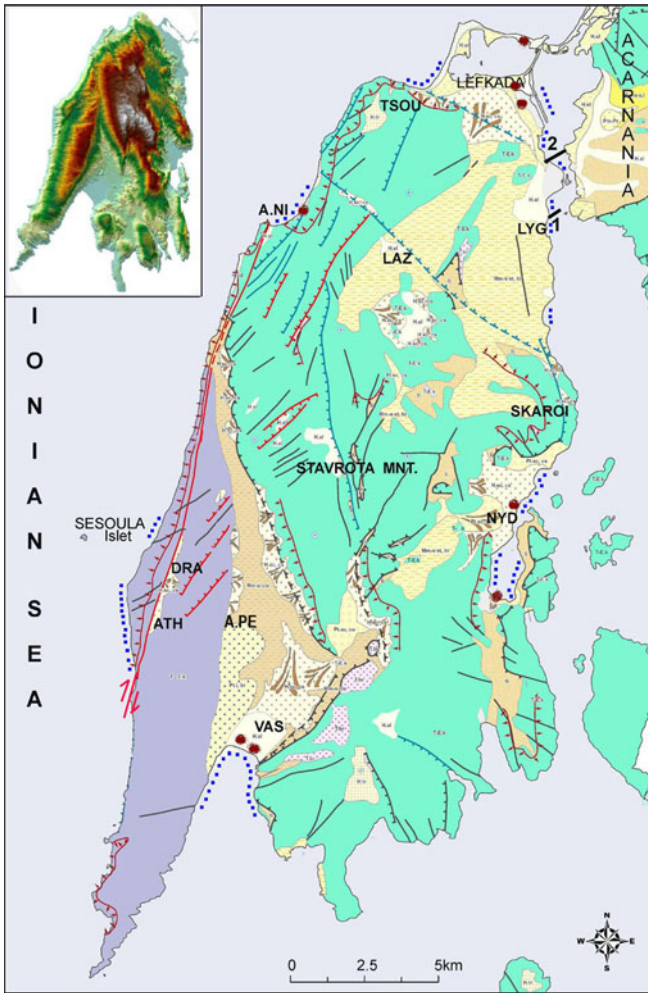
Data processing was based on Matlab 7.X and latest versions. Entry files have been created starting from the chronologically first seismic rupture with the addition of one rupture at a time. As a result of the superposition principle, assuming linear elastic behaviour of the crust, the Coulomb stresses caused by each subsequent rupture were added to the stresses calculated from previous and all preexisting ruptures.

3 Fault evaluation

The neotectonic fault pattern in Lefkada consists of a large number of faults, mainly “inherited” from older tectonic phases. They present well formed polished surfaces in preneogene limestones and dolomites, and on their hanging wall, different generations of breccias are accumulated, indicating their repeated activity. Many small faults affect also the neogene formations that crop out in the north-east and south-west parts of the island. These are mainly inverse and strike-slip faults and secondarily oblique-slip and normal faults. There is a characteristic difference in recent tectonism between the eastern and the western part of the island, which is most interesting from the perspective of geological hazard. Near the east coasts, faults are smaller with much eroded surfaces, which show that they are not active, while weathering factors have played major role in the evolution of this area. Or, the important active faults are located in the western part of Lefkada, as illustrated on the map of Fig. 3.

A similar difference between the eastern and western part of the island is also noted in vertical movements. In the western part, the uplift phenomena prevail, as shown by marine notches in coastal rocky cliffs and by small scarps in talus cones outcropping at certain areas of the coastal zone. On the contrary, according to geological and archaeological data, the east coasts undergo subsidence. Mild morphology and submerged talus cones prove the constant rising of the sea that continued through the historic ages. According to Murray (1982), Mycenaean tombs and ancient port jetties submerged, as well as Roman bridges covered with sediments, show that the level of the sea has raised by 3 m in the last 3,000 years.

