

Article

Reconstructing Impact of the 1867 Ionian Sea (Western Greece) Earthquake by Focusing on New Contemporary and Modern Sources for Building Damage, Environmental and Health Effects

Spyridon Mavroulis ^{1,*} , Maria Mavrouli ², Efthymios Lekkas ¹ and Panayotis Carydis ³ 

¹ Department of Dynamic Tectonic Applied Geology, Faculty of Geology and Geoenvironment, School of Sciences, National and Kapodistrian University of Athens, 15784 Athens, Greece; elekkas@geol.uoa.gr

² Department of Microbiology, Medical School, National and Kapodistrian University of Athens, 11527 Athens, Greece; mmavrouli@med.uoa.gr

³ European Academy of Sciences and Arts, A-5020 Salzburg, Austria; pkary@tee.gr

* Correspondence: smavroulis@geol.uoa.gr



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Abstract: The 4 February 1867 Cephalonia (Western Greece) earthquake is the largest in the Ionian Islands and one of the largest in the Eastern Mediterranean. However, it remained one of the least studied historical events. For reconstructing this earthquake, we reevaluated existing knowledge and used new contemporary and modern sources, including scientific and local writers' reports and books, local and national journals, newspapers, and ecclesiastical chronicles. The extracted information covered the earthquake parameters, population impact, building damage, and earthquake environmental effects (EEEs). The earthquake parameters included the origin time and duration of the main shock, epicenter location, precursors, aftershocks, and characteristics of the earthquake ground motion. The population impact involved direct and indirect health effects and population change. Building data highlighted the dominant building types and the types, grades, and distribution of damage. The EEEs included ground cracks, landslides, liquefaction, hydrological anomalies, and mild sea disturbances. Field surveys were also conducted for validation. The quantitative and qualitative information enabled the application of seismic intensity scales (EMS-98, ESI-07). The study concluded that since the affected areas were mainly composed of post-alpine deposits and secondarily of clay–clastic alpine formations with poor geotechnical properties, they were highly susceptible to failure. Effects and maximum intensities occurred in highly susceptible areas with a rich inventory.

Keywords: historical earthquakes; Ionian Islands; building damage; earthquake environmental effects; seismic intensity; intensity scales; EMS-98; ESI-07; contemporary sources

1. Introduction

Recent research on historical earthquakes using contemporary sources, archaeological findings, and paleoseismology has greatly informed seismology and earthquake geology. Historical sources usually provide information related to the earthquake parameters, the impacts on population and infrastructure, and primary and secondary environmental effects.

Re-evaluating historical earthquake data, focusing on primary and secondary environmental effects, enables the parameterization of descriptive data, integration into GIS databases, and the modern mapping of effects. This allows the use of seismic intensity scales, the assignment of relative intensities to affected areas, and the creation of isoseismal and shake maps [1]. This approach helps identify the most affected fault blocks and susceptible zones [2–5].

Studying the impact of historical earthquakes on buildings and infrastructure reveals damage patterns and construction deficiencies. Recording the macroseismic effects with modern tools creates comprehensive datasets, including macroseismic data points

(MDPs) [6], which contribute to the understanding of intensity distribution using scales such as the Modified Mercalli Intensity (MM) [7] or the European Macroseismic Scale (EMS-98) [8].

Combining localities and macroseismic data points provides a comprehensive view of earthquake effects and intensity, enhancing seismic risk reduction, urban planning, zoning, and emergency preparedness. This information helps scientists and civil protection staff assess seismic hazard and risk more accurately and develop strategies for impact mitigation, covering all stages of the disaster management cycle. Key actions include adopting safe construction practices, updating seismic regulations and building codes, strengthening buildings and the infrastructure, designing early warning systems, training civil protection staff, and raising public awareness through the implementation of emergency plans and exercises [9].

The search for new, previously unknown or unexplored historical sources or the re-evaluation of those already discovered is moving in this direction. Historical documents are currently being examined in the context of modern methodologies and new approaches are applied to the research of individual earthquakes. This is the approach applied in the present research, which examines the impact of the 4 February 1867 Cephalonia earthquake in the northwestern part of the Hellenic Arc and Trench System (Figure 1).

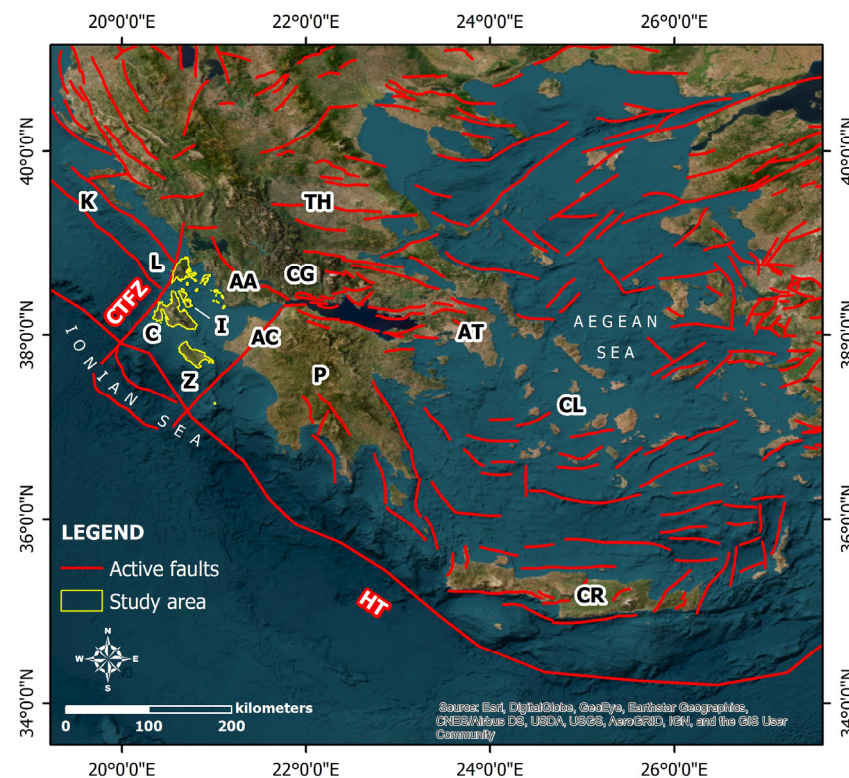


Figure 1. The study area (yellow frame) comprising Lefkada (L), Cephalonia (C), Ithaki (I), and Zakynthos (Z) Islands is located east of the Cephalonia Transform Fault Zone (CTFZ) and a few km away from the Hellenic Trench (HT). K: Kerkyra; AA: Aetoloakarnania; CG: Central Greece; AC: Achaia; P: Peloponnese; TH: Thessaly; AT: Attica; CL: Cyclades Islands; CR: Crete Island. Active faults (red lines) are based on Styron and Pagani [10]. Sources of the basemap: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

This study refers to the largest earthquake recorded in the Ionian Islands and one of the largest in the Eastern Mediterranean based on the updated catalogue of Makropoulos et al. [11]. It systematically records the earthquake parameters, precursor phenomena, aftershock sequence, and effects on the population, public health, built environment, and natural envi-

ronment, using existing knowledge, along with new contemporary and modern sources, which will be presented in detail in the Methodology Section.

Using several sources with detailed information on the earthquake's impact at settlement level allowed the application of intensity scales based on building damage and environmental effects. This approach offers a complete picture of the earthquake effects and identifies the areas susceptible to the generation of building damage and environmental effects.

In the context of the present research on the 1867 Ionian Sea major earthquake and for a better understanding of the geology and geoenvironment of the research area, reference will be made to the seismotectonic setting of the Ionian Islands, their geological structure, with an emphasis on the active and seismic faults, as well as the historical and recent seismicity of the Ionian Islands, especially on the destructive earthquakes.

