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The 20 and 27 April 1894 (Locris, Central Greece) Earthquake Sources through Coeval Records on Macroseismic Effects

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Abstract Newly retrieved coeval records on the effects of the two large earthquakes of 20 and 27 April 1894 in Locris (central Greece) have been analyzed to assess macroseismic intensities according to the European Macroseismic Scale (Grünthal, 1998). An intensity equal or higher than 8 has been estimated at 70 different places. The two earthquakes were close in time and both focused on the same area; this asked for an interpretation free, as much as possible, from the prejudice due to the accumulative descriptions implied, for instance, by the 1894 scientists' reports. To image the earthquake sources and derive the main seismic parameters, we processed the macroseismic intensity data by using the Boxer method proposed by Gasperini *et al.* (1999). On the basis of this approach and our new sets of data, we obtain **M** 6.4 and 6.5 for the 20 and 27 April earthquakes, respectively, the latter being substantially smaller than the estimates proposed in previous works. Results obtained from the processing of macroseismic data have been tested and compared to recent geological data. Our preferred interpretation is that the 20 and 27 April 1894 earthquakes ruptured together the whole Atalanti fault. The internal structural complexity of the Atalanti fault appears to have controlled the rupture propagation: the change in strike of the fault trace along with its intersection with the Malesina fault, near Proskinas, is interpreted as a geometric barrier that is the boundary between the two individual earthquake sources. The 20 April earthquake would have ruptured between Proskinas and Skroponeri Mountain, southeast of the village of Larimna, whereas the 27 April earthquake ruptured between Proskinas and the northwest Chlomon fault zone, north of the town of Atalanti.

Introduction

The two earthquakes of 20 and 27 April 1894 seriously damaged about 70 places, mostly located in Locris, a region of central Greece, to the northeast of Athens and facing the island of Evia (Fig. 1). Both earthquakes were felt in Athens and were known, before the earthquake of 7 September 1999 (M_s 5.9, National Observatory of Athens), as those responsible for the strongest observed effects in the last hundred years of the seismic history of the city (intensity at the site = 6 Medredev-Sponhever-Karnik [MSK] scale).

Recent studies (Ambraseys and Jackson, 1990; Makropoulos and Kouskouna, 1994) have significantly improved our knowledge about the size and location of both earthquakes. Anyway, being two earthquakes close in time, just 1 week apart, doubts still existed on the distribution of macroseismic effects due to each individual shock; this uncertainty affected both the size estimate and association with their seismogenic sources. Recent geological and geomorphological investigations were performed in an attempt to address this problem (Pantosti *et al.*, 2001), but, while the whole Atalanti fault (Fig. 2) was considered responsible for the 27 April earthquake, no resolving field evidence was found to locate the source for the 20 April event.

This study accepted the challenge posed by the closeness in time of the two earthquakes and focused on the possibility of describing the effects of the first earthquake, that of 20 April, through coeval records, which had to be unbiased by the effects caused by the 27 April event as much as possible. Retrieval of coeval sources not considered so far and a reinterpretation of already known sources has allowed us to perform a thorough reappraisal of the distribution of damage and effects of the 20 April 1894 earthquake. This distribution is quite exclusively based on reports published before the second earthquake took place. A completely revised distribution of effects due to the 27 April event is also presented, although in assessing macroseismic intensity for those places already heavily damaged by the 20 April event *ad hoc* decisions had to be taken to weight, and possibly reduce, inferences due to the changes in the building asset and vulnerability caused by the 20 April earthquake. For both earthquakes, the macroseismic intensity has been as-

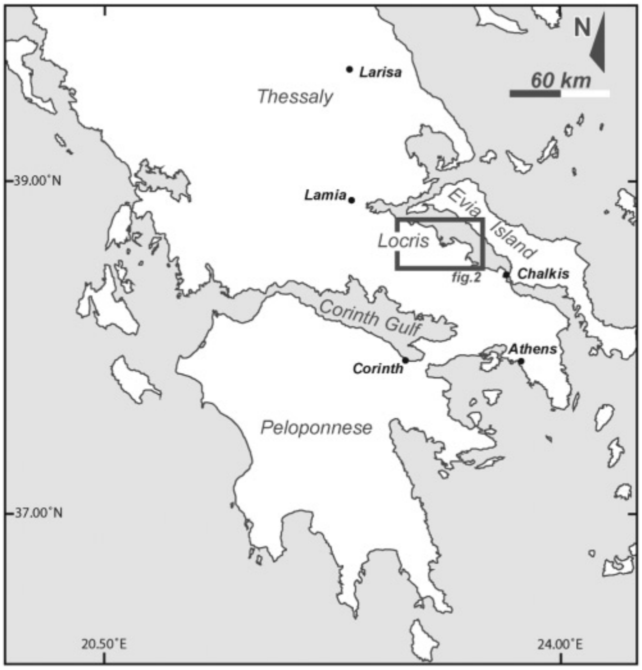

Figure 1. Location of the study area in central Greece. Inset encloses the area of Figures 2, 10, 11, and 12.

sessed according to the European Macroseismic Scale (EMS98) (Grünthal, 1998).

The two new sets of data are used to evaluate the parameters of each earthquake according to the method proposed by Gasperini *et al.* (1999). To obtain a multidisciplinary and up-to-date description of the potential seismic sources of the area, results are compared with the evidence (Fig. 2) gathered by recent geological and paleoseismological studies (Pantosti *et al.*, 2001, 2004).

Previous Intepretations of the 1894 Earthquakes

Seismological Studies

The 20 and 27 April 1894 earthquakes are well known and represented in the seismological literature of the last 30 years. Among the published papers, we will here consider those supplying a comprehensive set of earthquake parameters, including a magnitude assessment (Table 1; Fig. 2).

1. Parametric earthquake catalogs: Karnik (1971), Shebalin *et al.* (1974), and Papazachos and Papazachou (1989, 1997)
2. A study showing the areas of damage for each earthquake but no intensity assessment: Ambraseys and Jackson (1990)
3. A study supplying a set of intensity data points in the European Macroseismic Scale 1992 (the previous version of EMS98): Makropoulos and Kouskouna (1994)

Comparing the parameters suggested by these studies, without considering as relevant the differences in types and relations each study used to determine magnitudes, it can be observed that there is a common trend in estimating the 20 April earthquake to be smaller than that of 27 April.

The epicenters are scattered in a wide area between Agios Kostantinos and Pavlos, with preference given to the southernmost part in the case of the 20 April earthquake. Both earthquakes appear to have been located on the hanging wall of the Atalanti fault (Fig. 2), suggesting their possible association with this fault.

Ambraseys and Jackson (1990) and Makropoulos and Kouskouna (1994) underlined that, given two earthquakes so close in time, the task of separating the damage caused by each event is not an easy one. On the one hand, they did not report on how much the cumulative effects of the sequence have been processed in identifying the damage and assessing intensities for the 27 April earthquake; on the other hand, they recognized the importance of cumulative effects in magnitude determination and epicentral location of each earthquake.

Plotting the sources of information in chronological order of their publication, and showing the relationships among them and the studies by Ambraseys and Jackson (1990) and Makropoulos and Kouskouna (1994) (Fig. 3), it emerges that both the latter studies have used the same scientific reports and mainly relied upon Skouphos (1894) and Mitsopoulos (1894). But apart from Skouphos (1894), who surveyed only 10 places of the area damaged by the 20 April earthquake between the 25 and 27 April events (Table 2; Fig. 4), the other scientists visited the area only after the second earthquake (Mitsopoulos, 1894; Papavasiliou, 1894a,b) or relied upon second-hand information (e.g., C. Davison, in *Nature* [1894a–c]).

Some considerations follow (1) on the fact that these scientific reports, although coeval to the earthquakes, merged the damage and effects of the two earthquakes and (2) on how this merging has affected so far the interpretation of the 20 April event.

Geological Studies

The 1894 earthquakes in central Greece are among the best documented historical events of surface faulting in the Mediterranean area. Ground ruptures, landslides, and major disturbances of the landscape were described by contemporary authors (C. Davison, in *Nature*, [1894a–c]; Mitsopoulos [1894, 1895]; Papavasiliou, [1894a,b]; Philippson [1894a]; and Skouphos [1894]). According to their reports (Fig. 3), the first earthquake appears to have produced small ruptures, cracks, and landslides mainly in the Malesina peninsula and along the coast (mostly liquefaction effects). These effects were described by Skouphos (1894) as being secondary compared to those produced by the second earthquake, which seriously perturbed a coastal area exceeding 60 km in length (between the town of Agios Kostantinos and Cape Gatza, Fig. 2). Most of the ruptures from the second

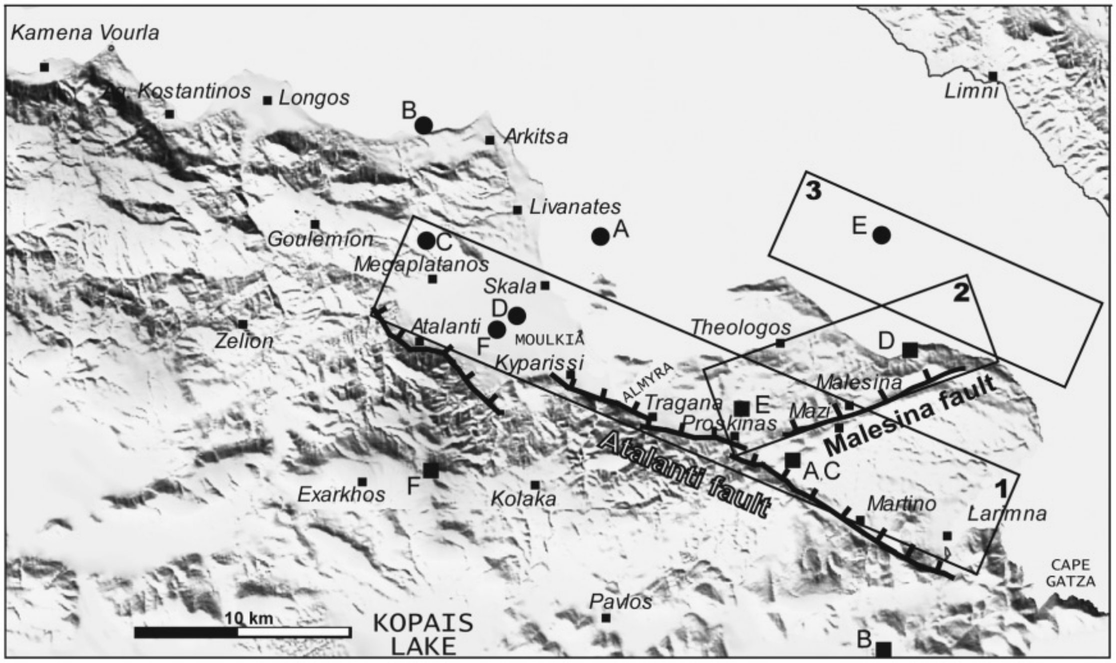

Figure 2. Map of the Atalanti fault (from Pantosti *et al.*, 2001) and epicenters of 20 (squares) and 27 (circles) April 1894 earthquakes according to previous studies (A = Karnik, 1971; B = Shebalin *et al.*, 1974; C = Papazachos and Papazachou, 1989; D = Ambraseys and Jackson, 1990; E = Papazachos and Papazachou, 1997; F = Makropoulos and Kouskouna, 1994). Rectangles are the fault models proposed by Pantosti *et al.* (2001): 1 = source for the 27 April earthquake; 2 and 3 = sources for the 20 April earthquake. DEM courtesy of N. Palyvos.

Table 1
Comparison of the Parameters Available from Previous Seismological Studies on April 1894 Earthquakes

Catalog or Study	IDP	I_x	I_o	Lat	Lon	*M*
20 April 1894						
Karnik, 1971	—	—	10	38.600	23.200	6.7
Shebalin *et al.*, 1974	—	—	10	38.500	23.250	
Papazachos and Papazachou, 1989	—	—	10	38.600	23.200	6.7
Papazachos and Papazachou, 1997	—	—	10	38.600	23.000	6.7
Ambraseys and Jackson, 1990*	19	—	>9	38.650	23.267	6.4
Makropoulos and Kouskouna, 1994*	39	11	11	38.618	23.170	6.7
27 April 1894						
Karnik, 1971	—	—	11	38.700	23.100	6.9
Shebalin *et al.*, 1974	—	—	11	38.750	23.000	—
Papazachos and Papazachou, 1989	—	—	10	38.700	23.000	7.0
Papazachos and Papazachou, 1997	—	—	10	38.660	23.040	7.2
Ambraseys and Jackson, 1990*	53	—	>9	38.667	23.050	6.9
Makropoulos and Kouskouna, 1994*	28	11	11	38.700	23.250	7.0

IDP = number of intensity data points (Ambraseys and Jackson [1990] assessed intensity for a few places only; the figure refers to the places shown in their figures A4 and A6, respectively, the legend of which is given in their figure A2); I_x = maximum intensity; I_o = epicentral intensity; Lat and Lon = epicenter coordinates; M = magnitude.