Among the active faults of Lefkada, the most important, regarding seismic hazard, is the Athani strike-slip fault, which seems to be responsible for the largest part of the island’s recent deformation. It has a NNE-SSW direction and an eastern dip. The Athani fault is located a few hundred metres from the west coastline of Lefkada and is visible from the bay of Aghios Nikitas in the North to the village Athani in the South. It is very well delineated on satellite imagery and aerial photographs as well. The fault’s trace, well expressed in the region’s morphology, extends inland for a length of 17 km. In its northernmost part, in the area of Aghios Nikitas on the few exposed polished surfaces, tectonic striations with 5°–10° pitch are observed. Recent scree crop out in front of the



◀ **Fig. 3** Neotectonic map of Lefkada, (after Rondoyanni Th et al. 2007, modified), showing also the distribution of rockfalls-landslides as well as liquefaction and tsunami locations. *Inset* a 3D relief model presented in a tilted view. Explanations for the geological formations and tectonic elements are given in the Legend. 1. Site of the submerged ancient port, 2. Site of the Roman bridge covered by sediments. *TSOU* Tsoukalades, *LAZ* Lazarata, *A.NI* Aghios Nikitas, *DRA* Dragano, *ATH* Athani, *A.PE* Aghios Petros, *VAS* Vassiliki, *NYD* Nydri, *LYG* Lygia

fault's surface, over the basement's disintegrated dolomitic limestones. The southern inland fault termination is well visible at the steep coast front, some kilometres south-west of Athani village, where a very large polished surface with subhorizontal slip striations crops out (Fig. 4). Additionally, artificially exposed numerous small polished surfaces with relevant geometric and kinematic characteristics were identified in the zone of dolomitic limestones covering the area extending from the west of the fault to the coast.

The most impressive fault surface is observed near the village Dragano, where it has 65° dip and presents characteristic “canellures” (tectonic undulations) of 8° dip (Fig. 5). In front of the fault's surface, an elongated depression is developing, which is 4 km long and 100–500 m wide. This, near the village Athani, is filled with recent red clay deposits about 50 m thick (Fig. 6). Cushing (1985) reports that the total horizontal displacement of this fault is of 860 m approximately, meaning that the slip rate during the Quaternary was of about 8 mm/yr.

The processing of tectonic measurements, obtained on the Athani fault surface, gave the following results regarding the direction of tectonic stresses: $\sigma_1 = 6^\circ/\text{N}233^\circ$, $\sigma_2 = 83^\circ/\text{N}59^\circ$, $\sigma_3 = 0.7^\circ/\text{N}323^\circ$ (Fig. 7a). The impressive similarity of the Athani fault's geometric and kinematic characteristics with those of the Lefkada segment of the KLTF, as determined from seismic and seismological surveys and from the focal mechanism of the

Fig. 4 View of the Athani fault surface, with subhorizontal striations, at its southern inland expression. *Red arrows* show the relative movement of the two fault blocks





Fig. 5 View of the Athani fault surface with large tectonic striations (dextral movement indicating by the red arrows)

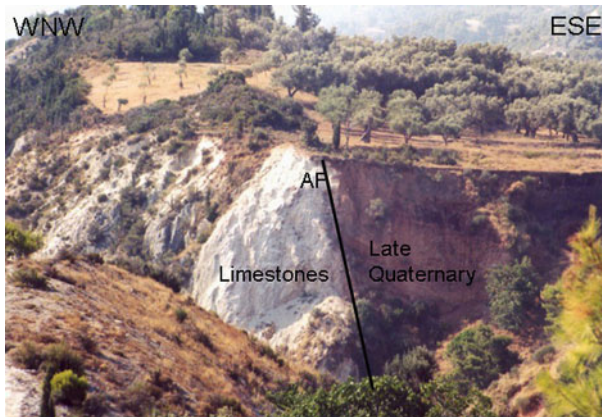


Fig. 6 View of the Athani fault, to the south vicinity of Athani village, where recent deposits have been accumulated in a small depression on the hanging wall

2003 earthquake (Fig. 7b), leads to the thought that the Athani fault seems to constitute a second-order duplex expression of the northern segment of the KLTF. These comparable faults run parallel to each other with the same kinematic features, but their interaction is not well documented. Besides, the question of whether some of the strong earthquakes manifested in the past generated by the Athani fault reactivation remains unanswered.