2. Review of the Existing Studies on the Ionian Sea Historical Earthquakes

To study historical earthquakes in Greece, sources spanning 2500 years are used. These sources include unpublished manuscripts, archival material, ancient and Byzantine texts, newspapers, published sources, textbooks, maps, guides, seismological surveys, and earthquake catalogues [12,13]. The completeness of these sources varies over time, dividing the historical earthquake period into four sub-periods: (i) antiquity to 1000 AD; (ii) 1000–1500; (iii) 1500–1800; (iv) 1800–1900 [13]. The most significant sources for earthquakes before 1500 have likely been exploited [12].

Research on historical seismicity in Western Greece, focusing on destructive earthquakes in the Ionian Islands, has yielded significant conclusions. These have been published by various authors: Albini and Vogt [14] for the 17th century, Kouskouna et al. [15] and Makropoulos and Kouskouna [16] for the 18th century, Albini [17,18] for the 19th century, Lekkas et al. [19] and Mavroulis et al. [2] for the Zakynthos Island, and Mavroulis [3] for the central and southern Ionian Islands and western Peloponnese.

Albini and Vogt [14] researched seismicity in the Ionian Islands during the 17th century, noting gaps and uncertainties in the historical records. They collected numerous sources, primarily from the Archives of the Republic of Venice, which at the time governed the three main islands of the Ionian Sea. With newly available documents, they filled some gaps, providing reliable knowledge of the seismic activity in the Ionian Islands from 1658 to 1664. They corrected dates for earthquakes in 1658 and 1660 and clarified events previously attributed to 1664, preventing the overestimation of earthquake magnitude and intensity.

Kouskouna et al. [15] focused on the earthquake of 22 July 1767. Limited original sources were supplemented by the Venice State Archives, revealing the earthquake parameters, macroseismic effects, administrative organization, emergency management procedures, and repair processes. The importance of this research lies in the conversion of seismic effects into macroseismic intensities.

Makropoulos and Kouskouna [16] analyzed 18th-century earthquakes in the Ionian Islands, including the 22 July 1767 earthquake in Cephalonia. They estimate macroseismic intensities and create relevant maps based on the available data, underscoring the importance of historical information in seismic hazard assessment. Studying historical earthquakes contributes to the better estimation of return periods of large earthquakes, leading to more accurate intensity and magnitude assessments. Their analysis suggests that the 1767 earthquake had a macroseismic magnitude of 7.25, a maximum intensity of X, and a similar impact distribution in Cephalonia's built environment to recent 20th-century seismic events in the area.

Albini [17] chronicled earthquakes in the United States of the Ionian Islands from 1815 to 1864, a period under the British protectorate. She used both regular and irregular sources, including administrative documents, a local newspaper ("Gazzetta" or "Ephimeris"), European periodical press, contemporary scientific literature, private journals and reports, historical-geographical works, and travelogues. These sources yielded a large number of earthquake records of high quality, enabling the application of the EMS-98 and the

estimation of 147 new intensities for major cities, such as Kerkyra, Cephalonia, Lefkada, and Zakynthos.

Albini [18] examined nine major earthquakes in the United States of the Ionian Islands from 1815 to 1864, with documented effects at multiple locations. These earthquakes occurred on the following dates: 29 December 1820, 6 January 1821, 21 February 1824, 19 January 1825, 5 June 1834, 3 August 1837, 30 October 1840, 26 February 1841, and 14 March 1862. Albini [18] conducted a systematic survey of contemporary local documents of various types, improving upon previous interpretations by relying solely on carefully correlated and independent seismic records.

Lekkas et al. [19] and Mavroulis et al. [2] interpreted the available descriptions of the historical earthquakes that struck Zakynthos. They obtained information on the effects of earthquakes on the natural environment and correlated their occurrence with the geological structure and active faults.

Mavroulis [3] presented the primary and secondary environmental effects of historical and recent earthquakes in Western Greece, including events in the central and southern Ionian Islands, their correlation with active tectonics and their distribution, along with the application of the Environmental Seismic Intensity (ESI-07) scale within susceptible areas.

Mavroulis and Lekkas [4] utilized contemporary newspapers, both local and national, to reconstruct the primary and secondary effects of the August 1953 earthquakes in the central and southern Ionian Islands. This filled a significant gap in the earthquake geology literature regarding the secondary environmental effects of the 1953 earthquakes. In addition to previous studies focusing on primary effects [20,21] and the built environment [22], they analyzed digitized records from local journals and 15 Greek newspapers. This approach resulted in the reconstruction of a comprehensive distribution of environmental effects from the 1953 earthquakes. A total of 120 effects were identified: 33 primary and 87 secondary. These effects, including slope failures, coseismic uplift, hydrological anomalies, ground cracks, tsunami, liquefaction, dust clouds, hydrocarbon-related phenomena, jumping stones, and vegetation effects, were mainly observed on the Cephalonia Island, with secondary impacts on the Ithaki and Zakynthos Islands. Primary effects, such as coseismic uplift up to 70 cm, were concentrated in the eastern part of Cephalonia [20,21], while secondary effects occurred in specific zones susceptible to earthquake-related hazards [4,5].

From the presentation of the above research on the historical and the most destructive earthquakes in the Ionian Sea, a gap in seismological and earthquake geology research is noted. This gap can be detected at the end of the 19th century, especially after 1864, a period during which the 1867 earthquake occurred, with hitherto unexplored effects on the natural environment (EEEs), the built environment (buildings and infrastructure), and the local population and its evolution. This gap is filled by the present study, which adopts a methodology that exploits the advantages of research on historical seismicity and the innovations of modern approaches. The methodology is presented in detail in the following chapter.

3. Methodology

Seismological parameters for the 1867 earthquake are extracted from the SHARE European Earthquake Catalogue (SHEEC) 1000–1899 [6] and its updated version in the European PreInstrumental Earthquake Catalogue (EPICA) 1000–1899 [23,24].

The compilation of the SHEEC 1000–1899 occurred within the scope of the EC project “SHARE” (Seismic Hazard Harmonization in Europe; 2009–2012). This effort draws upon the knowledge gained from the EC I3 project “Network of Research Infrastructures for European Seismology” (NERIES; 2006–2010), which included a component dedicated to forming the “European Archive of Historical Earthquake Data” (AHEAD) and developing methodologies for homogeneously extracting earthquake parameters from macroseismic data. AHEAD has provided the final earthquake catalogue, achieved by resolving duplicates and discarding numerous fake events, along with the latest historical dataset.

The EPICA is a seismic catalogue covering the period from 1000 to 1899 [23,24]. EPICA version 1.1 encompasses 5703 earthquakes meeting the criteria of either maximum observed intensity ≥ 5 or $M_w \geq 4.0$. It draws upon data from 160 sources of MDPs and 39 regional catalogs sourced from AHEAD. Parameters for 3297 earthquakes have been freshly evaluated from MDPs using standardized procedures.

The 1867 earthquake attracted scientists, including the director of the Observatory of Athens, Johann Friedrich Julius Schmidt [25–27], the professor of Geology at the National University, Hercules Mitsopoulos, and the famous naturalist of the time, Ferdinand Fouqué [28] (Table 1), who visited the affected areas shortly after the generation of the devastating earthquake. Journalists and local writers also reported on the event (Table 1). While non-experts could not scientifically document natural phenomena, their accounts of adverse conditions due to the main shock and aftershocks contribute to the understanding of their impact, enriching the overall picture of the largest earthquakes in the Ionian Islands and the Eastern Mediterranean to date.

Table 1. The contemporary and relatively recent sources used to obtain information on the effects of the 1867 earthquake on the central part of the Ionian Islands. The same list includes extensive reports published in local newspapers of the time. ps: primary source; ss: secondary source.