*These are studies; all other entries are catalogs.

event appear systematically arranged along or very close to the Atalanti fault, with exceptions such as liquefaction effects along the coast, a landslide in Skender Aga (now Megaplatanos), some ruptures in Moulkia territory, and discontinuous ruptures between Atalanti and Agios Kostantinos (Fig. 2). An intense debate between the contemporary observers about the significance of the ruptures was started. On the one side, Mitsopoulos (1895) claimed a nontectonic origin for these ruptures but a purely gravitational one; on the other side, Skouphos (1894), who interestingly had been a

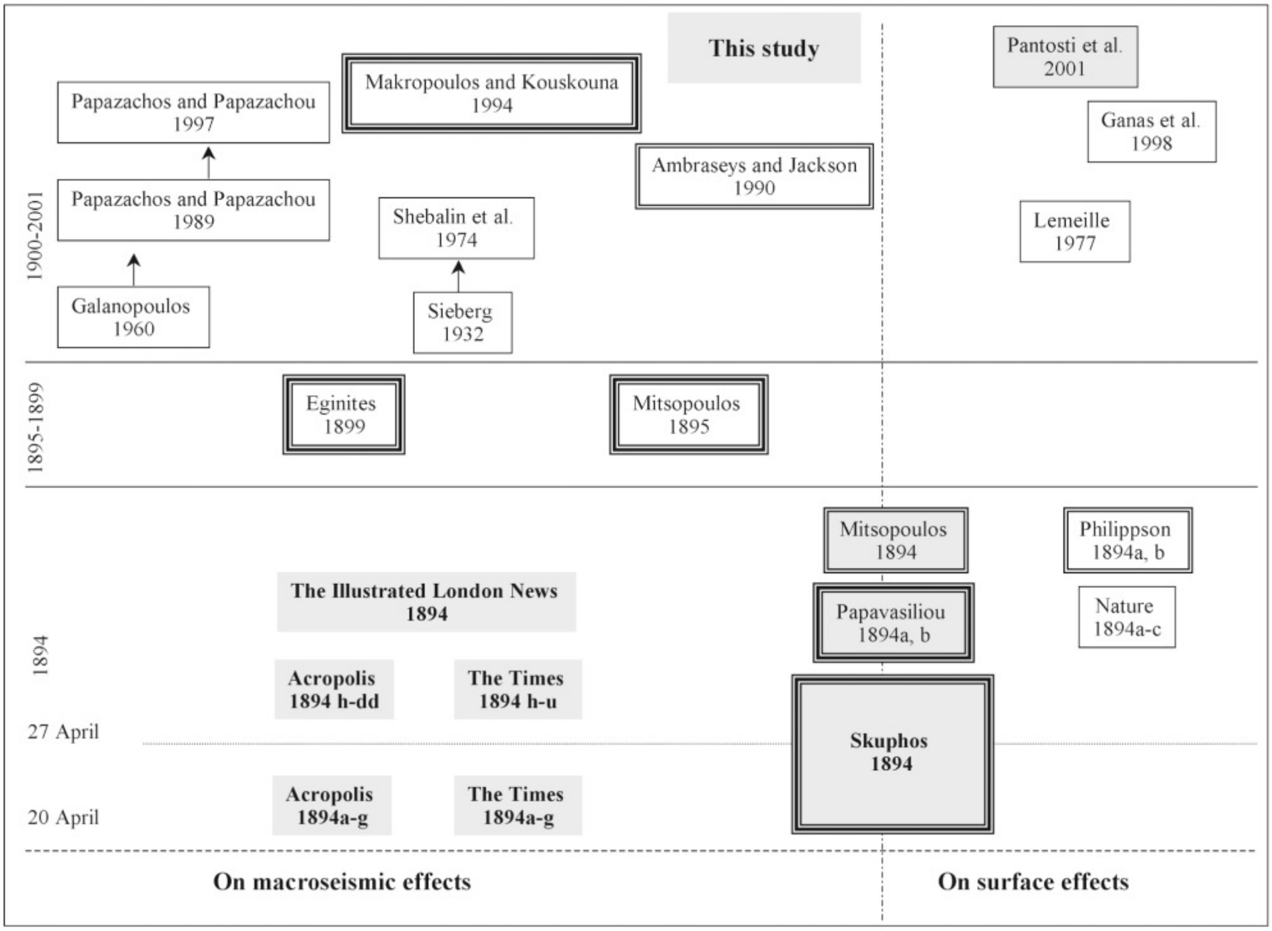

Figure 3. Modern scientific studies and their relationships with sources of information on April 1894 earthquakes effects. On the left side, sources mostly dealing with macroseismic effects; on the right side, sources dealing with surface effects. Sources with a three-line box are used both by Ambraseys and Jackson (1990) and Makropoulos and Kouskouna (1994).

Mitsopoulos student, and Papavasiliou (1894a, b) advocated a direct tectonic origin and thus understood already the potential coming from the study of the coseismic surface effects to investigate the seismic source at depth. Also the total length of the ruptures was a matter of conflicting views: 60 km for Skouphos (1894) versus 10–15 km for Mitsopoulos (1895). Even from a geological point of view, the temporal closeness of the two events as well as the pressure of the contemporary debate certainly did not help in defining the seismogenic sources for the two events (IGME, 1989; Ganas, 1997; Ganas and Buck, 1998; Ganas *et al.*, 1998; Cundy *et al.*, 2000; Pantosti *et al.*, 2001). Recent work by Pantosti *et al.* (2001) used contemporary reports coupled with investigations performed in the 1970s by Lemeille (1977) and a new aerial photo and field survey to conclude that the 20 April earthquake may have ruptured the Malesina structure (box 2 in Fig. 2) or alternatively an Atalanti-parallel fault located just offshore the Malesina peninsula (box 3 in Fig. 2), whereas the April 27 earthquake ruptured the whole Atalanti fault between the towns of Atalanti and Larimna, possibly up to Cape Gatza (box 1 in Fig. 2).

The association of the April 20 earthquake with a clearly identified seismic source is still an open question, thus confirming the need for further investigation in this direction.

The Regional Setting of Locris in 1894

The area affected by the two earthquakes stretches along the eastern coast of Locris, between the Malesina peninsula and Agios Konstantinos. The coastal area at the time of the earthquakes was part of the administrative district of Livadhia and was divided from the inland by the Kopais Lake region, a large marsh reclaimed in the late nineteenth century (Fig. 2). Also the island of Evia, to the east of Locris, was affected by the earthquakes (Tables 3 and 4).

Communications by land were scarce, and roads were poor. The main road to Locris ran from Athens through Thivai. Railway infrastructures were being developed, but at

Table 2
Three Observers on the Spot

Place	Date (dd-mm)				
	23-04	24-04	25-04	26-04	27-04
Chalkis	KG	WB	KG		
Livanates	KG		WB	TS	
Megaplatanos			WB	TS	
Kato Pelli	KG	WB	TS		
Atalanti	KG	WB	TS		
Ano Pelli				TS	
Kyparissi		KG		WB	TS
Proskinas		KG		WB	TS
Martino		KG		WB	TS*
Masi		KG			TS
Malesina		KG		WB	TS
Larimna			KG	WB	
Topolia					WB
Karditsa					WB
Mouriki					WB
Thivai					WB

KG = King George I; WB = W. Bourchier; TS = T. Skouphos.
*Place where Skouphos experienced the 27 April earthquake, at about 9:15 p.m. local time.

that time the fastest way to reach the damaged area was by sea. This was the route taken by governmental relief supplies (tents and food), as well as by the earliest visitors of the area (Table 2), who got there by sailing from Athens to Chalkis (Fig. 4). A ship of the British Royal Navy fleet and Russian cargo ships cast anchor in the Evia channel for relief reasons as well.

Identification of places mentioned in coeval sources, both in Greek and other languages, has been quite a demanding task. It required the help of a coeval map (Anonymous, 1885), for almost no place was referred to in 1894 records by the name it has today. Some places were called by two different names at the same time (e.g., Drachmani and/or Elatea for today's Elatia), while others had changed from the classical name (e.g., Orchomenos into Skripou) to be changed again in more recent times back to the ancient one; or, the name that had been in use for centuries during Ottoman rule had been changed into a completely different and new one (e.g., Skender Aga into Megaplatanos; Karditsa is today Akraifnion, and the old Topolia is now Kastro, a very common name in the area and throughout Greece). This situation has required special accuracy in locating many of the affected places; this is the reason for the column "QuLoc" in Tables 5 and 6, which gives the names as quoted by coeval sources together with the place as it was identified (column "IdLoc") and its geographical coordinates.

When the 1894 earthquakes struck Locris and neighboring districts, Greece was a crowned democracy under King George I (Danish house of Glucksburg), appointed in 1863 as the new king by the Great (or Protecting) Powers (Britain, France, and Russia). At that time, the countries of the Balkan area were under a continuous crisis and in this period of relative peace, before the Greek–Turkish war for the possession of Crete (1897), Great Britain was Greece's most important supporter (Magosci, 1993). A single-chamber parliament was then ruling the country. After several administrative changes in the previous 50 years, at the end of the nineteenth century Greece was divided into districts, also called "eparchies" or provinces (Fig. 4) and *demos*; the latter being the smallest administrative entities and ruled by a *demarchos*. From the local officers of the districts of Locris, Livadhia, Thivai, Chalkis, and Xerochori, telegrams were sent both to the Ministry of the Interior and the Athenian newspapers to report on the damage and effects caused by the 1894 earthquakes.

Greece did not adopt the Gregorian calendar until 1953. Thus, Greek newspapers gave dates according to the old style, counting for the nineteenth century 12 days less than the new style. Greek scientists, such as Skouphos and Mitsopoulos, gave dates in the old and new styles. Both dates are here given in the titles of the sections and in the reference list for original Greek sources only.

The Observers and Their Reports

In the following sections, the coeval records about the 20 and 27 April 1894 earthquakes are presented, strictly separated according to the time of their production. In choosing this approach, we are looking for an interpretation of each earthquake free, as much as possible, of overlapping and confusion of their respective macroseismic effects.

From 8/20 to 15/27 April 1894

The Friday 20 April earthquake happened at about 7 p.m. local time. The time is given unequivocally by different sources, for example, 6:52 p.m. (Skouphos, 1894; Mitsopoulos, 1894) and 6:55 in the evening (*Acropolis*, 1894a; *Times*, 1894a).

The earthquake was strongly felt in Athens, and its severity was confirmed quite immediately (1 hr later) by telegrams from the most damaged area, corresponding roughly to the 1894 administrative districts of Locris, Livadhia, Thivai, and Chalkis.

Less than 3 full days after the earthquake, that is on the morning of Monday 23 April, of the three observers who left Athens for the damaged area, the first to reach it was George I, King of the Hellenes, then came the British William C. Bourchier and the Greek Theodor Skouphos. Apart from the latter, they left before the evening of Good Friday 27 April, when the second large earthquake took place. For our purposes this means that they effectively surveyed and described the territory and the damage the settlements had sustained before the 27 April earthquake. Their surveys, whose itineraries are shown in Figure 4, supply us with precious and reliable information to discriminate between the two large earthquakes and to try and reconstruct the 20 April earthquake effects.

King George I of Greece and Other Authorities. The newspaper *Acropolis*, published daily in Athens, devoted many