The other active faults, illustrated on the map of Fig. 3, form a group of subparallel NE-SW-striking oblique-slip and normal faults that have a maximum length of 5 km. They affect mesozoic dolomitic limestones, and their last movement is indicated by the displacement of semi- and non-cohesive scree, which covering in places their hanging wall. In the northern part of the island, two NW-SE-striking normal faults that form an echelon steep morphology have been identified. The southern is the 10-km-long Lazarata fault, while the northern is the Tsoukalades fault that bounds the 200-m-high Tsoukalades plateau from the laguna and the small plain of Lefkada city. It has a length of about 6 km and was previously considered as an active fault (Lekkas et al. 2001). According to our study, these two faults could not be considered as active faults, because of any absence of clear fault surfaces and of their incompatibility with the regional stress field. Concerning

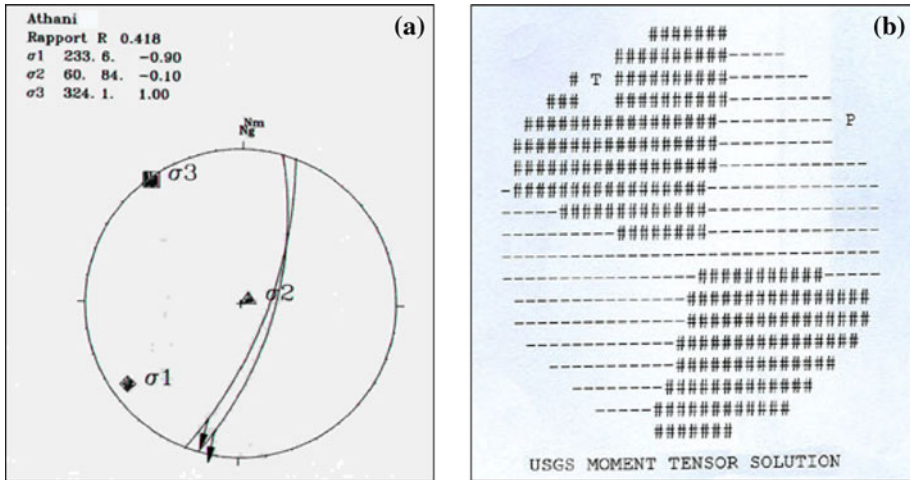


Fig. 7 **a** Active stress field deduced from the tectonic analysis of the Athani fault surfaces. **b** Active stress field deduced from the fault plane solution of the Lefkada 2003 earthquake (from USGS 2003)



Fig. 8 View of Tsoukalades scarp, indicating gravitational instability

especially the Tsoukalades scarp, it is obvious that its present eroded form is due to the combined result of repeated rockfalls, landslide and coastal erosion phenomena (Fig. 8).

Of note is the nature of the geological material (limestones and dolomites) found in the several hundred metres thick zone along the west coastal area, which is highly tectonized, almost disintegrated and at places powdered. Intense faulting has caused rock disintegration, while additionally, in places, cavernous dolomites have been transformed into dolomite sand. In places, where the rocks have somehow preserved their structure, the faults present polished surfaces of small width and length, with several directions and slip striations whose pitch varies from 5° up to 90°. They are preexisting discontinuity surfaces within this disintegrated zone, with the trace of small-scale displacements imprinted on them, due to tectonism or even gravity action in certain cases. Within this zone, intense rockfall and landslide phenomena of natural and man-made slopes are observed during earthquakes (Fig. 9). It must be noted that no large normal faults along the west coast, as generally was previously considered, have been identified.



Fig. 9 View of Lefkada west coast, showing intense landslide morphology

4 Earthquakes and secondary phenomena

The main seismic events evaluated in this study were based on the literature (Sathas 1867; Stamatelos 1870; Machairas 1940, 1951; Galanopoulos 1955; Zoras 1973; Rondoyannis 1982; Mougias 1994; Papazachos and Papazachou 1997), on the Archives of the Institute of Geodynamics of the National Observatory of Athens and of the Institute of Geology and Mineral Exploration and mainly on data obtained from the Archive of the Municipality of Lefkada concerning the 1469–1957 period.

It should be pointed out that serious archaeological and historical data about the seismicity of the Ionian islands are missing, if we take into account that the first reference to an earthquake in the Greek territory dates from 2,400 BC (Mougias 1994). From 1,100 to 625 BC and from the 3rd to the 9th century AD, there are very few testimonies and archaeological findings for the island of Lefkada (Zachos and Douzougli 2003). There is only one reference (Rondoyannis 1982) according to which the walls of ancient Lefkada were destroyed, probably because of an earthquake in the 6th century AD. Then, the first documented earthquake took place in the spring of 1469. It caused serious damage on the walls of Lefkada and also seriously affected Kefalonia and Zakynthos Ionian islands.

According to descriptions of older earthquakes and observations of the recent ones, most of them are associated with the manifestation of secondary phenomena such as landslides and rockfalls, subsidence of limited extent, liquefaction and tsunamis (Table 1; Fig. 3).