Type	No	Publication Year	Author	Title	Reference
ps	1	1867	Johann Friedrich Julius Schmidt	Essay on the 23 January 1867 Earthquake of Kefallinia	[25]
	2	1867	Panayotis Vergotis	The earthquake of 23 January 1867 in Kefallinia	[29]
	3	1867	Spyridon Kompothekras	Speech delivered on the Sunday of Orthodoxy, 5 March 1867, at the church of St. George in Argostoli of Kefallinia	[30]
	4	1867	G. Solomos	The Disaster generated in Cephalonia	[31]
	5	1868	Nikolaos Joseph Typaldos	The earthquake in Cephalonia. Report to the Council of Ministers in Athens	[32]
	6	1868	Ferdinand Fouqué	Rapport sur les tremblements de terre de Céphalonie et de Mételin en 1867	[28]
	7	1873	Andreas Laskaratos	The earthquake of 4 February 1867 in Kefallinia	[33]
	8	1879	Johann Friedrich Julius Schmidt	Studien über Erdbeben	[26]
	9	1881	Johann Friedrich Julius Schmidt	Studien über Vulkanen und Erdbeben	[27]
	10	1890	Antonios Miliarakis	New and Ancient Political Geography of the Prefecture of Kefallinia: Kefallinia, Ithaca, Atokos, Arkoudi, Kalamos, Kastos and Echinades	[34]
	11	1892	Joseph Partsch	Kefallinia and Ithaca: Geographical Monograph	[35]
ss	12	1941	Sokratis Kougeas	Anecdotal opinion of Andreas Laskaratos	[36]
	13	1953	Eleni Lampiri	The 1867 earthquakes in Cephalonia [A page of Laskaratos]	[37]
	14	1960	Ilias Tsitselis	Kefallinia's Mixed: contributions to the history and folklore of the island of Kefallinia in three volumes. Volume Two. Ecclesiastical. Monastery Histories. Chronographies. Political and Statistical Notes.	[38]
	15	1962	Georgios Alissandratos	The 1867 Cephalonia earthquake and Laskaratos	[39]
	16	1991	Panos G. Kallinikos	Ionian (mostly Ithaki) contributions	[40]

In addition to the aforementioned research and reports, this study also utilizes articles and reports from local and national newspapers, published shortly after or months following the earthquake (Table 2). The earthquake's impact was so significant that related articles continued for months, also covering disaster management and recovery efforts among other aspects.

Table 2. Local and national Greek newspapers used in this study for revisiting the 1867 Ionian Sea major earthquake ¹.

No	Newspapers	Newspapers (in Greek)	Newspapers (Lit)	Location of Newspaper	Circulation Period ²
1	AION	ΑΙΩΝ	Century	Athens	1 January 1862–10 November 1862 13 January 1866–28 December 1867
2	ALITHEIA	ΑΛΗΘΕΙΑ	Truth	Athens	18 October 1865–28 June 1868
3	ANAMORPHOSIS	ΑΝΑΜΟΡΦΩΣΙΣ	Reformation	Cephalonia	9 July 1866–1 July 1867
4	AVGI	ΑΥΓΗ	Dawn	Athens	1 January 1867–31 December 1867
5	ELLAS	ΕΛΛΑΣ	Greece	Athens	31 May 1865–31 December 1867
6	EPHIIMERIS TON FILOMATHON	ΕΦΗΜΕΡΙΣ ΤΩΝ ΦΙΛΟΜΑΘΩΝ	Philomath News	Athens	1 January 1867–31 December 1868
7	IMERA	ΗΜΕΡΑ	Day	Vienna	7 January 1865–28 December 1867
8	KEFALLINIA	ΚΕΦΑΛΛΗΝΙΑ	Cephalinia	Cephalonia (Argostoli)	22 May 1867–15 May 1869
9	MERIMNA	ΜΕΡΙΜΝΑ	Care	Athens	1 January 1861–31 December 1867
10	OMONOIA	ΟΜΟΝΟΙΑ	Concord	Zakynthos	12 February 1866–21 June 1867
11	PALIGENESIA	ΠΑΛΙΓΓΕΝΕΣΙΑ	Palingenesis	Athens	1 January 1867–31 December 1867
12	PROINOS KIRIX	ΠΡΩΪΝΟΣ ΚΗΡΥΞ	Morning Post	Athens	18 September 1865–31 December 1867
13	SYNTAGMA	ΣΥΝΤΑΓΜΑ	Constitution	Athens	30 November 1861–5 January 1862, 4 February 1867–1 January 1869
14	FONI TON HORIKON	ΦΩΝΗ ΤΩΝ ΧΩΡΙΚΩΝ	Voice of the Villagers	Kerkyra	8 August 1865–29 September 1867
15	ELPIS	ΕΛΠΙΣ	Hope	Athens	1 January 1862–17 September 1868
16	DIKAIOSINI	ΔΙΚΑΙΟΣΥΝΗ	Justice	Athens	30 September 1866–28 June 1875
17	ETHNOFILAX	ΕΘΝΟΦΥΛΑΞ	National Guard	Athens	1 January 1867–31 December 1867
18	FOS	ΦΩΣ	Light	Athens	1 January 1863–31 December 1869
19	ARKADIA	ΑΡΚΑΔΙΑ	Arcadia	Tripolis (Peloponnese)	12 July 1862–22 December 1873
20	NEA EPOHI	ΝΕΑ ΕΠΟΧΗ	New Season	Cephalonia	18 February 1867

¹ Newspapers 1–19 were extracted from the Digital Library of the Hellenic Parliament [41], while the last one was extracted from the Iakovateios Library of Lixouri (Cephalonia) [42]. ² Dates according to the Julian (old) calendar.

The evaluated newspapers belong to the following archives and newspaper collections:

- The Digital Library of the Hellenic Parliament [41]: It holds a vast collection of Greek and foreign newspapers and magazines dating from the 18th century to present. To preserve this sensitive material and accommodate a high number of visitors, the Library implemented digitization and microfilming in the 1980s, resulting in about 25,000 microfilms digitized for public access (Figure 2). We obtained information from 19 local and national newspapers, detailed in Table 2.
- The Iakovateios Public Central Library—Museum of Lixouri [42]: Thanks to the Typaldos–Iakovatos brothers, the Iakovateios Library houses a remarkable collection of books, ancient artifacts, and religious material, forming one of the Ionian Islands' richest private libraries. With around 30,000 volumes, the library covers several interests and continues to grow with modern additions.