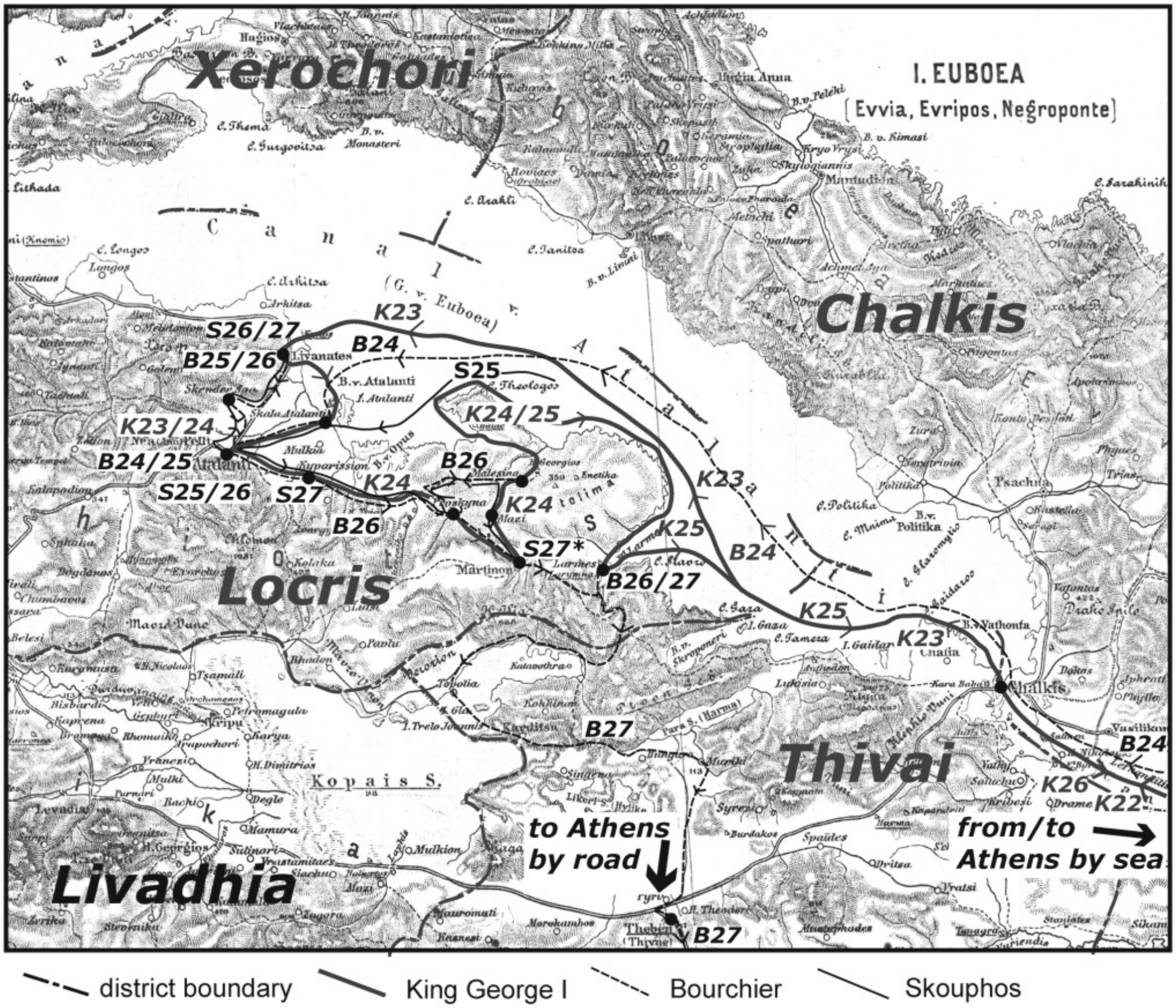

Figure 4. Itineraries followed by King George I, Bourchier, and Skouphos after the 20 April earthquake are represented with different patterns. The daily path is indicated by the initial of the visitor (K = King George I; B = Bourchier, S = Skouphos) and the date. Two days point at places where visitors spent the night. Arrows along the paths indicate the direction of the visit; note that some paths were followed in both directions. Black circles mark the main places visited and reported in Table 2. Asterisk indicates the position of Skouphos when the 27 April earthquake occurred, at about 9 p.m. In the background is a section of Table IV of a General Map of Greece by Anonymous (1885) (courtesy of the Royal Geographical Society, London). Borders and names of administrative districts in 1894 are shown.

items to the news coming from the affected places. In the seven issues between 21 and 27 April (*Acropolis*, 1894a–g) tens of items were published containing information gathered both from telegrams sent by local authorities (*demarchoi*) and the official reports delivered by the Ministry of the Interior. Of great value are also the reports written by *ad hoc* correspondents who accompanied the king on his visit.

George I left Athens on board the ship *Sfacteria* and arrived at Chalkis at 8 in the morning on Monday 23 April (Table 2; Fig. 4). Each of his 10 stops through the districts of Chalkis first and then Locris was detailed in a clichéd manner by an anonymous reporter: the king's entrance in the place, the reactions of the inhabitants to his presence, the grief of the inhabitants for the loss of life, the emotion of the king. In between, precise information on earthquake effects was given, in terms of number of collapsed and damaged private houses, churches, and public buildings.

W. C. Bourchier. The *Times*, London edition, published

Table 3
Places Most Damaged by the 20 April 1894 Earthquake

Place	District	Demos	Inhabitants	Buildings: Existing	Buildings: Collapsed	Buildings: Uninhabitable or Heavily Damaged	Dead	Injured
Malesina	Locris	Larimna	951	300	200		130	30
Martino	Locris	Larimna	1434	480	480		40	50
Mazi	Locris	Larimna	118	50	50		6	25
Proskyna	Locris	Larimna	516	120	120		33	25
Kastri/Larimna	Locris	Larimna	143		38			
Pavlo	Locris	Larimna	596		12			
Livanates	Locris	Dafnesion	1021		200		5	29
Arkitsa	Locris	Dafnesion	350		48			
Goulemio	Locris	Dafnesion	160	35	8			
Kyparissi	Locris	Atalanti	183	32	Most		3	4
Atalanti	Locris	Atalanti	1700		Few	Many		
Kato Pelli	Locris	Atalanti	800		50		4	
Skender Agas	Locris	Atalanti	300				5	
Kalapodi	Locris	Atalanti	357	70		22		
Zelion	Locris	Atalanti	457	100	5			
Kolakas	Locris	Atalanti	232		Most			
Exarchos	Locris	Atalanti	398		4			
Arapochori	Livadhia	Livadhia	163	27	17			
Veli	Livadhia	Livadhia	165	22	3	14		
Bramaga	Livadhia	Livadhia	234	40	15	10		
Scripou	Livadhia	Orchomenos	684		Some			
Petromagoula	Livadhia	Orchomenos	798		8			
Karya	Livadhia	Orchomenos	455		15	Most		
Vranesi	Livadhia	Orchomenos	278		3	Most		
Degle	Livadhia	Orchomenos	82		Some	Most		
Rhachi	Livadhia	Orchomenos	73	Most				
Limni	Chalkis	Limni	1869		2	Some		
Agia Anna	Chalkis	—	1382		50	Many		
Tsouka	Chalkis	—			4	8		
Kourkouloi	Chalkis	—			5			

Data are taken from *Acropolis* (1894d–f) and from Skouphos (1894). Names are given as quoted by the sources (see Table 5 for today's place names).

eight items on this subject between 21 and 28 April (*Times*, 1894a–g). The first report appeared in the 21 April issue and was dated "Athens, 20 April, 7:40 p.m." The eight items were in fact dated between 20 and 27 April, and, although published as anonymous, they have been found to be written by W. C. Bourchier of the Royal Navy, "naval chaplain to H.M.S. *Hood*, of the Mediterranean Squadron" (*Illustrated London News*, 1894). His presence on the spot is confirmed by the newspaper *Acropolis* (1894f) reporting his visit to Malesina.

Bourchier wrote his first reports from Athens (*Times*, 1894a–c) and then from Atalanti (*Times*, 1894d–e), Martino (*Times*, 1894f), and Thivai (*Times*, 1894g). During his survey, started on 24 April from Chalkis (Table 2; Fig. 4), he visited about 15 places, describing the effects with short but precise information on damage and other effects. He was on his way back to Athens via the road passing from Thivai in the afternoon of the same 27 April, when the second earthquake occurred.

T. Skouphos. Skouphos was a geologist who had studied at the University of Athens, and Mitsopoulos had been one of his professors. On 22 April, he was asked by the editor of the newspaper *Ephemeris ton Sitiseon* ("Journal des Debats," as Skouphos himself translated the title) to write a report on what had happened in the area affected by the 20 April earthquake. He was then asked by the same editor to visit the damaged area and to record by means of telegrams his observations in the field. On Tuesday 24 April, he left Athens on the steamer *Pelops* and reached Skala of Atalanti (Kato Pelli) on the evening of 25 April (Skouphos, 1894). From there he started the first part of his survey (Table 2; Fig. 4), which ended in the evening of 27 April at Martino, where he experienced the second large earthquake of the sequence.

The outstanding value of Skouphos's survey depends on his specialistic approach in comparison with the officiality or the extreme synthesis characterizing the other observations. Skouphos's results were fully reported and enriched with information collected in weeks of field work in his 1894 essay (Skouphos, 1894) and published 6 months later in a prestigious scientific journal of the University of Berlin. For the 20 April earthquake his information on damage is used for the 10 places he had the occasion to survey between 25

Table 4
Places Most Damaged by the 27 April 1894 Earthquake

				Buildings				
Place	District	Demos	Inhabitants	Existing	Collapsed	Uninhabitable or Heavily Damaged	Dead	Injured
Atalanti	Locris	Atalanti	1700		Most	Many		3
Arkitsa	Locris	Dafnesion	350		Most			2
Agios Kostantinos	Locris	Dafnesion	327		Many	Most	3	4
Livanates	Locris	Dafnesion	1021		250			
Glounitsa–Drimea	Locris	Dadhion	510	90	30	Most		
Dadhion	Locris	Dadhion	—			Most		
Charma	Locris	Thronion	120		20	Many		
Rigginion	Locris	Thronion	516		70			
Kamena + Bourla	Locris	Thronion	288		16			
Drachmani	Locris	Elatea	903		Few	Many	2	2
Kamaria	Xerochori	—	560	—	17			
Lichades	Xerochori	—	—		30	Many		
Palaiochori	Xerochori	—	78			10		
Yaltra	Xerochori	—	672	83		50		
Xerochori	Xerochori	—	3027		2	Many		Some
Scripou	Livadhia	Orchomenos	684		40			
Arapochori	*Livadhia*	*Livadhia*	*163*	*27*	*27*			
Veli	*Livadhia*	*Livadhia*	*165*	*22*	*8*	*14*		
Bramaga	*Livadhia*	*Livadhia*	*234*	*40*	*25*	*20*		
Chalkis	Chalkis	Chalkis	9919		7	Most		
Lamia	—	—			3	30		

Data are taken from *Acropolis* (1894h–dd) and from Skouphos (1894). Names are given as quoted by the sources (see Table 6 for today's place names). For places in italic, figures give the number of collapsed buildings due to both earthquakes.

and 27 April and for his field observations around Proskinas and Malesina.

From 16/28 April 1894 On

The 27 April earthquake happened at about 9:15 p.m. local time (*Acropolis*, 1894h; Mitsopoulos, 1894; Skouphos, 1894; *Times*, 1894g) on Good Friday. Of the three observers of the 20 April event, the only one still in the field (and precisely at Martino) when the 27 April earthquake occurred was Skouphos. But the occurrence of the second earthquake, and mostly the importance of the surface faulting it caused, made more Greek scientists eager to reach Locris to "touch with their hands" the consequences of the seismic phenomena. Scientific interest captured by surveying and interpreting the surface effects meant less attention to damage effects in coeval Greek newspapers. In them, more space was given to the scientists' (e.g., Papavasiliou's and Mitsopoulos's) reports, and requests for information from damaged places were clearly disregarded, this having been, conversely, the main press concern on the occasion of the 20 April earthquake. As a consequence, information on damage was spread in a number of issues (*Acropolis*, 1894h–dd), and news on damaged places kept appearing until 3 weeks after the 27 April earthquake.

In the case of the 20 April earthquake, a reconstruction of the observers' tours and the identification of places they had surveyed was important to describe exactly the scenario the first earthquake had caused. This is not the case for the observers and the reports they produced after the second earthquake. In fact, such records, independently of the quality of the observations they relied upon, were mostly biased by the accumulation of effects. The most reliable pieces of information consequently turned out to be the locally produced ones (e.g., telegrams written by the *demarchoi*) and mostly all the observations explicitly stating to which earthquake the damage and effects had to be related. Nevertheless, later we give a list and some information on those acting on the stage of Locris after the 27 April event.

On 28 April, Skouphos moved from Martino to Atalanti, from where he sent a long telegram to the Minister of the Interior, Mr. Trikoupi, to inform him about the surface faulting "between Almyra and Kyparissi" and the sea wave on the Almyra coast (*Acropolis*, 1894i). He would not leave Locris for weeks, and his scientific opinions appearing on newspapers were discussed by some other scientists.

One antagonist of Skouphos was A. Papavasiliou, who reached Kato Pelli on 28 April and visited Atalanti and on the following days Proskinas (*Acropolis*, 1894j) and Larimna (*Acropolis*, 1894e). He later published his observations (Papavasiliou, 1894a, b).