As shown in this Table, most damages on urban and physical environment were seen in the area of Lefkada city and Dragano and Athani villages as well. Specific examples can be mentioned for the earthquakes of 1704 (subsidence in Dragano and uprooting of trees), 1722 (major damages in Athani), 1767 (complete destruction of Athani), 1783 (complete destruction of Dragano and Athani) and 1948 (major damages in Lefkada). Ground fissures of small width and size, which have been observed at different sites in Lefkada island, are associated with secondary phenomena, while until now, no surface ruptures of tectonic origin, directly connected to seismic fault reactivation, have been recorded. Liquefaction and subsidence phenomena occurred at Lefkada city and Nydri and Vassiliki villages, while the most frequent and intense landslides and rockfalls have been occurred along the west coasts. Small-scale tsunamis have been described at the west coast (at the area west of Athani village) and at the east coast as well (at Nydri bay). Concerning Lefkada city, Vött et al. (2008, 2009) based on geomorphic, geophysical and geochronological analyses determined tsunamogenic sediments in the region between Lefkada and the opposite land of Acarnania and estimated the time interval of tsunami events about 500–1,000 years. The most important event between them is considered a NW-derived tsunami, of 4–6 m height, during the Classical-Hellenistic period.

Table 1 List of destruction and ground failures in Lefkada island

Year	Lefkada City	Western part of the island (Ag. Nikitas-Dragano-Athani)	Central part (Stavrota Mnt.)	Southern part (Ag. Petros-Vassiliki)	Eastern part of the island (Skaroi-Lygia-Nydri)
1612	SSRU				
1613	DE				
1625	DE	DE		DE	DE
1630	SSRU				LA/RF, SSRU
1704	DE	SU			
1722		DE			
1723	DE				
1767		DE			
1769	DE				
1783		DE, LA/RF	LA/RF, SSRU		
1820	DE, SU				
1825	DE, SSRU				
1869	DE				
1885		LA/RF			
1911	SSRU				
1914	DE	LA/RF, SSRU, SU, TSU		LA/RF	LA/RF, SU, TSU
1915	DE		LA/RF		
1938	SSRU		LA/RF		
1948	SSRU, SU, LI	LA/RF, SSRU, SU, TSU	LA/RF	SSRU, TSU	LA/RF
2003	SSRU, SU, LI	LA/RF, SSRU, SU, LI	LA/RF, SSRU	SU, LI	SU, LI

DE Destruction, *LA/RF* Landslides/Rockfalls, *SSRU* Secondary Surface Rupturing, *SU* Subsidence, *LI* Liquefaction, *TSU* Tsunamis

The last strong earthquake occurred on August 14, 2003 (38.81°N, 20.56°E), located a few kilometres from the west coast of the island. It had $M_s = 6.4$ magnitude and 12 km focal depth (according to the National Observatory of Athens, Institute of Geodynamics), and the aftershock distribution almost covered the western part of the island (Fig. 10).

During this earthquake, most damages occurred in the city of Lefkada, in the small plateau of Lazarata and in the village Dragano, where macroseismic intensity reached VII in the MM and EMS scales (Papadopoulos et al. 2003). Surface fissures and deformation of secondary origin, accompanied by limited damages of technical works, were noted along the eastern and western seafront of the city of Lefkada, in the new marina and in the sandy beach in front of the lighthouse, related to local liquefaction phenomena (Gazetas 2004; Gazetas et al. 2006; Papathanassiou and Pavlides 2007). Fissures and a partial subsidence also observed in the port of Lygia, while similar phenomena but of lesser extent also occurred in the village Vassiliki, at the southern part of the island. Numerous fissures of small length were observed on the road towards the village Dragano. Moreover, in this area, the stonework of many cultivation terraces collapsed, and also many overturnings of isolated stones were observed.