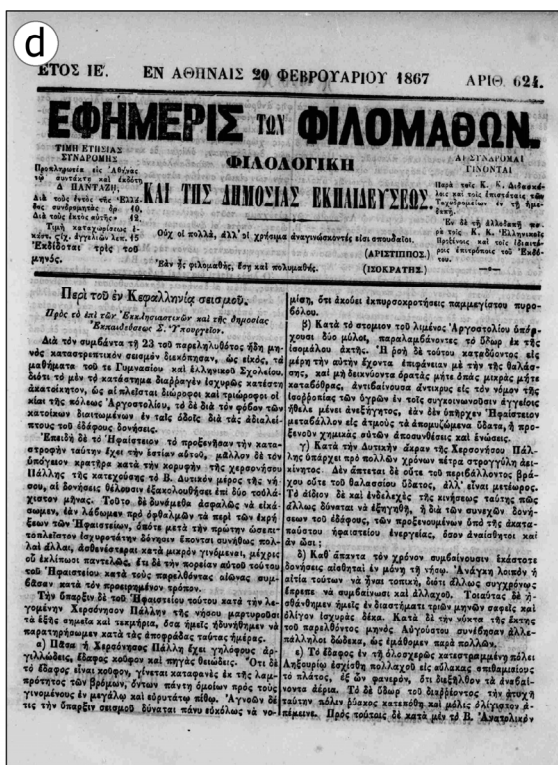
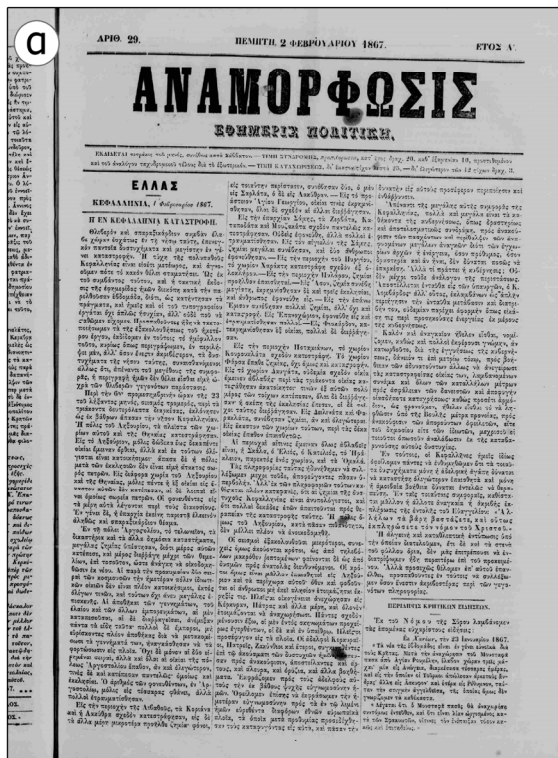


Figure 2. Digitized microfilms of the publicly accessible collection of the Digital Library of the Hellenic Parliament [41] presenting the front covers of the newspapers (a) “Anamorphosis” on 2/14 February 1867, (b) “Proinos Kirix” on 6/18 February 1867, (c) “Merimna” on 7/19 February 1867, and (d) “Ephimeris ton Filomathon” on 20 February/4 March 1867, referring to the 1867 Cephalonia earthquake disaster (dates of Julian calendar/Gregorian calendar).

The majority of the sources and relevant information were in Greek (Figure 3), which presents a significant language barrier for non-Greek speakers. However, there were notable exceptions to this linguistic homogeneity. Among these, were the scientific reports by Schmidt [26,27], which were written in German, providing a valuable perspective in a different European language. Additionally, the report of Fouqué [28], written in French, offered further diversity in linguistic and analytical viewpoints (Figure 3). Different languages often reflect distinct cultural and methodological approaches to recording and analyzing events. Moreover, different academic traditions have unique strengths. Combining these strengths can lead to more nuanced and interdisciplinary insights and provide a more comprehensive understanding of the earthquake's impact, as well as the various responses and interpretations from different communities and scholars.

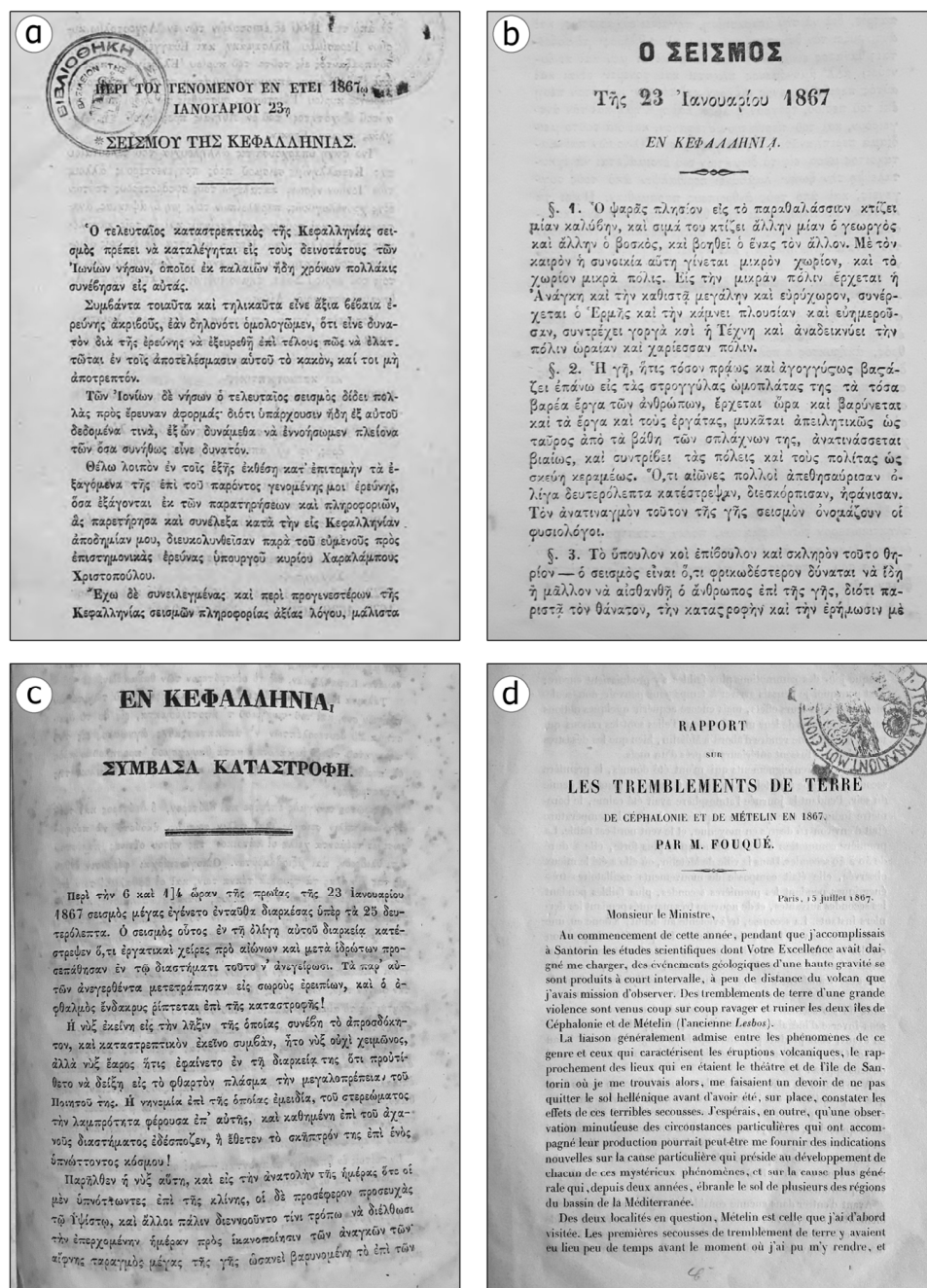


Figure 3. The first pages of the 4 February 1867 Cephallonia earthquake reports by (a) Schmidt [25], (b) Vergotis [29], (c) Solomos [31], and Fouqué [28].

Schmidt visited Cephalonia two months after the generation of the main shock. He reported that the time that passed without any scientific recording of the event and its effects was long enough for a lot of quantitative and qualitative information to be lost [26], which could have been used as a basis for further observations, results, interpretations, and conclusions. This fact emphasizes the importance of field surveys in the affected areas shortly after the earthquake. Additionally, it stresses the significant contribution of the daily and periodical press of local and national circulation to interpret the generated events and the triggered effects. In these sources, the first details from the disaster field are presented, including information on the impact on the population, building damage and the EEEs, along with the emergency response actions of domestic and foreign origin.

Aside from the pertinent articles found in the aforementioned newspapers, comprehensive reports detailing the earthquake's impact in the affected region were also published within them, including the following:

- The report of a high school principal, P.I. Spanopoulos [43,44], on the earthquake in Cephalonia, published by the newspapers "Alitheia" on 10/22 February 1867 and "Ephimeris ton Filomathon" on 20 February/4 March 1867.
- The report of the doctors Metaxas and Livieratos [45] to the Prefect of Cephalonia dated 2 March 1867 in the "Anamorphosis" newspaper on 11/23 March 1867, which described the situation of the earthquake victims in the villages of Anogi and Mesochoria in the Paliki Peninsula (Western Cephalonia).