Konstantinos Mitsopoulos, professor of geology at the University of Athens, was sent to Locris by the government with the task of giving an evaluation of the seismic event. After stopping in Chalkis, he arrived on 1 May at Kato Pelli on board the *Macedonia* (*Acropolis*, 1894k). He wrote his first report to the Ministry of the Interior from Atalanti on 2 May, a report published in the *Acropolis* (1894k) as well. The controversy with his former student Skouphos started

Table 5
Intensity Data Points for the 20 April 1894 Earthquake in EMS98

QuLoc	Dst	IdLoc	LatDp	LonDp	I_s EMS98
Proskyna	Loc	Proskinas	38.617	23.167	10
Masi	Loc	Mazi	38.600	23.217	10
Martino	Loc	Martino	38.567	23.217	10
Malessina	Loc	Malesina	38.617	23.233	10
Livanataes	Loc	Livanates	38.717	23.050	9
Kyparissi	Loc	Kyparissi	38.633	23.083	9
Skala	Loc	Kato Pelli	38.667	23.083	8–9
Arkitsa	Loc	Arkitsa	38.750	23.033	8–9
Kastri–Larymna	Loc	Larimna	38.567	23.283	8–9
Arapochori	Liv	Arapochori	38.480	22.950	8–9
Bragana	Loc	Tragana	38.616	23.122	8
Skender Aga	Loc	Megaplatanos	38.683	23.000	8
Manesi	Loc	Manesi–Lefkochori	38.600	22.767	8
Kolaka	Loc	Kolaka	38.583	23.033	8
Ano Pelli	Loc	Nea Pelli	38.667	22.983	8
Topolias	Thi	Kastron	38.500	23.167	8
Muriki	Thi	Mouriki	38.417	23.350	8
Kalapodion	Loc	Kalapodhion	38.633	22.883	8
Gkolemion	Loc	Golemi–Goulemion	38.717	22.933	8
Atalanti	Loc	Atalanti	38.650	23.000	8
Skripou	Liv	Orchomenos	38.500	22.983	8
Rachi	Liv	Rakhi	38.433	22.967	8
Katsoumala	Liv	Koutoumoula–Koronia	38.367	22.967	8
Karya	Liv	Karya	38.467	23.000	8
Bramesi–Vranesi	Liv	Vranezi–Agios Spiridhon	38.467	22.967	8
Bramaga	Liv	Thourion	38.483	22.883	8
Beli/Veli	LiV	Veli–Prosillo–Prosilion	38.500	22.933	8
Petromagoula	Liv	Petromagoula	38.500	23.000	8
Degle	Liv	Dheglesi–Mavroyia	38.433	22.983	8
Karditsa	Thi	Akraifnion	38.450	23.217	8
Zelion	Loc	Zelion	38.667	22.883	8
Sphakas	Loc	Sfaka	38.600	22.850	8
Pavlu	Loc	Pavlos	38.533	23.100	8
Lutzi	Loc	Lutsi	38.550	23.083	8
Exarchos	Loc	Exarkhos	38.583	22.950	8
Romaiko	Liv	Romaiikon	38.483	22.933	8
Petra	Liv	Petra–Siakhon	38.367	23.067	8
Agios Georgios	Liv	Agios Georgios	38.367	22.933	8
Limne	Cha	Limni	38.767	23.317	8
Kouraoulioi	Cha	Kourkouloi	38.834	23.340	8
Tanagras + Bratsi	Thi	Tanagra	38.317	23.533	7–8
Liatani	Thi	Liatani	38.283	23.583	7–8
Mantudion	Cha	Mantoudi–Mandoudhion	38.800	23.483	7–8
Keramia	Cha	Keramia	38.833	23.400	7–8
Kokkinon	Thi	Kokkinon	38.483	23.233	7–8
Agia Anna	Cha	Agia Anna	38.867	23.400	7–8
Agios Demetrios	Liv	Agios Dhimitrios	38.450	23.000	7
Chalkis	Cha	Chalkis	38.467	23.600	7
Kerkiais	Xer	Kechries	38.814	23.369	7
Thisvi	Thi	Thisvi	38.267	22.967	7
Spaidhes	Thi	Spaidhes	38.367	23.450	7
Schimasarion	Thi	Skhimatari	38.350	23.583	7
Plataion	Thi	Kapareli Plataion	38.233	23.217	7
Mountrades	Thi	Mustafadhes	38.317	23.450	7
Erimokastro + Thespion	Thi	Thespiai–Thespies	38.300	23.150	7
Chlimbotsari	Thi	Khlembotsarion–Asopia	38.300	23.500	7
Chalia	Thi	Khalia–Dhrosia	38.483	23.550	7
Xerokhori	Xer	Xirokhori–Istiaia	38.950	23.150	7
Tsouka	Xer	Tsouka	38.802	23.427	7
Korinthos	Xer	Kerinthos	38.810	23.444	7
Thivai	Thi	Thivai	38.317	23.317	7

(*continued*)

Table 5
Continued

QuLoc	Dst	IdLoc	LatDp	LonDp	I_s EMS98
Dhritsa	Thi	Dhritsa–Arma	38.350	23.483	7
Tachtali	Loc	Tachtali	38.690	22.840	7
Drachmani–Elatea	Loc	Elatia	38.633	22.767	7
Livadhia	Liv	Livadhia	38.433	22.883	7
Politika	Cha	Politika	38.600	23.550	7
Pyri	Thi	Piri	38.333	23.317	7
Zura	Cha	Kamaritsa	38.617	23.567	7
Nea Pharakli	Cha	Pharakla	38.783	23.400	7
Drasi	Cha	Dhrazion	38.717	23.450	7
Gardiki	Oth	Gardhiki–Pelasyia	38.950	22.833	6
Gialtra	Xer	Yaltra	38.867	22.967	6
Aidipsos	Xer	Aidhipsos	38.883	23.050	6
Pireus	Oth	Pireus	37.950	23.633	6
Lamia	Oth	Lamia	38.900	22.433	6
Molos	Loc	Molos	38.817	22.650	6
Agios Kostantinos	Loc	Agios Kostantinos	38.767	22.850	6
Belitza	Loc	Tithorea	38.583	22.667	6
Koukoura	Liv	Kukura	38.317	22.850	6
Davlia	Liv	Dhavlia	38.517	22.733	6
Eretria	Cha	Eretria	38.400	23.800	6
Athens	Oth	Athens	37.983	23.733	5–6
Megara	Oth	Megara	38.000	23.345	5
Phalero	Oth	Old Phalero	37.933	23.700	5
Aliverio	Cha	Aliverio	38.417	24.033	5
Skyros	Oth	Skiros	38.904	24.563	4
Skopelos	Oth	Skopelos	39.117	23.733	4
Skiathos	Oth	Skiathos	39.167	23.483	4
Karditsa	Oth	Karditsa	39.365	21.921	4
Corinth	Oth	Corinth	37.933	22.930	4
Nauplion	Oth	Nauplion	37.564	22.807	3
Volos	Oth	Volos	39.367	22.950	3
Sparti	Oth	Sparta	37.033	22.420	3
Patras	Oth	Patras	38.244	21.734	3
Larisa	Oth	Larisa	39.633	22.417	3
Egina	Oth	Egina	37.732	23.491	3

QuLoc = place name as quoted by coeval sources; Dst = district in 1894 (Loc = Locris; Liv = Livadhia; Thi = Thivai; Cha = Chalkis; Oth = other districts); IdLoc = place name identified on today's gazetteers and maps; Lat Dp = latitude of the data point; Lon Dp = longitude of the data point; I_s EMS98 = intensity at the site according to EMS98.

in the newspapers and continued in their essays published in German scientific journals (see Pantosti *et al.*, 2001).

Bourchier kept sending his reports to the *Times* (1894g–j, l–o). He went back to Locris some time later, and on this occasion he sketched the illustrations published by the *Illustrated London News* (1894) (Figs. 5 and 6). The pictures were mainly about Atalanti and the surface faulting in the area and were said to "show the scenes of havoc in that neighbourhood as they appeared on May 12" (*Illustrated London News*, 1894, p. 692).

An echo of the events reached other European newspapers. A sample search has considered the main newspapers published in Constantinople, the *Levant Herald and Eastern Express* (1894a–h), in English and French, *Stamboul* (1894a–e), in French, and the Italian *Corriere della Sera* (1894a–i), printed in Milano. These newspapers had no reporters in Greece at the time, so they explicitly mentioned other newspapers or simply made a summary of the items published elsewhere. They did not add any useful information and will not be considered further.

The following year, Mitsopoulos (1895) published a long essay of 40 pages in Greek; scanty information on macroseismic effects as collected in the *Bulletin of the the National Observatory* in Athens was later published by Eginites (1899).

Effects and Intensity Assessment

The stream of records available on the two earthquakes makes too long (and probably unclear) a thorough description of damage sustained by each place. Information on each earthquake is summarized in Tables 3 and 4, showing effects at the most damaged places in terms of collapsed and damaged buildings, dead, and injured. Ancillary data, such as the

Table 6
Intensity Data Points for the 27 April 1894 Earthquake in EMS98

QuLoc	Dst	IdLoc	LatDp	LonDp	I_s EMS98
Atalanti	Loc	Atalanti	38.650	23.000	10
Arkitsa	Loc	Arkitsa	38.750	23.033	10
Skender Aga	Loc	Megaplatanos	38.683	23.000	9
Skala	Loc	Kato Pelli	38.667	23.083	9
Palaiochori	Xer	Palaiokhorion	38.850	22.900	9
Manesi	Loc	Manesi–Lefkochori	38.600	22.767	9
Longos	Loc	Longos	38.767	22.900	9
Livanataes	Loc	Livanates	38.717	23.050	9
Kamaria	Xer	Kamaria	38.933	23.167	9
Agios Kostantinos	Loc	Agios Kostantinos	38.767	22.850	9
Glounitsa + Drumeia	Loc	Glounitsa–Drimea	38.717	22.550	9
Gkolemion	Loc	Golemi–Goulemion	38.717	22.933	9
Arapochori	Liv	Arapochori	38.480	22.950	9
Skripou	Liv	Orchomenos	38.500	22.983	8–9
Romaiko	Liv	Romaiikon	38.483	22.933	8–9
Petromagoula	Liv	Petromagoula	38.500	23.000	8–9
Petra	Liv	Petra–Siakhon	38.367	23.067	8–9
Lichades	Xer	Lichas	38.850	22.867	8–9
Gialtra	Xer	Yaltra	38.867	22.967	8–9
Drachmani–Elatea	Loc	Elatia	38.633	22.767	8–9
Charma	Loc	Kharma	38.733	22.750	8–9
Bramaga	Liv	Thourion	38.483	22.883	8–9
Beli–Veli	Liv	Veli–Prosillo–Prosilion	38.500	22.933	8–9
Xerokhori	Xer	Xirokhori–Istiaia	38.950	23.150	8
Topolias	Thi	Kastron	38.500	23.167	8
Thivai	Thi	Thivai	38.317	23.317	8
Stylis + Agia Marina	Oth	Stylis	38.917	22.617	8
Simia	Xer	Simia	38.867	23.217	8
Rigginion	Loc	Rigini	38.717	22.700	8
Muriki	Thi	Mouriki	38.417	23.350	8
Modion	Loc	Modion	38.667	22.667	8
Mesountion	Xer	Telethrion	38.883	23.167	8
Medenitsa	Loc	Mendenitsa	38.750	22.617	8
Livadhia	Liv	Livadhia	38.433	22.883	8
Limne	Cha	Limni	38.767	23.317	8
Lamia	Oth	Lamia	38.900	22.433	8
Komnena	Loc	Komnina	38.750	22.700	8
Karya	Loc	Karia	38.750	22.783	8
Kamena + Bourla	Loc	Kamena Vourla	38.783	22.783	8
Agia Anna	Cha	Agia Anna	38.867	23.400	8
Dadhion	Loc	Amfiklia	38.633	22.583	8
Aidipsos	Xer	Aidhipsos	38.883	23.050	8
Plataion	Thi	Kapareli Plataion	38.233	23.217	7–8
Kamaritsa	Cha	Kamaritsa	38.617	23.567	7–8
Vagia	Thi	Vagia	38.317	23.183	7
Molos	Loc	Molos	38.817	22.650	7
Gardiki	Oth	Gardhiki–Pelasyia	38.950	22.833	7
Erimokastro + Thespion	Thi	Thespiai–Thespies	38.300	23.150	7
Chalkis	Cha	Chalkis	38.467	23.600	7
Akladhion	Loc	Akladhion	38.885	22.817	7
Mavrommati	Thi	Mavrommation	38.333	23.133	6
Pireus	Oth	Pireus	37.950	23.633	5
Megara	Oth	Megara	38.000	23.345	5
Galaxidion	Oth	Galaxidhion	38.383	22.383	5
Athens	Oth	Athens	37.983	23.733	5
Aitoliko	Oth	Aitoliko	38.433	21.350	5
Patras	Oth	Patras	38.244	21.734	4
Larisa	Oth	Larisa	39.633	22.417	4
Akratous	Oth	Akrata	38.167	22.350	4
Proskyna*	Loc	Proskinas	38.617	23.167	—
Masi*	Loc	Mazi	38.600	23.217	—

(*continued*)

Table 6
Continued

QuLoc	Dst	IdLoc	LatDp	LonDp	I_s EMS98
Martino*	Loc	Martino	38.567	23.217	—
Malessina*	Loc	Malesina	38.617	23.233	—
Kyparissi*	Loc	Kyparissi	38.633	23.083	—
Bragana*	Loc	Tragana	38.616	23.122	—

QuLoc = place name as quoted by coeval sources; Dst = district in 1894 (Loc = Locris; Liv = Livadhia; Thi = Thivai; Cha = Chalkis; Oth = other districts); IdLoc = place name identified on today's gazetteers and maps; Lat Dp = latitude of the data point; Lon Dp = longitude of the data point; I_s EMS98 = intensity at the site according to EMS98.

*Disturbed points: information on these places did not allow us to assess an unbiased macroseismic intensity for the 27 April 1894 earthquake effects.