The focal mechanism of this earthquake (USGS 2003) showed activation of a strike-slip fault with a NNE-SSW direction and a right-lateral motion presenting a small normal component. The orientation of stress axes was the following: T:10°/N328°, N:80°/N159°, P:2°/N58° (Fig. 7b). Epicentre distribution of the 2003 earthquake, thoroughly studied by

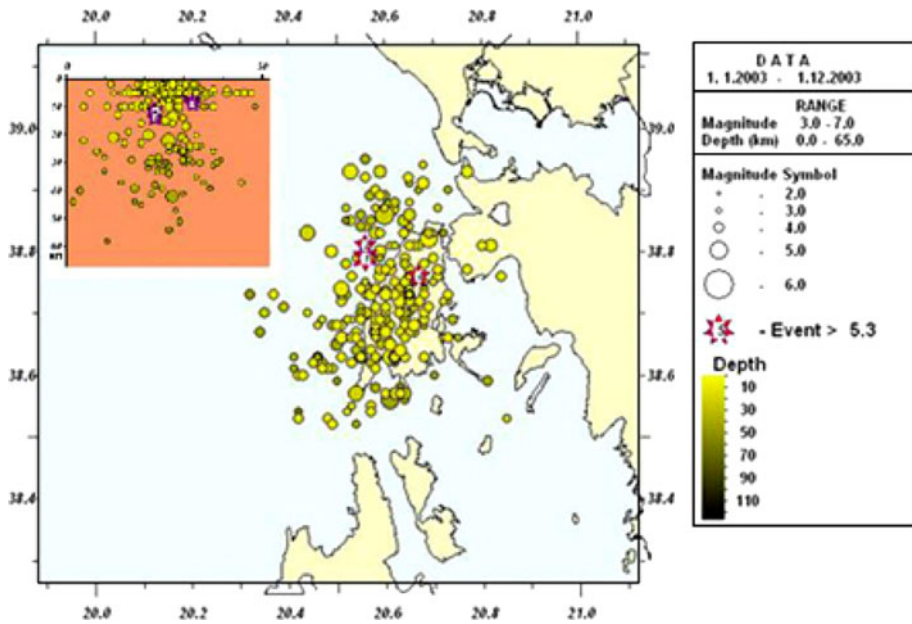


Fig. 10 Epicentre distribution and depth cross-section, normal to the strike of the main rupture of 2003 earthquake

many scientists, showed that the activity was concentrated along the west coast of Lefkada, as well as in the area between Lefkada and Kefalonia. Seismic fault projection was highly accordant with the morphology of the sea floor, running parallel and very near to the steep coastal line (Karakostas et al. 2004). Similar results were obtained from the study of the deformation in the islands of the Central Ionian Sea, based on DGPS and DInSAR data analysis between the years 1995 and 2006 (Lagios et al. 2007). Karakostas (2008) and Karakostas and Papadimitriou (2010) based on microseismicity, focal mechanism data and aftershock activity pointed out that the 2003 earthquake causative fault, which previously considered to be some kilometres offshore, bounds the island's west coastline.

5 Coulomb stress changes

Considering the lithosphere as a homogeneous elastic isotropic half space, Okada (1992) provided expressions for the displacement and strain fields due to a finite rectangular source, representing a fault of known geometry. More recent studies of earthquake-stress interaction have focused on coseismic stress changes immediately following an earthquake. A widely used model to describe fault interaction is the Coulomb stress change, which is the difference between the shear stress in the fault direction and the shear strength, assuming that the Mohr–Coulomb criterion expresses the strength of the crust material. The measure of this change allows estimating stress field changes produced by fault rupture during earthquakes, changes that may affect the behaviour of the other neighbouring faults (King et al. 1994; Stein et al. 1994; Toda et al. 1998; Lin and Stein 2004).

The most recent major seismic events evaluated in the island of Lefkada occurred from 1973 to 2003 (Table 2). The location and characteristics of the seismic faults were modelled

Table 2 List of Lefkada earthquake data used for the determination of Coulomb stress change

Date	Lat (°N)	Long (°E)	Depth (km)	M	Mechanism		L (km)	u (cm)	Lateral slip (cm)	Dip slip (cm)	w (cm)
					Strike (°)	Rake (°)					
4/11/1973	38.90	20.50	3–15	5.9	320	45	14.42	13.428	2.332	13.224	9.795
25/2/1994	38.76	20.54	3–15	5.5	22	58	9.02	6.31	-6.172	1.312	8.218
14/8/2003	38.82	20.57	3–15	6.2	180	63	20.51	23.66	0.000	6.677	11.17

on the basis of the seismological data. At least one of these faults – 1994 earthquake – seems to be well correlated with a submarine fault, determined on seismic profiles by Auroux (1984). The creation of entry files started from the chronologically first rupture and continued with successive addition of subsequent ruptures, so that Coulomb stresses were added to the previous and all preexisting ones. The reference point was the centre of the area under study, calculated as the mean of the geographical coordinates of all points constituting the area. For each new rupture, Coulomb stresses and horizontal displacements were calculated for a friction coefficient equal to 0.4 and a 7.5 and 10-km focal depth.