In addition to the aforementioned newspapers, we utilized information from the quarterly journal "I Kefalonitiki Proodos" (Greek: Η Κεφαλονίτικη Πρόοδος, lit: The Cephalonian Progress). Its initial editorial period ran from 1972 to 1978, comprising 82 volumes covering various topics on Ionian Islands' history, folklore, art, archaeology, and poetry. Since January 2012, the journal resumed publication, with a focus on the natural environment, including earthquakes and their impact, particularly on Cephalonia. These volumes contain valuable insights into the primary and secondary environmental effects induced by the 1867 Ionian Sea major earthquake in the central and southern Ionian Islands [46,47].

An important contribution to the research was made by the "Nea Estia" (Greek: Νέα Εστία, lit: New Hearth) and "Eos" (Greek: Ηώς, lit: Eos) journals. Nea Estia is the oldest literary journal in Greece. It has been circulating without interruption since 1927, even during World War II. It comprised several articles about the impact of the 1867 earthquake in Cephalonia, including those by Kougeas [36] and Lampiri [37], who presented information provided by Laskaratos [33]. Eos was a monthly illustrated review on tourism, history, folklore, art, and letters, with many special issues dedicated to several parts of Greece, including Cephalonia among others. In the context of the Cephalonian issue of Eos, Alissandratos [39] remarkably gathered all the available literature on the 1867 earthquake and provided significant information not only for the contemporary scientific reports but also for the reports by local writers. He placed emphasis on the information provided by Andreas Laskaratos, a notable satiric poet and writer from Cephalonia, who experienced the devastating earthquake with his family in the town of Argostoli and wrote distinctive texts about the earthquake's impact and the adverse conditions that were formed on the island.

All these sources were reviewed with an emphasis on the impact of the 1867 Ionian Sea earthquake on the local population, the natural and the built environment. Qualitative and quantitative information about the triggered effects was extracted (Figure 4). The damage to buildings in the residential parts of Cephalonia and adjacent areas is presented along with the dominant structural types, their vulnerability classes and the damage grades based on the guidelines of the EMS-98 scale. The environmental effects were classified into primary and secondary, based on the classification presented in the frame of the ESI-07 scale proposed by Michetti et al. [48]. Furthermore, field surveys were carried out in areas of the central and southern Ionian Islands impacted by the 1867 earthquake to identify the unfavorable characteristics contributing to the triggering of effects. Based on

the available information, the EMS-98 and the ESI-07 scales were applied to assess local seismic intensities and the most affected fault blocks in the study area (Figure 4).

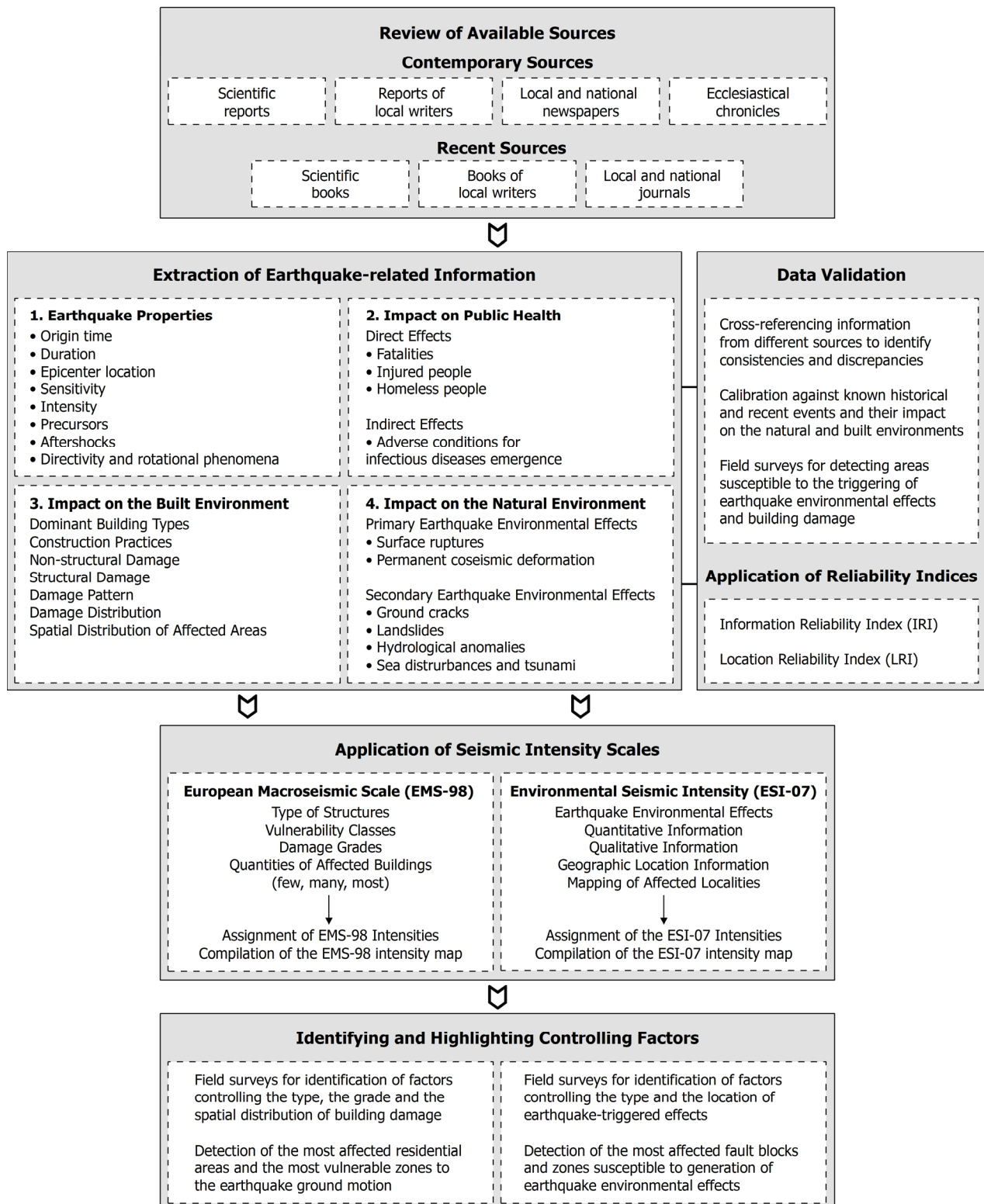


Figure 4. The flowchart of the applied methodology.

To address the lack of precise location data, we utilized a Location Reliability Index (LRI), a common tool in earthquake studies. Previous research, including studies on the 1908 Messina (Italy) earthquake [49] and the 1953 Cephalonia earthquakes [4], have employed LRIs. For the August 1953 earthquake sequence, the LRI includes four location approximation categories: (1) 0–100 m, (2) 0–1 km, (3) 0–10 km, and (4) >10 km, assigned to each documented earthquake effect. Despite inherent uncertainties in historical studies due to generic descriptions and textual data challenges, we also applied an Information Reliability Index (IRI). Similar methodologies have been applied to assess the aforementioned events. The IRI includes three reliability classes: (1) high, (2) moderate, and (3) low. Both indices are detailed in the Tables S1 and S2, comprising the building damage and environmental effects triggered by the 4 February 1867 Cephalonia earthquake, respectively.

To ascertain the randomness of the distribution of the damage and the environmental effects caused by the 4 February 1867 earthquake, we compared their inventory with published susceptibility maps [4,5] delineating the zones within the central and southern Ionian Islands prone to earthquake-induced hazards (Figure 4).