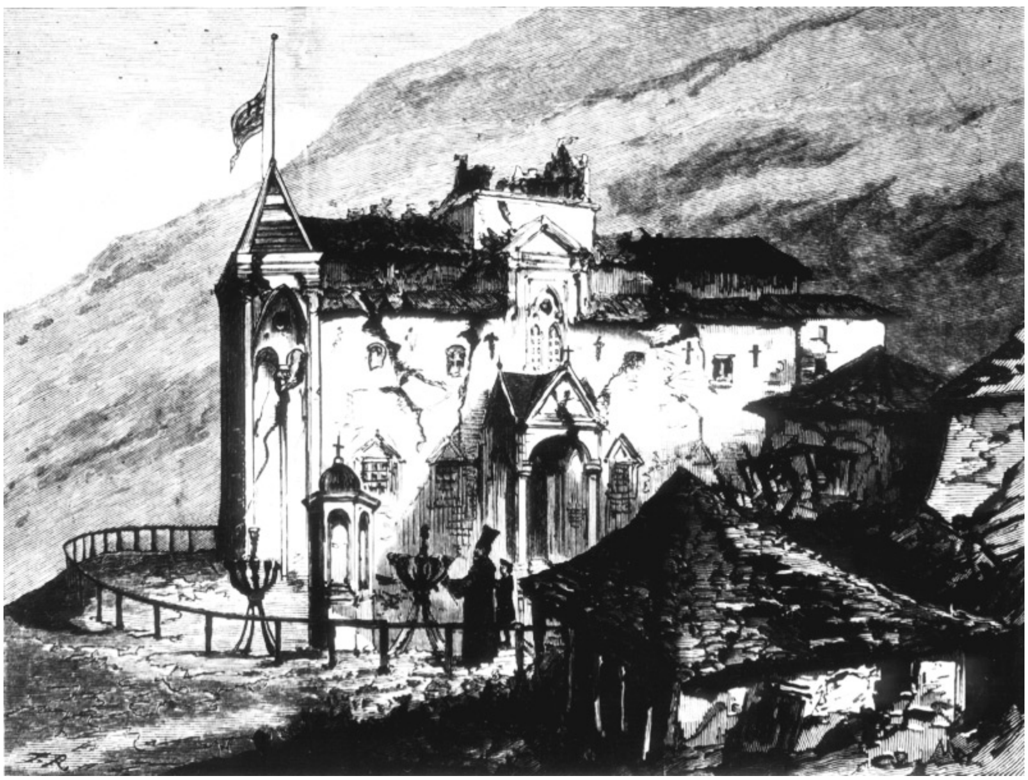

Figure 5. Main church damaged at Atalanti, drawn from a sketch by W. C. Bourchier (*Illustrated London News*, 1894).

number of existing buildings and inhabitants, are given whenever available from the same coeval records.

According to the EMS98 (Grünthal, 1998), the complementary data mentioned earlier are of great importance to coherently apply diagnostics as defined for each intensity degree. EMS98 also supplies a classification of damage to buildings, according to five grades from grade 1, negligible to slight damage, to grade 5, destruction. The classification of damage here applied is the one that EMS98 defines for all masonry buildings, as in the area of interest buildings were commonly of the masonry type (adobe-earth brick or fieldstone), sometimes with an underground basement. In many cases descriptions refer to two-story buildings, of the type that can be seen in a picture of Livadhia at the beginning of the twentieth century (Fig. 7). That there were private houses in a good state of repair one can learn from the list of gentlemen mentioned by the newspapers as owners of some damaged buildings. To comply with EMS98 criteria, the vulnerability of the buildings was also evaluated; in general, a vulnerability class A was assessed, since the percentage of buildings that could be attributed to class B (public buildings in good state of repair, for instance) was not considered significant with respect to the vulnerability class assessment.

The interpretation of all data supplied by the historical records in combination with the grade of damage and vulnerability class assessment has allowed us to evaluate the

Figure 6. Survivors at Atalanti, drawn from a sketch by W. C. Bourchier (*Illustrated London News*, 1894).

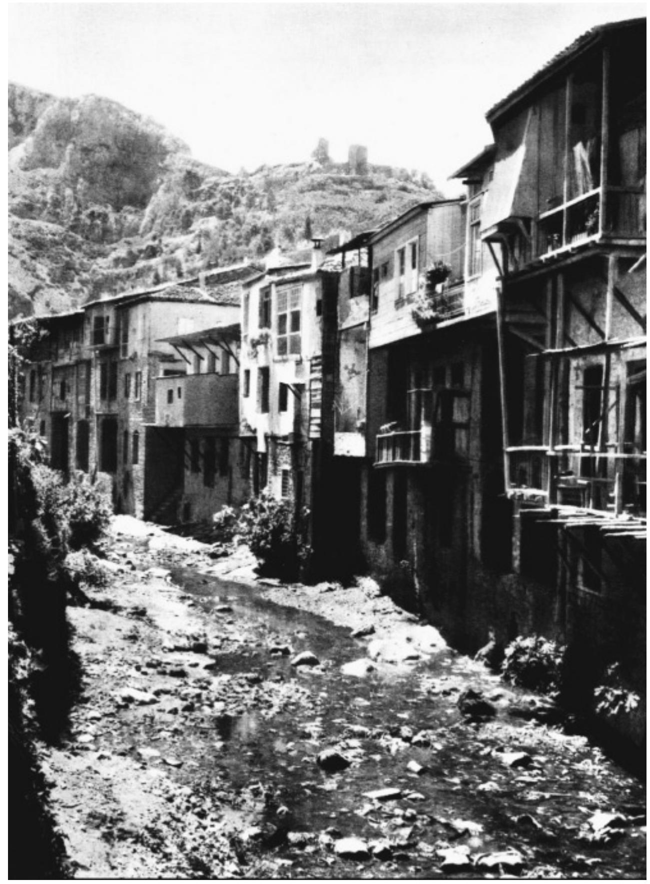

Figure 7. A street of Livadhia in early twentieth century (from Bon [1932]).

macroseismic intensity, in the EMS98 meaning of "classification of the severity of ground shaking on the basis of the observed effects in a limited area" (Grünthal, 1998, p. 21).

Intensity Distribution for the 8/20 April 1894 Earthquake

The scenario of the 20 April 1894 earthquake, as pieced together in this contribution, relies upon a number of coeval records, chosen as the most reliable because they were written by eyewitnesses and observers and then published before the occurrence of the 27 April event (see the earlier section From 8/20 to 15/27 April).

Each newspaper item and each piece of information has been referred to each individual place affected by the 20 April earthquake. Macroseismic intensity at 81 places has been assessed between degree 10 and 6 EMS98. A comprehensive description of the effects was pieced together for 96 places (Fig. 8; Table 5).

In the district of Locris (Fig. 4) damage was reported from 80% of the settlements existing there at the time of the earthquake, their distribution being very similar to today's. The settlements in the Malesina peninsula, in the *demos* of Larimna, were those that suffered the heaviest consequences (Table 3).

Malesina was quite completely in ruins and sustained the highest death toll: 130 out of a population of 951 inhabitants (*Acropolis*, 1894d). Martino was described as having not a single house left standing, 40 dead, and 50 injured (*Acropolis*, 1894d). Then comes Proskinas, with 33 dead, mostly children under the ruin of the church; and all its 120 houses collapsed (*Acropolis*, 1894d). Finally, there was Masi, where out of the 118 inhabitants 7 died and 25 were wounded, and out of 50 houses all either collapsed or suffered serious damage (*Acropolis*, 1894c).

In four more places to the west and northwest of the Malesina peninsula, the earthquake caused death and injuries: at Kyparissi, 4 dead and 14 wounded; at Kato Pelli (Skala), 4 dead; at Skender Aga (Megaplatanos), 5 dead; and at Livanates, 5 dead and 29 injured. In Arkitsa 48 houses collapsed, but there were no casualties, as was the case in Atalanti. In the latter the 20 April effects were less serious than those recorded for the settlements in the Malesina peninsula. Other places in the district of Locris to be mentioned as seriously damaged are Kalapodi and Kolakas.

In the district of Livadhia, the two *demoi* of Livadhia

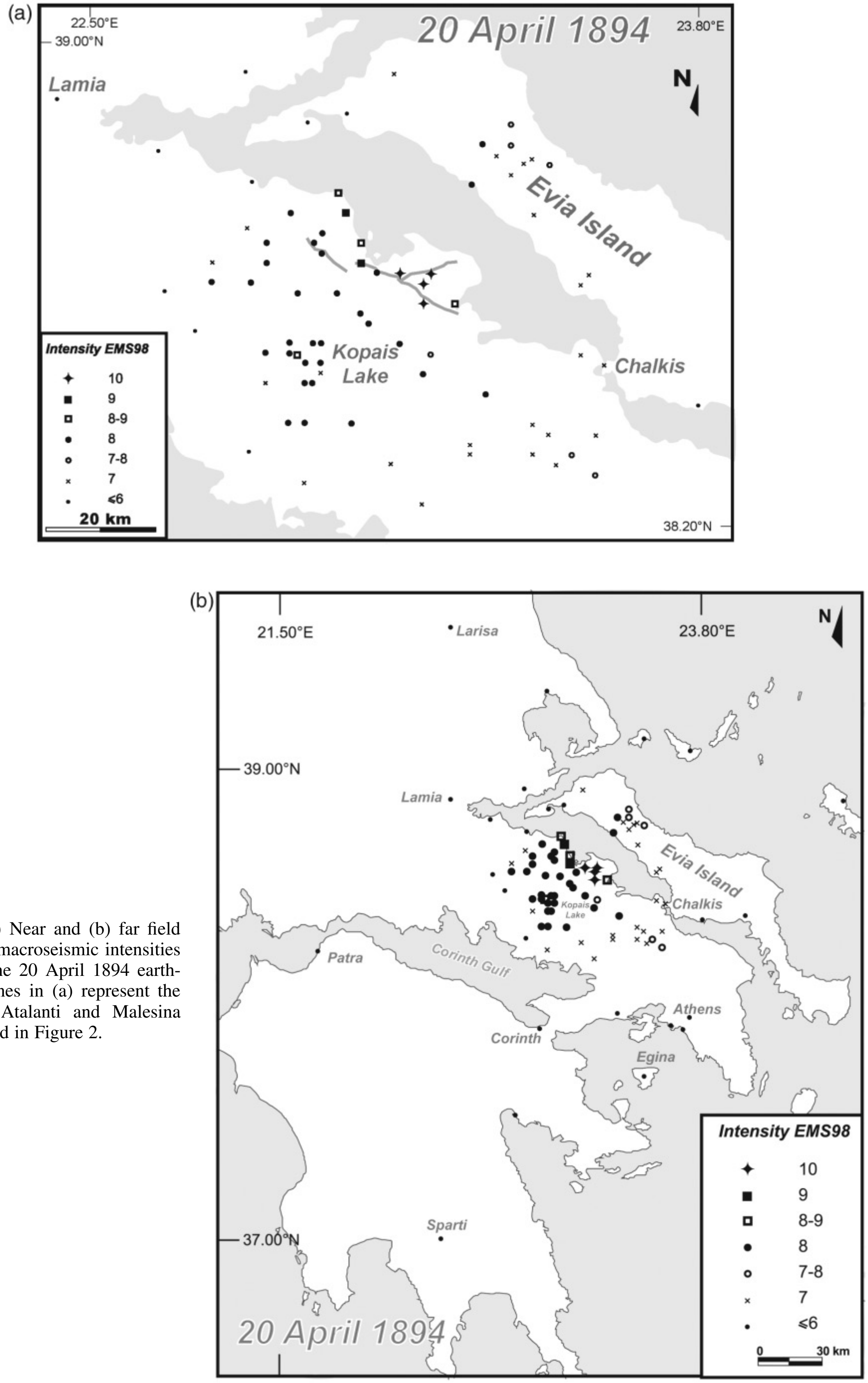

Figure 8. (a) Near and (b) far field distribution of macroseismic intensities (EMS98) for the 20 April 1894 earthquake. Gray lines in (a) represent the traces of the Atalanti and Malesina faults as mapped in Figure 2.

and Orchomenos sustained heavy damage and especially Arapochori, Veli, Bramaga (Thourion), Karya, and Degle.

Damage is reported from the district of Chalkis, then including most of Evia Island. The large villages of Limni and Agia Anna had some collapsed buildings, but information of the same type was made available also for small villages such as Tsouka and Kourkouloi.

Grades of damage, as defined by EMS98, vary between 5, destruction, and 4, very heavy damage, in the southeastern part of the Locris district (Malesina, Martino, Masi, and Proskinas) and between 5 and 3, substantial to heavy damage, in the rest of the district (Kyparissi, Livanates); in the district of Livadhia there were few cases of grade of damage 5 (Arapochori, Veli) but many of grade 4 and 3 (the *demos* of Orchomenos, see Table 3) were described by coeval records. Few cases of grade of damage 4 and many of grade 3 were instead recorded for the 1894 districts of Thivai, Chalkis, and Xerochori.

Effects in Athens were described by newspapers (*Acropolis*, 1894a–b; *Times*, 1894a–b) and by Mitsopoulos (1894). Exaggerations of the first hour were evidenced by the same newspapers for damage to monuments in Athens and for the damage sustained by other large towns, such as Thivai and Megara (*Acropolis*, 1894e).

Intensity Distribution for the 15/27 April 1894 Earthquake

Information on effects other than surface faulting is scattered in the records available for the 27 April earthquake. The recording is biased also by the "inefficiency" of the settlements destroyed by the previous earthquake, which can be looked on as disturbed instruments. This means that coeval records could not supply information on this event for places that were in the most damaged area by the 20 April earthquake, mainly from the Malesina peninsula. Details on 21 heavily damaged places are given in Table 4. Fifteen of them do not appear in Table 3 among the places damaged by the 20 April earthquake, while six of those appearing in the 20 April earthquake list are omitted here (see Table 6, disturbed points). This is to stress that these localities suffered for the second earthquake too, but their intensity could not be evaluated because of the disturbance in coeval records. Intensity has been assessed for 59 places, for 47 of them with a degree between 10 and 7 EMS98 (Table 6).