It should be noted that the Athani fault, considered to be the main active fault in the island, was also included in the above group, with zero seismic moment into the entry file as there were no indications of rupture during the last earthquake. As no data exist regarding the seismic activity of Athani fault, to calculate the fault's width, we used the equations of Papazachos and Papazachou (1997)-(1,2,3) applicable on the Greek territory in particular, and the empirical relationships of Wells and Coppersmith (1994)-(4,5) deduced from the study of earthquakes around the world. Analogous empirical relationships have been also proposed by Ambraseys and Jackson (1998) and Pavlides and Caputo (2004) for the Eastern Mediterranean and Aegean region, respectively. Using the above mentioned equations, a hypothetical earthquake magnitude was first calculated in case of the Athani fault rupture, and the resulting magnitude was used to calculate the fault's width. To increase the method's reliability, the width was calculated with both equations, and their mean value was adopted.

$$S = L \cdot W \quad (1)$$

$$\log S = s_1 + s_2 \cdot M \quad (2)$$

$$\log L = \lambda_1 + \lambda_2 \cdot M \quad (3)$$

$$M = 5.08 + 1.16 \cdot \log L \quad (4)$$

$$\log W = 0.19 \cdot M - 0.13 \quad (5)$$

where M is the earthquake's magnitude, S is the surface of the fault (in km^2), L is its length (in km), W is its width and s_1 , s_2 , λ_1 , λ_2 are constants, whose values corresponding to the Greek territory are: $s_1 = -1.98$, $s_2 = 0.7$, $\lambda_1 = 1.85$ and $\lambda_2 = 0.51$ (Papazachos 1997). Athani fault data were obtained as mean values of field measurements in various sites using the above equations. The inland fault's mapped length is 17 km, but there is no information concerning its offshore continuation both to the North and to the South. Its strike considered 10° to the North, its dip 70° to the East and its slip vector 8° to the South. Its motion is right lateral as confirmed by tectonic striations on the fault surface. Uncertainty regarding the fault's depth is reduced, and a 10-km depth is considered reasonable, because of the fault's nature and the distribution of epicentres on seismological sections. Based on these data, the fault's width was subsequently calculated.

The results of these procedures are illustrated on Fig. 11a–c, for 1973, 1994 and 2003 earthquakes, respectively. Positive Coulomb stress values are represented in red colour and negative ones in blue. As shown by the static stress transfer calculations, the first earthquake (due to a reverse fault of NW-SE strike) seems to have a small relation with the triggering of the 1994 event. On the contrary, there is a strong indication that the 1994 earthquake (due to a strike-slip fault striking NNE-SSW) may have affected the 2003 strike-slip causative fault, as positive values of shearing stress are observed on the northern part of this fault. After the last 2003 earthquake, positive Coulomb stress changes dominate in