Before proceeding to the following sections, it should be noted that dates in many contemporary sources regarding the earthquake are based on the Julian calendar, where the occurrence date may appear as 23 January 1867. Greece adopted the Gregorian calendar from 16 February 1923 onwards. To prevent confusion, both calendar dates are provided in all sections.

4. Geological Setting of the Central and Southern Ionian Islands

From a geotectonic perspective, the central and southern Ionian Islands are situated in the outer section of the Hellenic Arc and to the east of the Hellenic Trench, which marks the convergent boundary between the Nubian and Eurasian plates. The central and southern Ionian Islands, which include Lefkada, Cephalonia, Ithaki, and Zakynthos, are primarily characterized by alpine formations of the Paxoi and Ionian geotectonic units (Figure 5) [50]. The Ionian unit exhibits a flysch sequence dating from the Oligocene to the Lower Miocene, along with a carbonate sequence spanning from the Upper Triassic to the Upper Cretaceous in all three islands [51,52]. Additionally, Lefkada, Cephalonia, and Zakynthos comprise evaporites dating back to the Triassic [53] (Figure 5). The Paxoi unit consists of a Miocene clay–clastic sequence and a carbonate sequence from Jurassic to Middle Miocene (Figure 5). Apart from these alpine formations, the geological structure also includes post-alpine deposits from Pliocene and Quaternary [51,52] (Figure 5). From a neotectonic viewpoint, the studied islands are intersected by faults, resulting in the formation of fault blocks with distinct geological formations and kinematic evolution during the neotectonic period [2,19,51,52,54,55]. Cephalonia comprises fault blocks, such as the Aenos Mt and the eastern Cephalonia, alongside the Paliki, Erissos, and Argostoli peninsulas [51,55]. Ithaki is segmented into three fault blocks, namely the northern, central, and southern blocks [51], while Zakynthos consists of fault blocks including Northern Zakynthos, Central Zakynthos, Keri Bay, Southern Zakynthos, and Skopos Mt [2,52] (Figure 5).

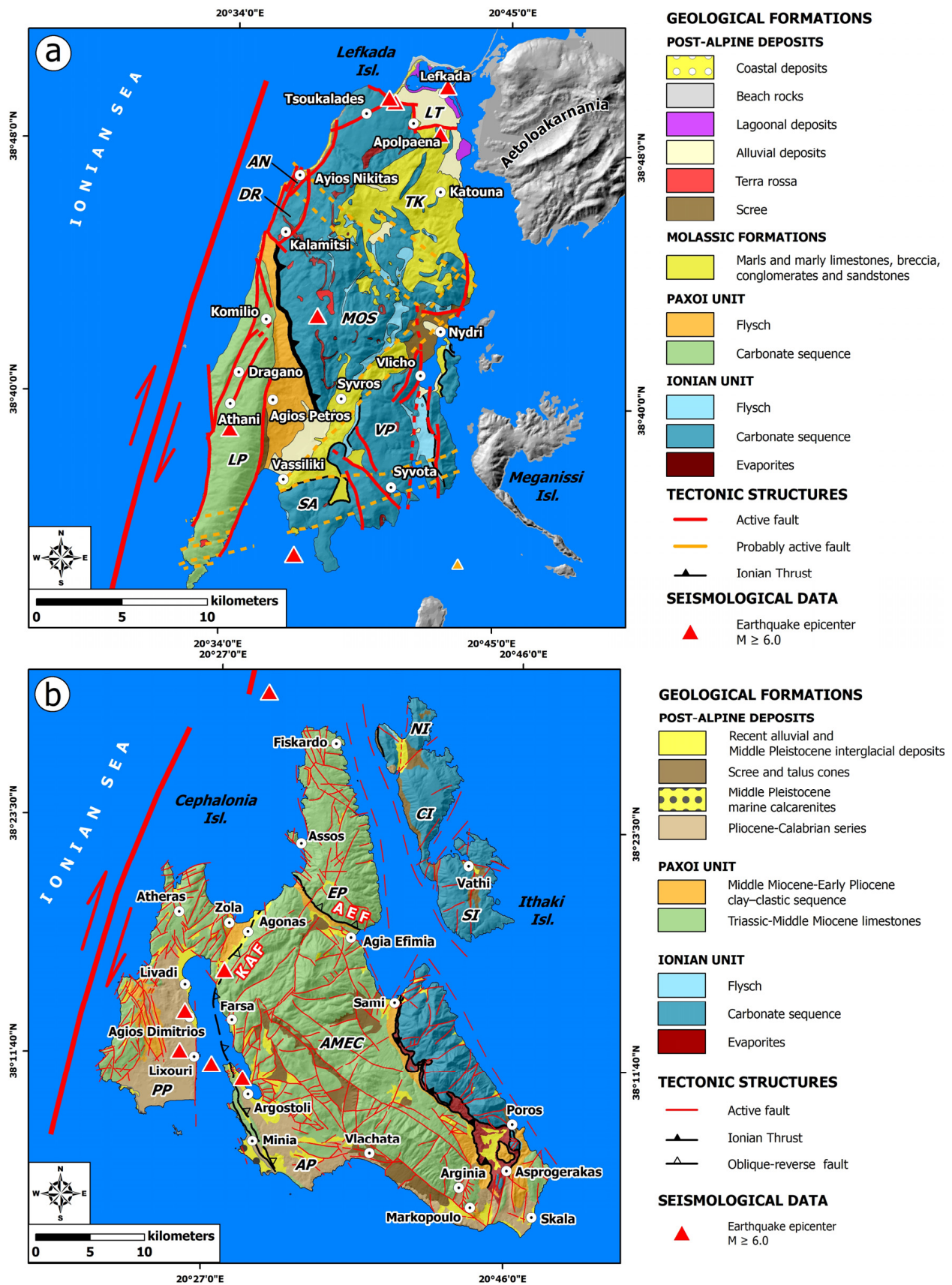


Figure 5. Cont.