Casualties were reported from Agios Kostantinos and Drachmani (Elatia), but there were really few in comparison with those caused by the 20 April earthquake. Again, although it was in ruins and crossed by a large fracture, no dead and few injured were reported from Atalanti.

Damage extended to the northwestern part of the Locris district (Fig. 4), in the *demoi* of Atalanti, Dafnesion, Dadhion, and Thronion (Table 6; Fig. 9). The situation in Atalanti itself was well shown by the illustrations by Bourchier (Figs. 5 and 6). Available information points at three villages of the *demos* of Dafnesion as the most damaged: the westernmost one is Agios Kostantinos, about which there was just a small piece of information in *Acropolis* (1894k), while Skouphos (1894) reported a second-hand description, since he did not visit this village. Another one is Arkitsa, which was not even mentioned in the newspaper items after the 27 April event. Skouphos (1894) referred to it as having become a heap of ruins due to the 27 April earthquake; the intensity assessment here proposed takes his statement as reliable. Information is lacking on Livanates as well, except for a request of bread, which could not be baked on the spot because all the ovens collapsed (*Acropolis*, 1894i).

The other seriously damaged villages belonged to the *demoi* of Dadhion and Thronion (*Acropolis*, 1894l). Belonging to the former are Glounitsa, where 30 houses out of 90 collapsed, and Charma, where 20 out of 120 houses were made uninhabitable; in the *demos* of Thronion, two villages sustained heavy damage, since at Rigginion 70 houses collapsed as well as 16 at Kamena Vourla.

The 27 April event caused damage in some villages of the northwestern part of the island of Evia, roughly corresponding to the 1894 district of Xerochori (see Fig. 4); collapsed houses were reported in Xerochori itself (*Acropolis*, 1894h,k), Lichas (*Acropolis*, 1894k,p), and Kamaria (*Acropolis*, 1894l), and also heavily damaged were Palaiochori and Yaltra (*Acropolis*, 1894j,l).

Assessing intensity for places reported as damaged by the 27 April earthquake has been a tricky task: there has been no way to disentangle pieces of information on effects due to this earthquake only from those in fact reporting cumulative effects. This applies mostly to coeval scientific contributions referred to earlier (e.g., Mitsopoulos, 1894; Skouphos, 1894). For instance, while precisely discriminating on surface effects due to each earthquake, Skouphos (1894) simply merged the information on damage at 69 places due to both earthquakes by composing a comprehensive table in the last section of his essay. In that table, for each place he gave the number of inhabitants, damaged houses, dead, and injured, without any chronological differentiation. For this reason and as explained earlier, we trusted more what in our opinion are the less influenced sources of information, those produced by local observers and forwarded to the coeval Greek newspapers.

Cases of grade of damage 5, as defined by EMS98, were reported from the districts of Locris (Atalanti, Arkitsa, Agios Kostantinos, Glounitsa, Charma, Rigginion, and Kamena Vourla) and Xerochori (Xerochori village, Lichas, Kamaria, and Palaiochori). While data on houses just collapsed, or heavily damaged before and now collapsed, could be taken as sufficiently reliable, details needed to assess lesser grades of damage (4 and 3 mainly) are completely lacking from all coeval records.

At those places where intensity had been estimated at equal to or greater than 9 EMS98 for the 20 April earthquake and for which no new independent information was supplied by coeval records, no intensity has been assessed (see disturbed points in Table 6). This is mainly the case for the four places with $I = 10$ (Proskinas, Malesina, Mazi, and Martino)

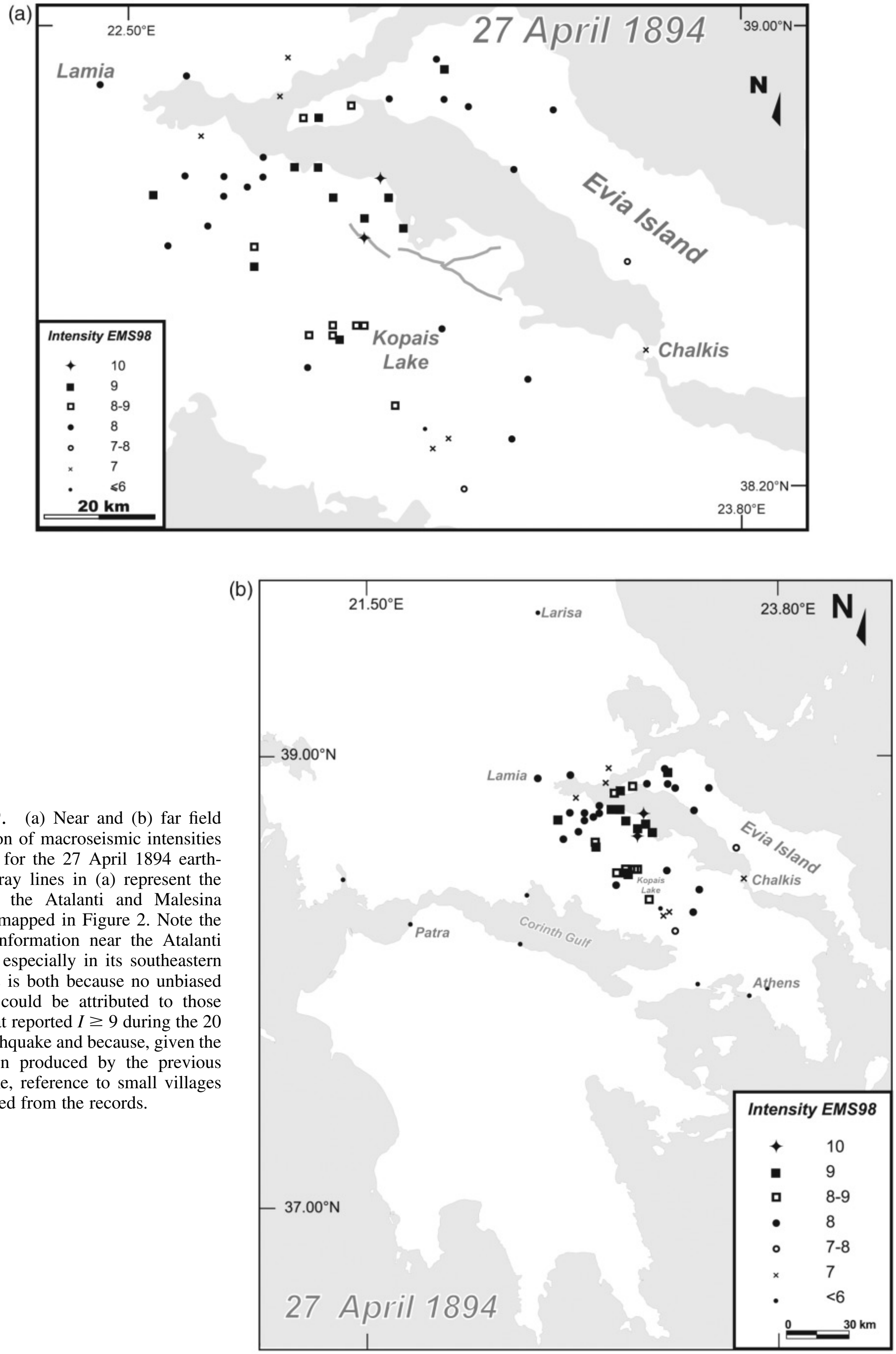

Figure 9. (a) Near and (b) far field distribution of macroseismic intensities (EMS98) for the 27 April 1894 earthquake. Gray lines in (a) represent the traces of the Atalanti and Malesina faults as mapped in Figure 2. Note the lack of information near the Atalanti fault and especially in its southeastern part. This is both because no unbiased intensity could be attributed to those places that reported $I \geq 9$ during the 20 April earthquake and because, given the destruction produced by the previous earthquake, reference to small villages disappeared from the records.

and for others with $I = 9$ and also $I = 8–9$, such as Kiparissi, Kato Pelli (Skala), and Larimna.

How the decision of not including the highest intensity values due to the 20 April earthquake in the intensity distribution of the 27 April earthquake will affect the possibility of describing the seismogenic source of the latter is discussed in the following section.

Imaging the Seismogenic Sources

Macroseismic intensities for the 20 and 27 April earthquakes have been used as input for defining the earthquake sources by using the Boxer program (Gasperini *et al.*, 1999; Gasperini and Valensise, 2000). This method is based on the observation that earthquake damage distribution reflects as a whole the physical characteristics of the causative earthquake fault. The use of different degrees of intensity by the Boxer program has been proven to provide stability in the results, and local effects are generally overcome by considering the complete distribution of effects. The Boxer approach was tested for several modern earthquakes, whose source was known independently, in peninsular Italy; good agreement was found (Gasperini *et al.*, 1999; Gasperini and Valensise, 2000). The Boxer program contains algorithms that process intensity data to compute the earthquake epicenter expressed as the center of the distribution of damage, assess the earthquake moment magnitude (**M**), and provide a physical description of the earthquake source (i.e., strike, length, width). The source is represented as a "rectangle centered on the macroseismic epicenter. The rectangle represents either the actual surface projection of the causative fault or, at least, the surface projection of the portion of the Earth crust within which the earthquake fault is more likely to be located" (Gasperini and Valensise, 2000, p. 766). No inference about the fault dip is provided; in the box representation the dip is by default 45° perpendicular to the strike. In the following text and figures, we will refer to this rectangle as a "box" and use it as the best description of the seismogenic source that can be obtained with the available set of data.

As already mentioned, the Boxer program was conceived and tested for earthquakes that occurred in peninsular Italy. However, considering that peninsular Italy and Locris share similarities in the present kinematics and upper crust setting, which are among the main factors controlling the pattern of ground shaking at the surface, and that the Boxer approach already includes uncertainties related to the high variability in this type of data (i.e., intensity estimates, seismic-wave propagation characteristics, relations between rupture size and M, between M and I, etc.), we assume we can use the Boxer program with confidence in the Locris case too.

What image of the seismogenic sources of the 20 and 27 April earthquakes has been obtained by processing the macroseismic intensity data as assessed by this study?

The 20 April 1894 intensity distribution (Fig. 8) appears to be a fair one, the information on effects from coeval sources having been recorded in a situation of normality and stability, although the lack of information in the Evia Channel is a reason of disturbance in the overall reliable macroseismic scenario for this earthquake.

The default box obtained by applying the Boxer method to the set of data of Table 5 (Fig. 10; Table 7) indicates that the macroseismic epicenter is on the Malesina peninsula and **M** is 6.4, in agreement with the Ambrayses and Jackson (1990) estimate (Table 1). The box strike and location suggest that the 20 April earthquake could have ruptured the southern portion of the Atalanti fault, possibly between Kyparissi and Larimna. The standard deviation for the computed azimuth is $\pm 34.4°$ (shown in Fig. 10 by the shaded boxes); thus we cannot completely rule out the possibility that the rupture could have occurred on the Malesina fault (Fig. 2, box 2).

The uncertainty in azimuth and the lack of observations inside the Evia Channel highlight the need for some tests on the stability of the default results. We present two of the tests we performed, both done by adding virtual intensity data points in the middle of the sea between Locris and Evia (Table 7; Fig. 10, virtual points 1, 2, 3). The location of the virtual points was based on the fact we would like to understand if the offshore source, proposed by Pantosti *et al.* (2001) (box 3, Fig. 2), could be considered as a potential source for the 20 April earthquake. Therefore the three virtual points were located within this box. Test 1 included two virtual points (1 and 2) with $I = 10$. The only parameter that changed substantially was the strike of the box, but the standard deviation increased substantially (± 62.8). This increased uncertainty associated to the solution of test 1 can be read as evidence of the fact that the two added virtual points represent an anomaly within the whole intensity distribution pattern, and they would be meaningless.

Test 2 included three virtual points with $I = 9$. The solution is very similar to the default one, but with a higher standard deviation for the strike; thus we conclude that the default solution is stable enough to be conceivably representative of the April 20 earthquake source. On this basis we can also rule out completely the hypothesis of Pantosti *et al.* (2001) of an offshore source for this event (box 3, Fig. 2).

As already mentioned, the 27 April intensity data are less unbiased and clean than the 20 April data (see Intensity Distribution for the 15/27 April 1894 Earthquake [earlier section] and Fig. 9). It is worth recalling that no macroseismic intensity has been estimated for the 27 April earthquake at those places that were the most damaged by the 20 April event, in particular at the villages southeast of Atalanti and the four settlements in the Malesina peninsula (compare Figs. 8a and 9a). For the sake of completeness, these places are separately listed as "disturbed" at the bottom of Table 6 with no intensity evaluation.