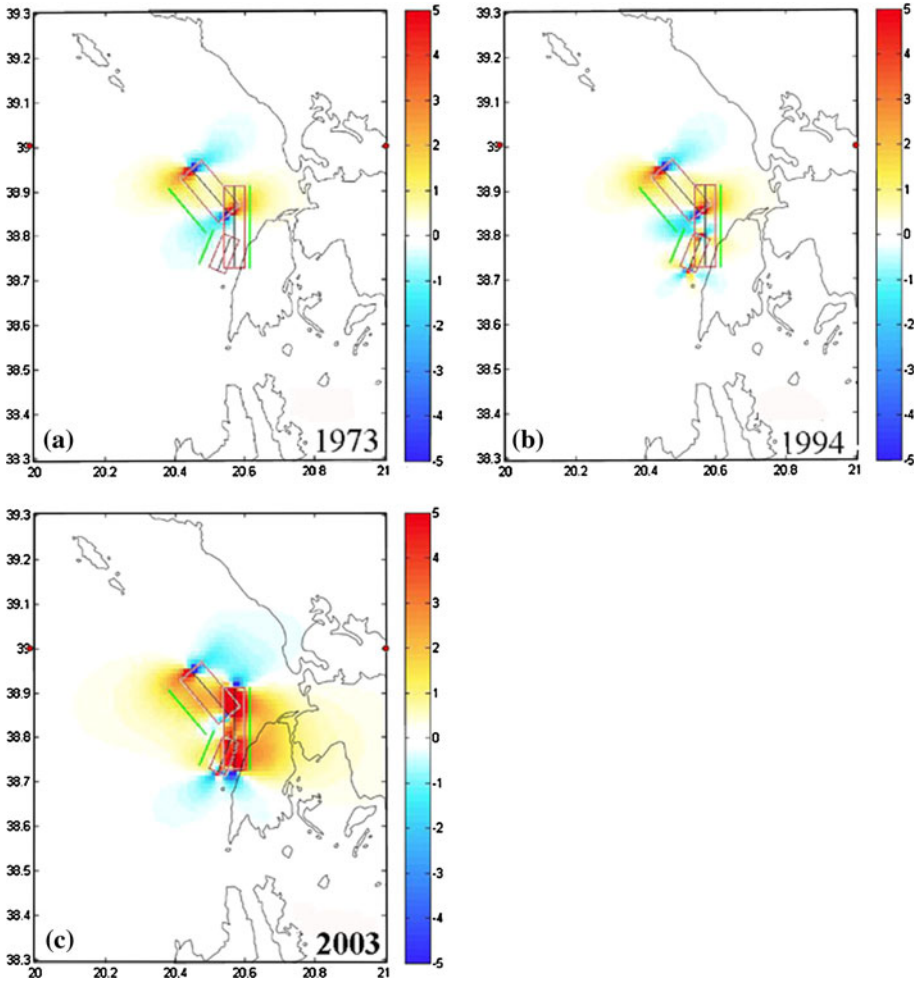


Fig. 11 Coulomb stress changes in Lefkada area after the 1973 (a), 1994 (b) and 2003 (c) earthquakes. Positive Coulomb stress values in red colour, negative ones in blue. The three seismic faults are also noted by green lines

the northern part of the Athani fault, showing its possible reactivation in the future. So, the seismic hazard posed by the Athani fault can be considered higher in comparison to that posed of the other faults of Lefkada island.

6 Conclusions

This paper outlines the active faulting and deformation accompanying strong earthquakes in Lefkada Island. Detailed field mapping and tectonic analysis provided a reasonable basis for the compilation of the active fault map with the locations of earthquake secondary phenomena, which can be used as a document for the island’s seismic protection. For this

evaluation, historical and recent seismotectonic data as well as Coulomb stress changes were also used. The main conclusions that can be drawn are the following:

1. The fault pattern of Lefkada Island consists of a number of normal, strike-slip and inverse faults, formed in older tectonic phases. The activity evaluation of the mapped faults showed that the active faults are of strike-slip and oblique-slip character.
2. Among them the most important is the NNE-SSW-striking Athani fault, very well expressed in the region's morphology and marked on satellite images and aerial photos. The impressive polished fault surface is observed at places along its trace, presenting large subhorizontal tectonic striations. The tectonic analysis showed that the dominated tectonic stresses are compressional in a NE-SW direction. The Athani fault can be considered as an inland duplex of the Kefalonia-Lefkada Transform Fault (KLTF) because of the striking similarity presenting their geometrical and kinematic characteristics.
3. Other NE-SW-striking active faults, of oblique-slip or normal character, are subsidiary faults, related to the development of the major Athani fault.
4. The morphology of the west steep coasts of Lefkada Island is closely related to gravitational and instability phenomena, due to the cataclastic nature of the rock mass. No field indication that the coastline coincides with a normal fault trace could be found. It can be considered that this coastal zone represents the intensively tectonized area between two parallel strike-slip faults, namely the northern branch of the KLTF and the Athani fault.
5. The earthquake secondary effects are mainly rockfalls and landslides, liquefaction and small-scale subsidence and tsunamis, according to the descriptions of historical and recent earthquakes and the field observations after the last strong event of 2003. These phenomena can be considered as well predictable and appropriately confronted, because they occur repeatedly at the same places.
6. Surface rupturing of tectonic origin has never been observed during strong earthquakes, while rare small-length cracks were associated to secondary phenomena. This is a surprising fact related to strong shallow earthquakes. Although the majority of the earthquakes have their foci on offshore faults, aftershock distribution was well extended in almost all the western part of the island.
7. The Coulomb stress changes analysis showed that, after the 2003 earthquake, they are positive in the western and northern part of the island, extending up to the centre of the Athani fault, fact that may favour its future reactivation.

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