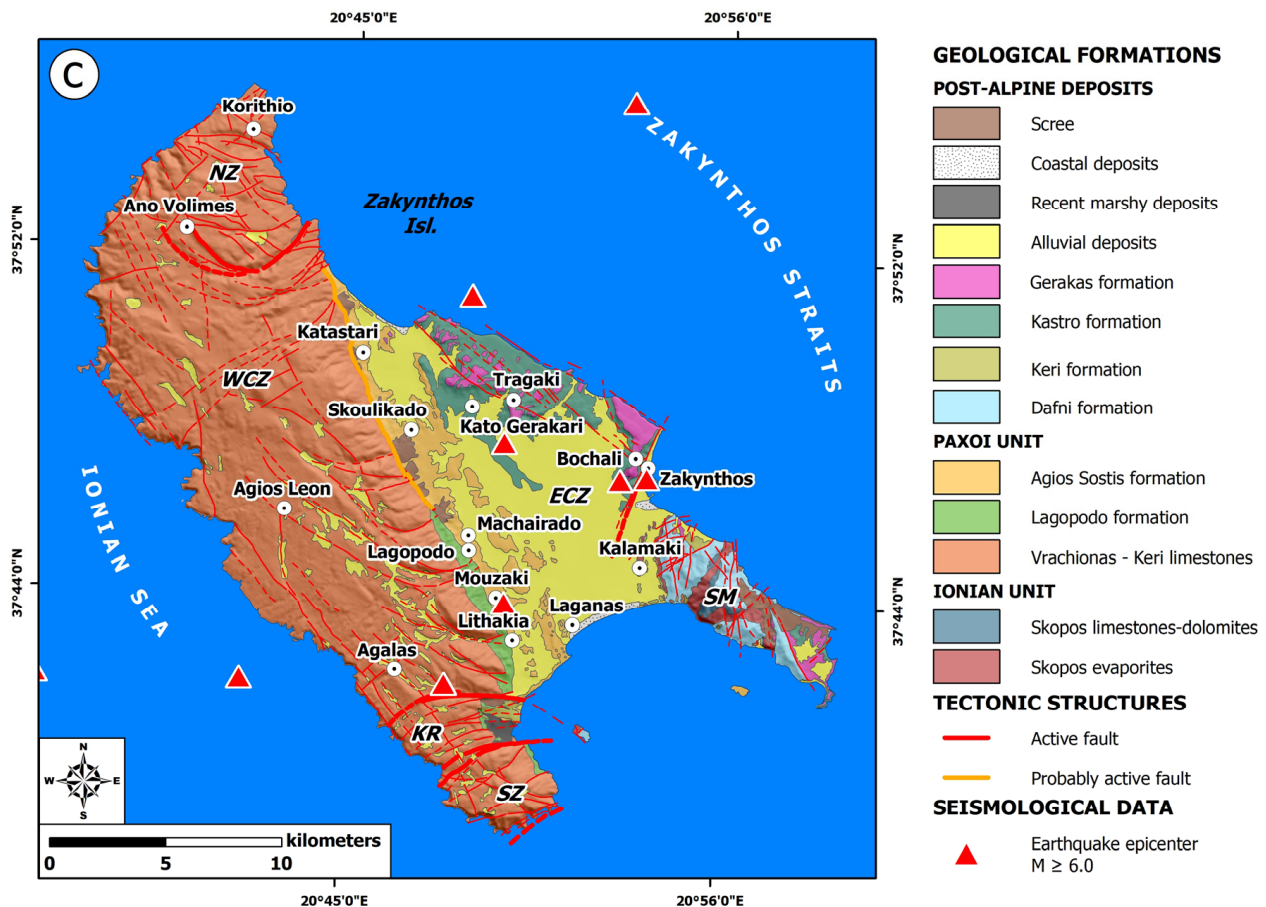


Figure 5. Simplified neotectonic maps of Lefkada (a), Cephalonia and Ithaki (b), and Zakynthos (c) Islands based on Lekkas et al. [51,52] and Mavroulis et al. [2], along with their fault blocks. Fault blocks of (i) Lefkada: Lefkada town (LT), Tsoukalades-Katouna (TK), Agios Nikitas (AN), Drymonas (DR), Mega Oros-Skaroi (MOS), Vlichio-Poros (VP), Sykeros-Achrada (SA), and Lefkada peninsula (LP). (ii) Cephalonia: Erissos Peninsula (EP), Paliki Peninsula (PP), the Aenos Mt and eastern Cephalonia (AMEC), Argostoli Peninsula (AP). (iii) Zakynthos: northern Zakynthos (NZ), western part of central Zakynthos (WCZ), eastern part of central Zakynthos (ECZ), Keri (KR), southern Zakynthos (SZ), Skopos Mt (SM). The earthquake epicenters are from the EPICA version 1.1 [23].

5. Historical and Recent Seismicity of the Ionian Islands

Due to their geotectonic location, the central and southern Ionian Islands represent one of the most seismic active regions not only in the Mediterranean but also in Europe and globally [56].

Historical records spanning 500 years document seismic activity in the study area, revealing frequent shallow events above macroseismic magnitude 7.0 and intensities [Modified Mercalli (MM) scale] surpassing X [57–59]. Notably, the seismic data indicate that significant earthquakes often occur in pairs or clusters within intervals ranging from days to five years [60]. For instance, typical events include the 1948 earthquakes in Lefkada (22 April and 30 June), as well as those in 1953 (9, 11, and 12 August), 1983 (17 and 19 January and 23 March), and 2014 (26 January and 3 February) in Cephalonia [58]. The stress interaction is the most possible explanation for the occurrence mode of strong earthquakes in the Ionian Islands, particularly in the Cephalonia and Lefkada Islands and related earthquakes [60].

The major seismic fault zone in this region is the Cephalonia Transform Fault Zone (CTFZ) (Figure 6). The CTFZ consists of two segments: the Lefkada segment in the north,

offshore western Lefkada, and the Cephalonia segment in the south, offshore western Cephalonia [61–66].

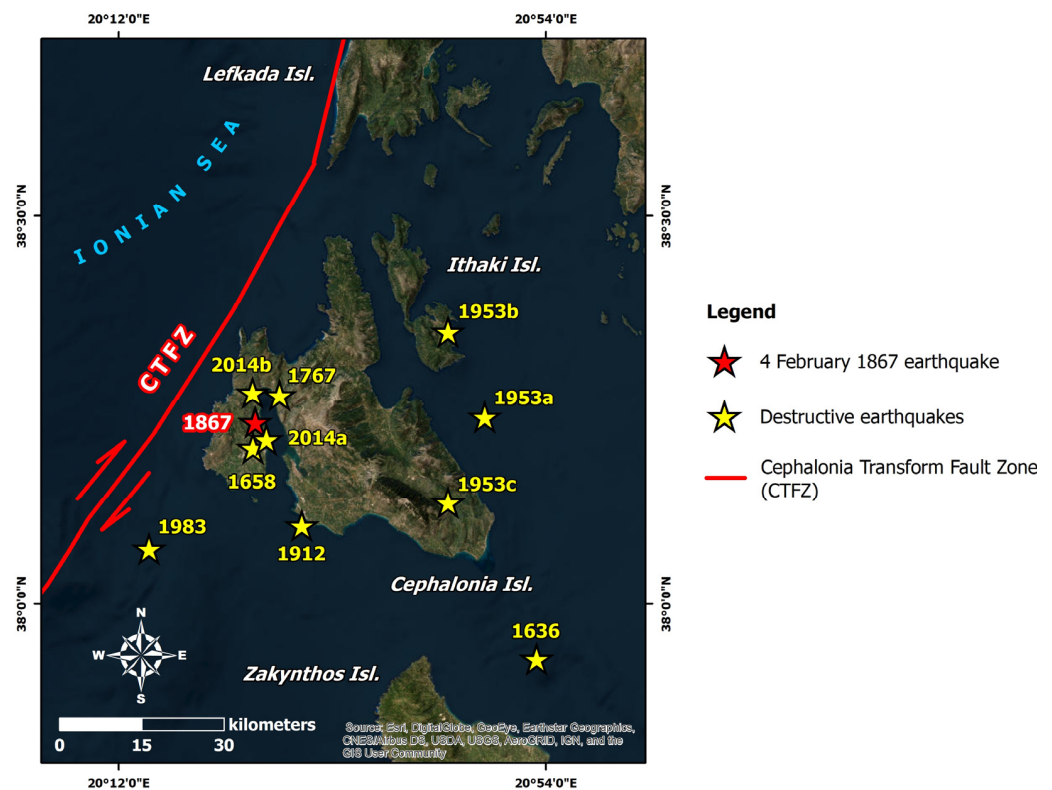


Figure 6. The epicenter of the 4 February 1867 Cephalonia earthquake, along with the epicenters of significant earthquakes, based on the catalogue of Makropoulos et al. [11]. Active faults come from Styron and Pagani [10]. The CTFZ is located offshore, west of Lefkada and Cephalonia. Sources of the basemap: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

The Lefkada segment, spanning 40 km and striking NE–SW with an ESE dip, extends from the northwest offshore of Lefkada to the northern offshore of Cephalonia [53,63]. It exhibits dextral strike-slip motion with a minor thrust component. Conversely, the Cephalonia segment, 90 km in length and also striking NE–SW with an ESE dip, is situated close to the western offshore of Cephalonia [64,65]. It is known for its high seismicity in the western Hellenic Arc [56–59], notably associated with devastating earthquakes.