Processing the intensity data obtained by this study for the 27 April earthquake from the data of Table 6, with the exclusion of the disturbed ones, with the Boxer method pro-

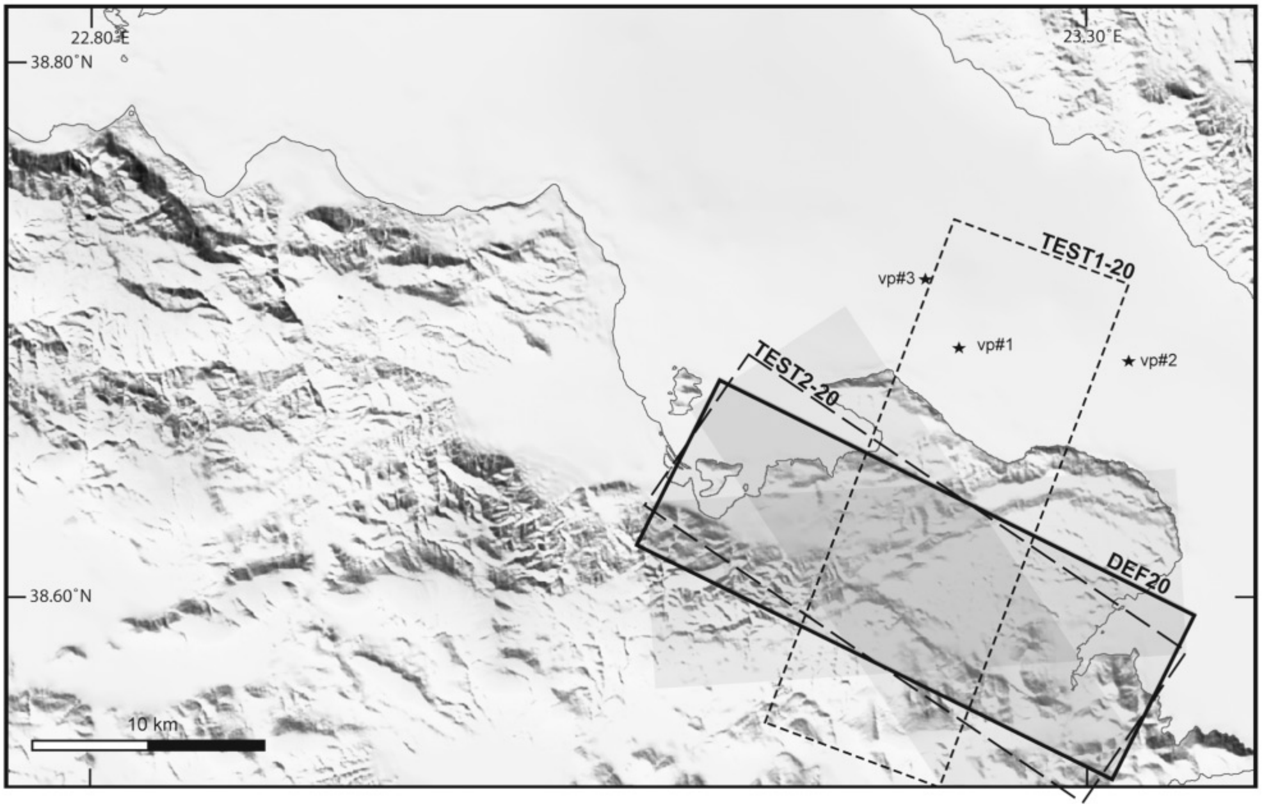

Figure 10. Boxes obtained by applying the Boxer method (Gasperini *et al.*, 1999) on the set of macroseismic intensity data for the 20 April 1894 earthquake (Table 5). Solutions of this computation and from two tests are in Table 7. DEF 20 is the default solution, with the shaded boxes indicating the width of the uncertainty. Dashed boxes represent the two solutions from the tests made by adding virtual points 1 and 2 with $I = 10$ (Test 1) and 1, 2, and 3 with $I = 9$ (Test 2) to the data set of Table 5.

Table 7
Earthquake and Fault Parameters Obtained from the Boxer Program (Gasperini *et al.*, 1999)

Data	IDP	I_x	I_o	Lat	Lon	**M**	FLE	FAZ	Std AZ
20 April 1894 (see Fig. 10 for reference)									
Default: IDPs from Table 5	**96**	**10**	**10**	**38.600**	**23.208**	**6.44**	**22.8**	**117.8**	**34.4**
Test 1: IDPs from Table 5 + virtual points 1 and 2 $I = 10$	98	10	10	38.629	23.225	6.45	23.3	21.9	62.8
Test 2: IDPs from Table 5 + virtual points 1, 2, 3 $I = 9$	99	10	10	38.600	23.208	6.44	22.8	125.7	72.8
27 April 1894 (see Fig. 11 for reference)									
Default: IDPs from Table 6	59	10	10	38.717	22.959	6.64	30.1	113.4	112.6
Test 6: IDPs from Table 6 + virtual points 4, 6 $I = 10$	**61**	**10**	**10**	**38.662**	**23.070**	**6.54**	**26.2**	**128.9**	**30.4**
Test 7: IDPs from Table 6 + virtual points 4, 5, 6 $I = 10$	**62**	**10**	**10**	**38.633**	**23.079**	**6.53**	**26.0**	**124.6**	**20.2**
Test 8: IDPs from Table 6 + virtual points 4–9 $I = 10$	65	10	10	38.620	23.147	6.55	26.6	114.9	11.7
Test 9: IDPs from Table 6 + virtual points 4–9 $I = 10$	64	10	10	38.623	23.143	6.55	26.6	115.3	14.1

IDP = number of intensity data points; I_x = maximum intensity; I_o = epicentral intensity; Lat and Lon = epicenter coordinates; **M** = moment magnitude; FLE = fault length; FAZ = fault azimuth; Std AZ = standard deviation for azimuth.

vides a solution with an epicenter location northwest of the Atalanti plain, near the village of Goulemi and **M** 6.6, substantially smaller than the one estimated before (Table 1). The box strike and location suggest that this earthquake may have ruptured the northern portion of the Atalanti fault, from Almyra to Atalanti, including also a northernmost rupture at Agios Kostantinos on an unknown continuation of the Atalanti fault (Fig. 11 and Table 7). However, this solution has a low significance because of the ±112.6 azimuth standard deviation (see shaded circle in Fig. 11). This means that the default intensity distribution and box obtained cannot be accepted.

We suspect that this large uncertainty is due to the strong information control on the 27 April damage distri-

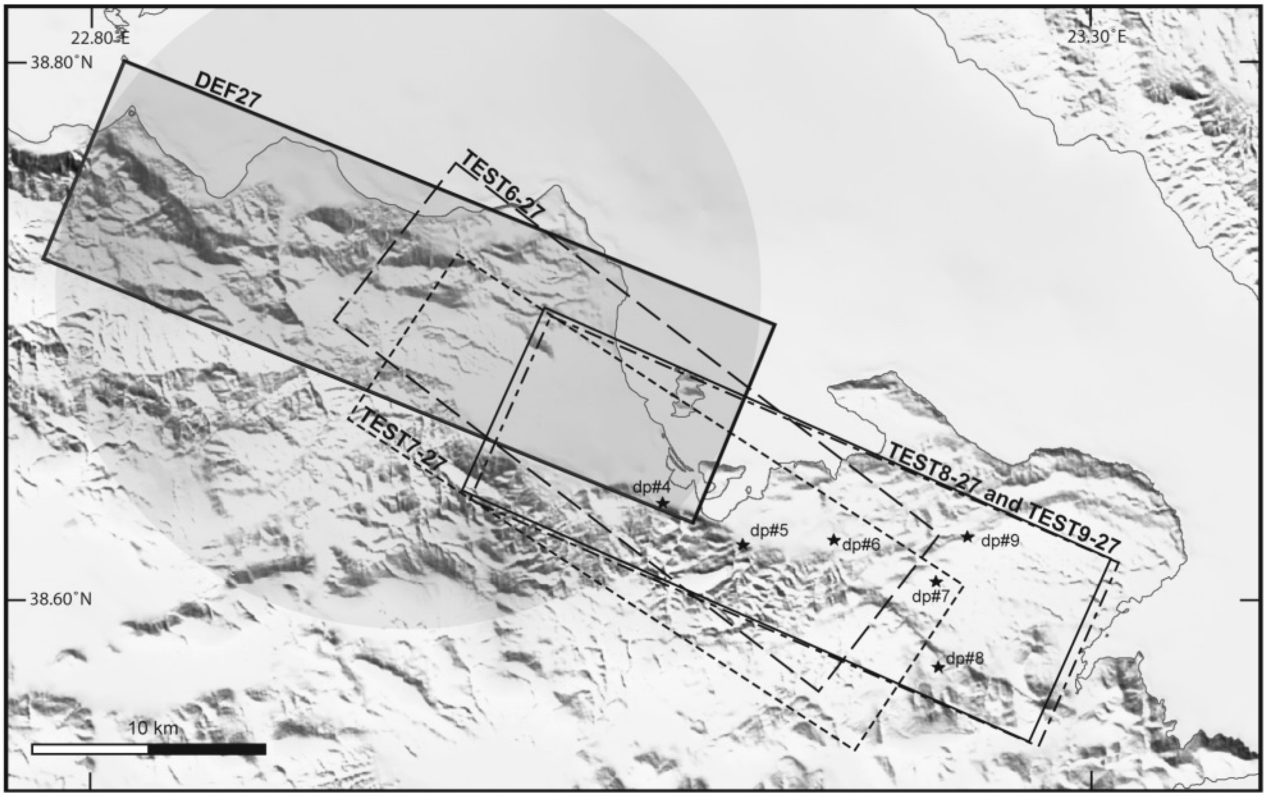

Figure 11. Boxes obtained by applying the Boxer method (Gasperini *et al.*, 1999) on the set of macroseismic intensity data for the 27 April 1894 earthquake (Table 6). Solutions of this computation and from four tests are in Table 7. DEF 27 is the default solution, with the shaded circle indicating the width of the uncertainty. Dashed and thin boxes represent the four solutions from the tests made by adding disturbed points with $I = 10$ at the locations for which no intensity was given because they suffered $I \geq 9$ during the previous earthquake.

bution caused by the occurrence of the 20 April event 7 days before. In fact, as already discussed, no intensity was attributed to some localities that suffered very heavy damage on the occasion of the April 20 event and in particular to those in the Malesina peninsula (Mazi, Martino, and Malesina). This could have caused the default source for the 27 April earthquake to shift to the northwest; thus, we decided to perform some tests to verify this hypothesis. The tests consisted in adding to the default set the disturbed points (Table 6), namely Kyparissi, Tragana, Proskinas, Mazi, Martino, Malesina (dp4–dp9, respectively), and in attributing them $I = 10$. We discuss only the four more significant tests out of the nine performed, which differ in the number as well as in the location of the disturbed points taken into account (Table 7; Fig. 11, dp4–dp9). With respect to the default one, all the test solutions show a consistent shift of the epicenter to the southeast, a shorter fault length, and a smaller **M**; strike remains stable. It is worth noticing that all the boxes obtained have a shorter length than the whole Atalanti fault as mapped by Pantosti *et al.* (2001). All the test solutions appear to be more conceivable than the default one and in agreement with the trace of the surface faulting produced by the April 27 earthquake. Our preferred solutions, expected to provide the best image for the 27 April rupture area, are those obtained by test 6 and test 7, because we feel these are less subjectively manipulated. In fact, it is clear from the report by Skouphos (1894) that the 27 April surface faulting occurred at least between Proskinas and Atalanti; thus it is conceivable to infer that the villages of Kyparissi, Tragana, and Proskinas (dp4–dp6 in Fig. 11) suffered, like the town of Atalanti, $I = 10$.

Conclusions

Coeval reports collected and published by Greek and other newspapers (e.g., *Acropolis*, 1894a–dd; *Times*, 1894a–u) are used to propose a new image for the sources responsible for the 20 and 27 April 1894 earthquakes. The reports are in complete agreement with the survey by the geologist Skouphos (1894) in that the 20 and 27 April earthquakes heavily damaged about 70 places, causing the collapse of hundreds of buildings and making uninhabitable a total of 4000. There were more than 250 dead and about 170 injured. The 27 April earthquake caused only five deaths, but it dramatically increased losses in places already hit and in 15 additional places.

Effects of the 20 April 1894 earthquake have been reconstructed by means of coeval sources not biased by the consequences of the 27 April earthquake. Also, the intensity assessment of the 27 April earthquake has taken into account problems of accumulative effects in an area that had sustained a dramatic change in its building assets and vulnerability only 1 week before.

An intensity equal to or higher than 7 EMS98 was assessed at 70 and 47 places on the occasion of the 20 and 27 April earthquakes, respectively, and $I \geq 8$ was assessed in all at 70 different places. The number of places for which intensity is available for the 20 April earthquake is doubled compared to previous studies referred to earlier.

We have used the Boxer program (Gasperini *et al.*, 1999) to characterize the earthquake and fault parameters on the basis of our new sets of macroseismic data. Tests have also been performed to evaluate the influence of different intensity distributions of each earthquake on the determination of the earthquake size and location.

In all, data as collected and interpreted in this study are considered reliable for a new assessment of (1) the magnitude of each earthquake and (2) location and association with a seismogenic source. In comparison with what suggested by previous studies, that is the 20 April event being smaller than the 27 April one, the size of the two earthquakes is now very similar, **M** 6.4 for the 20 April event and **M** 6.5 for 27 April.

The most representative sources of the 1894 earthquakes are shown as boxes in Figure 12. For the 20 April earthquake the default box has been chosen (Table 7), suggesting a rupture of the southern portion of the Atalanti fault. For the 27 April earthquake both solutions from test 6 and test 7 are preferred, because they seem to make the geological and macroseismic data converge. Because the source derived for the April 27 earthquake is too small to comply with the rupture of the whole Atalanti fault, we prefer to exclude the Malesina fault as that responsible for the April 20 earthquake and to assume that the two earthquakes have ruptured the whole Atalanti fault as mapped from its surface expression (see Pantosti *et al.*, 2001). There is some overlap of the two sources in the central part of the fault that we cannot solve. As discussed in Pantosti *et al.* (2001), the Atalanti fault shows some internal complexity that can control fault segmentation. A potential rupture boundary in agreement with the earthquake sources we have just imaged can be set at the subtle Atalanti fault trace change in strike and intersection with the Malesina fault near the village of Proskinas (Fig. 12). Following this reasoning, the 20 April earthquake would have ruptured the Atalanti fault from the Proskinas boundary to Skroponeri Mountain for about 16 km, whereas the 27 April earthquake ruptured at least from the northwest Chlomon fault zone (fault boundary according Pantosti *et al.* [2001]) to Proskinas for about 20 km. These estimated lengths are found in agreement with the Wells and Coppersmith (1994) empirical relations, according to which an M 6.4–6.5 normal-faulting earthquake is consistent with a 16 to 20-km-long surface rupture.

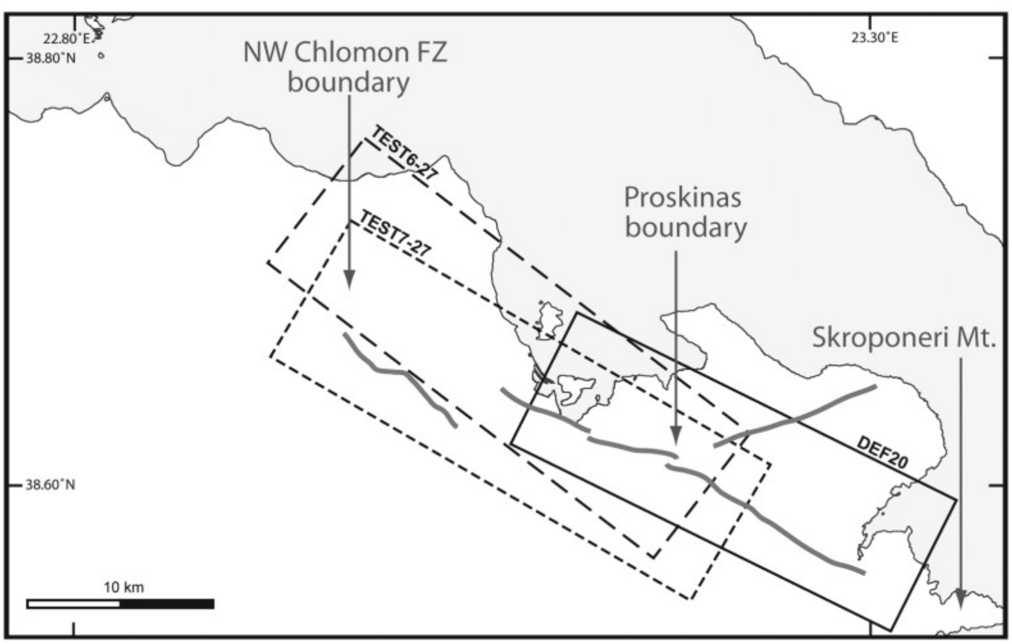

Figure 12. Preferred solution for the 20 and 27 April 1894 seismogenic sources. Both Test 6 and Test 7 are considered good representations of the 27 April source. The whole Atalanti fault appears to have ruptured during these two events, between Proskinas and Skroponeri Mountain during the 20 April earthquake and between Proskinas and Atalanti during the 27 April earthquake.

Although some uncertainties still remains, we conclude that the 20 and 27 April 1894 earthquakes together ruptured the whole Atalanti fault (Fig. 12).

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References

Coeval Sources

Newspapers

Acropolis (1894a–dd). Athens. (a) April 9 (21), no. 4372; (b) April 10 (22), no. 4373; (c) April 11 (23), no. 4374; (d) April 12 (24), no. 4375; (e) April 13 (25), no. 4376; (f) April 14 (26), no. 4377; (g) April 15 (27), no. 4378; (h) April 16 (28), no. 4379; (i) April 17 (29), no. 4380; (j) April 19 (May 1), no. 4381; (k) April 20 (May 2), no. 4382; (l) April 21 (May 3), no. 4383; (m) April 22 (May 4), no. 4384; (n) April 23 (May 5), no. 4385; (o) April 24 (May 6), no. 4386; (p) April 25 (May 7), no. 4387; (q) April 26 (May 8), no. 4388; (r) April 27 (May 9), no. 4389; (s) April 28 (May 10), no. 4390; (t) April 29 (May 11), no. 4391; (u) April 30 (May 12), no. 4392; (v) May 1 (13), no. 4393; (w) May 2 (14), no. 4393 [*sic*]; (x) May 3 (15), no. 4394; (y) May 4 (16), no. 4395; (z) May 5 (17), no. 4396; (aa) May 6 (18), no. 4397; (bb) May 7 (19), no. 4398; (cc) May 8 (20), no. 4399; (dd) May 9 (21), no. 4490.

Corriere della Sera (1894a–i). Milano. (a) 22–23 April, no. 110; (b) 24–25 April, no. 112; (c) 25–26 April, no. 113; (d) 28–29 April, no. 116; (e) 29–30 April, no. 117; (f) 30 April–1 May, no. 118; (g) 3–4 May, no. 120; (h) 6–7 May, no. 123; (i) 9–10 May, no. 126.

Levant Herald and Eastern Express (1894a–h). Constantinople. (a) April 21, no. 93; (b) April 23, no. 94; (c) April 24, no. 95; (d) April 25, no. 96; (e) April 26, no. 97; (f) May 1, no. 100; (g) May 2, no. 101; (h) May 3, no. 102.

Stamboul (1894a–e). Constantinople. (a) 21 April; (b) 23 April; (c) 24 April; (d) 8 May; (e) 15 May.

Times (1894a–u). London. (a) April 21, no. 34244; (b) April 23, no. 34245; (c) April 24, no. 34246; (d) April 25, no. 34247; (e) April 26, no. 34248; (f) April 27, no. 34249; (g) April 28, no. 34250; (h) April 30, no. 34251; (i) May 1, no. 34252; (j) May 2, no. 34253; (k) May 3, no. 34254; (l) May 4, no. 34255; (m) May 5, no. 34256; (n) May 7, no. 34257; (o) May 8, no. 34258; (p) May 9, no. 34259; (q) May 10, no. 34260; (r) May 11, no. 342561; (s) May 12, no. 34262; (t) May 14, no. 34263; (u) May 15, no. 34264.

Maps and Pictures

Bon, A. (1932). *In Greece*, Kauffman Publisher, Athens.

Illustrated London News (1894). June 2, no. 2876, vol. 54.

Anonymous (1885). Tables IV and VII of a general map of Greece. Edited by K. K. Militär, Geografisches Institut, Vienna (courtesy of the Royal Geographical Society, London), scale 1:300,000.

Seismological Studies

Eginites, D. 1899. Tremblements de terre observés en Grèce de 1893 à 1898, *Annales Obs. Natl. Athenes*, **2.**

Mitsopoulos, K. (1894). Die Erdbeben von Theben und Lokris in den Jahren 1893 und 1894. Abdruck aus Dr. A. Petermanns Geographische Mitteilungen, Heft X, 1–11.

Mitsopoulos, K. (1895). *O megas tis Lokridos seismos kata aprilion tou 1894*, Ethnikon Typographeion, Athinai, 40 pp. (in Greek).

Nature. (1894). (a) April 26, no. 1278, vol. 49, p. 604; (b) May 3, no. 1279, vol. 50, pp. 7, 13; (c) October 18, no. 1303, vol. 50, p. 607.

Papavasiliou, A. (1894a). Sur le tremblement de terre de Locride (Grèce) du mois d'avril 1894, *C. R. Hebdomadaires des Séances de l'Acad. Sci.* **69,** 112–114.

Papavasiliou, A. (1894b). Sur la nature de la grande crevasse produite à la suite du dernier tremblement de terre de Locride, *C. R. Hebdomadaires des Séances de l'Acad. Sci.* **69,** 380–381.

Philippson, A. (1894a). Das diesjährige Erdbeben in Lokris, *Verhandlungen der Gesellschaft für Erdkunde zu Berlin*, **21,** 332–334.

Philippson, A. (1894b). Bericht: *Sitzung der naturw. Sektion vom 4. Niederrheinische Gesellschaft in Bonn*, 63–65.

Skouphos, Th. G. (1894). Die zwei grossen Erdbeben in Lokris am 8/20 und 15/27 April 1894, *Zeitschrift der Gesellschaft für Erdkunde zu Berlin*, **29,** 409–475.

Scientific Papers

Ambraseys, N. N. and J. Jackson 1990. Seismicity and associated strain of central Greece between 1890 and 1988, *Geophys. J. Int.* **101,** 663–708.

Cundy, A. B., S. Kortekaas, T. Dewez, I. S. Stewart, I. W. Croudace, H. Maroukian, D. Papanastassiou, K. Gaki-Papanastassiou, K. Pavlopoulos, and A. Dawson (2000). Coastal impacts of the 1894 Gulf of Atalanti earthquakes, central Greece, *Marine Geol. Spec. Publ.* **170,** 3–26.

Galanopoulos, A. G. (1960). A catalogue of shocks with $I_o \geq$ VI or $M \geq$ 5 for the years 1801–1958, Athens Seismol. Lab. Univ. of Athens, 119 pp.

Ganas, A. (1997). Fault segmentation and seismic hazard assessment in the Gulf of Evia rift, central Greece, *Ph.D. Thesis*, University of Reading, United Kingdom, 368 pp.

Ganas, A., and A. V. Buck (1998). A model for the tectonic subsidence of the Allai archaeological site, central Greece, *Bull. Geol. Soc. Greece*, **32,** no. 1, 181–187.

Ganas, A., G. P. Roberts, and T. Memou (1998). Segment boundaries, the 1894 ruptures, and strain patterns along the Atalanti fault, central Greece, *J. Geodyn.* **26,** no. 2–4, 461–486.

Gasperini, P., and G. Valensise (2000). From earthquake intensities to earthquake sources: extending the contribution of historical seismology to seismotectonic studies, *Ann. Geofis.* **43,** no. 4, 765–785.

Gasperini, P., F. Bernardini, G. Valensise, and E. Boschi (1999). Defining seismogenic sources from historical earthquake felt report, *Bull. Seism. Soc. Am.* **89,** 94–110.

Grünthal, G. (Editor) (1998). European Macroseismic Scale 1998, in *Cah. du Centre Européen de Géodinamique et de Séismologie*, Vol. 15, Luxembourg, 99 pp.

Institute of Geology and Mineral Exploration (IGME) (1989). Seismotectonic map of Greece, scale 1:500.000. IGME, Athens.

Karnik, V. (1971). *The Seismicity of the European Area*, Vol. 2, D. Reidel Publishing Co., Dordrecht.

Lemeille, F. (1977). Etudes néotectoniques en Grèce centrale nord-orientale (Eubée centrale, Attique, Béotie, Locride) et dans le Sporades du Nord (île de Skiros), *Thèse de Troisème Cycle*, Université Paris XI, Centre Orsay, 173 pp.

Magosci, P. R. (1993). *Historical Atlas of East Central Europe: A History of East Central Europe*, Vol. 1, University of Washington Press, Seattle, 218 pp.

Makropoulos, K. C., and V. Kouskouna (1994). The 1894 April 20 and 27 Atalanti earthquakes: 100 years after—lessons learnt, in *Proc. XXIV ESC General Assembly*, Athens, Greece 19–24 September 1994, Vol. 1, 61–71.

Pantosti, D., P. M. De Martini, D. Papanastassiou, N. Palyvos, F. Lemeille, and G. Stavrakakis (2001). A reappraisal of the 1894 Atalanti earthquake surface ruptures, central Greece, *Bull. Seism. Soc. Am.* **91,** no. 4, 760–780.

Pantosti, D., P. M. De Martini, D. Papanastassiou, F. Lemeille, N. Palyvos, and G. Stavrakakis (2004). Paleoseismological trenching across the Atalanti (Central Greece): evidence for the ancestors of the 1894 earthquake during the Middle Ages and Roman times, *Bull. Seism. Soc. Am.* **94,** no. 2, 531–549.

Papazachos, B., and K. Papazachou (1989). *Oi Seismoe tis Ellados* (The Earthquakes of Greece), Ekdoseis Ziti, Thessaloniki, 356 pp.

Papazachos, B., and K. Papazachou (1997). *The Earthquakes of Greece*, Editions Ziti, Thessaloniki, 304 pp.

Shebalin, N. V., V. Karnik, and D. Hadzievski (Editors) (1974). Catalogue of earthquakes of the Balkan region, I, UNDP-UNESCO survey of the seismicity of the Balkan region, Printing Office of the University Kiril and Metodij, Skopje, 600 pp.

Sieberg, A. (1932). Erdbebengeographie, in *Handbuch der Geophysik*, B. Gutenberg (Editor), Verlag von Gebrüder Borntraeger, Berlin, Band 4, Lieferung 3, 687–1005.

Wells, D. L., and K. J. Coppersmith. (1994). New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, *Bull. Seism. Soc. Am.* **84,** 974–1002.

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