In the southern Ionian Islands, seismic activity above magnitude 5.0 is concentrated in specific seismic zones: the offshore areas of Cephalonia and Lefkada in the west, the Zakynthos channel, the basin between Zakynthos Island and the Peloponnese, and the southwest of Zakynthos Island [2]. These zones are known for their frequent destructive earthquakes throughout history [67].

Regarding the pre-1867 seismicity in the central and southern Ionian Islands, a major earthquake in Cephalonia had occurred almost 5 years earlier, on 2/14 March 1862. This earthquake had a macroseismic magnitude $M_w = 6.5$, a maximum intensity $I_{max} = IX$, an epicentral intensity $I_0 = VIII-IX$ and caused destruction in the town of Argostoli ($I = IX$), heavy damage in the town of Lixouri ($I = VIII$), slight damage in Kerkyra, and a high perceptibility in the Zakynthos Island [6,23,24,57,58].

The March 1862 earthquake in Cephalonia ended a relatively quiet 20-year period in the Ionian Islands following the $M_w = 6.5$ earthquake in Zakynthos on 18/30 October 1840. Felt across the Ionian Islands, Epirus, and Messinia, it mainly impacted the town of Zakynthos [2,19,58]. It triggered secondary EEEs, including coseismic subsidence, ground oscillation, hydrological anomalies, tree shaking, hydrocarbon-related phenomena,

liquefaction, and slope failures [2,3]. This period notably lacked destructive earthquakes in the Ionian Islands.

Regarding the characteristics of seismicity in the Ionian Islands in the following years after the 1867 Cephalonia earthquake, the epicenters of strong earthquakes show a trend to shift towards Lefkada. More specifically, a new strong earthquake or aftershock occurred northwards, in Lefkada, on 7/19 February 1867 [57,68] and caused significant damage, including building collapses in the settlements of the southern part of Lefkada (Vasiliki, Kontaraina, Athani, Sivros, Agios Petros, Diamiliani, Komilio), while in the town of Lefkada, extensive cracks were caused in the stone buildings [57].

Two years after the Cephalonia and Lefkada earthquakes, in February 1867, another devastating earthquake struck again in Lefkada, on 16/28 December 1869, with a magnitude $M = 6.4$ and an intensity $I = X$ in the town of Lefkada. The town was destroyed for the 13th time according to the list given by Stamatellos in “Ephimeris ton Philomathon” in 1870 [69]. It was turned into ruins, with only 20–25 houses remaining intact from the strong ground shaking [57,58,69].

6. The 1867 Ionian Sea Major Earthquake

6.1. Earthquake Parameters and Properties

6.1.1. Origin Time and Duration of the Main Shock

Various sources provide differing accounts of the occurrence time of the main shock, but all suggest it happened within the first twenty minutes after 06:00 (local time). Schmidt [25], Partsch [35], and Tsitselis [38] stated 06:00, while Vergotis [29] and Solomos [31] mentioned 06:15. More recent studies by Ambraseys [59] and Papazachos and Papazachou [58] suggested 06:12 and 06:19, respectively. The SHARE European Earthquake Catalogue [6] and its updated EPICA version [23,24] indicated 06:19. Newspaper reports vary, with “Elpis”, “Merimna”, “Ellas”, and “Nea Epohi” citing 06:00, “Avgi” mentioning either 06:00 or 06:10, and “Omonoia” reporting 06:15.

Accounts of the main shock’s duration also vary widely. Solomos [31] stated 25 s, while Partsch [35] and Tsitselis [38] suggested 25 to 30 s. Newspaper reports differ as well: “Anamorphosis”, “Avgi”, and “Merimna” indicated 30 s, “Nea Epohi” suggested 30 to 45 s, and “Omonoia” reported only 12 s.

6.1.2. Magnitude, Intensity, Epicenter Location, and Perceptibility of the Main Earthquake

Earthquake parameters such as epicenter location, magnitude, and intensity are taken from the EPICA catalogue [23,24] and Papazachos and Papazachou [58] and presented in Table 3.

Table 3. Parameters of the 4 February 1867 Ionian Sea major earthquake from all available sources.

Source	Occurrence Time (Local Time)	Latitude	Longitude	Focal Depth	Magnitude (M _w)	Epicentral Intensity (I _o)
Papazachos and Papazachou [58]	4 February 1867, 06:19	38.390	20.520	-	7.4	X
Stucchi et al. [6]	4 February 1867, 06:19	38.233	20.424	-	7.15 (±0.35)	X
INGV [23]	4 February 1867, 06:19	38.233	20.424	-	7.15 (±0.35)	X

The magnitude of the earthquake according to the former is $M_w = 7.4$, while according to the SHEEC catalogue (1000–1899), it is $M_w = 7.15 \pm 0.35$, a magnitude which was also adopted by the EPICA catalogue. The maximum, as well as the epicentral intensity, have the same value ($I_{\max} = X$, $I_o = X$) based on the MM scale in all available sources [6,23,24,58]. The focal depth of the earthquake has not been determined, as in the majority of historical earthquakes in the region [6,23,24,58].

The epicenter of the earthquake had already been determined from the first days after the earthquake in Western Cephalonia, more specifically, in the fault block of the Paliki

Peninsula, as reported by the majority of the contemporary sources. According to the reports by Fouqué [28], Partsch [35], Alissandratos [39], and Tsitselis [38], the epicenter was located in the area between the villages of Rifi, Damoulanata, and Agia Thekli, which, as will be described in the corresponding section, had suffered significant damage not only from the main earthquake but also from the triggering of extensive landslides. In addition, on the surrounding islands of Ithaki to the east, Lefkada to the north, and Zakynthos to the south, the damage was mild to negligible [25]. Only one newspaper (“Syntagma” on 25 February/9 March 1867) claimed that the epicenter must have been in the area offshore the western Paliki, as the sea was reported receding at the time of the earthquake.

Partsch [35] mentioned that this strong earthquake affected a vast area. Schmidt [25] describes the impact zone as an ellipse centered on Cephalonia, 105 miles by 58 miles, covering 4900 square miles. The ellipse includes parts of the Peloponnese, Central Greece, Thessaly, the Cyclades, Albania, and southeastern Italy [25]. The earthquake was the most intense in the central and southern Ionian Sea and nearby regions, such as Aetoloakarnania and northwestern Peloponnese.

6.1.3. Hydrometeorological Phenomena Prior to the Main Shock

Schmidt [25] noted the occurrence of hydrometeorological phenomena prior to the main shock. In particular, he reported that 48 days before the earthquake, and more specifically on 6/18 December 1866, a major storm occurred. Vergotis [29] stated that storms had also occurred earlier before major earthquakes in Cephalonia. The most characteristic example is the storm that occurred 52 days before the earthquake of 1766 and caused damage to the tiles of houses in Lixouri area and in particular in the villages of Chavriata, Vouni, Mantzavinata, Illaroi, and Michalitsata.

The night before the earthquake, at dawn on 23 January/4 February 1867, the sky was clear. In the morning, however, it became cloudy and it rained in Lixouri and Argostoli, while hail fell in the area of Livathos [25]. From the day after the earthquake (24 January/5 February) onwards, the sky became clear. Good weather was maintained for the next 20 days, except in early February, when it rained heavily for two days in Kerkyra, Cephalonia, and Ithaki. No other notable hydrometeorological phenomena occurred in the first months after the earthquake (January, February, and March) [25]. The bad weather of December 1866 is also mentioned by Vergotis [29] and Tsitselis [38]. The bad weather uprooted olive trees, swept people, animals, and ships ashore, and damaged many other anchored vessels. In addition, he reported the occurrence of several weaker earthquakes in the summer before the 1867 event.

6.1.4. Precursors

Apart from the above hydrometeorological phenomena, Schmidt [25] mentioned the appearance of seismic lights in the sea, as he deduced from a simple reference to a testimony of a resident of Lixouri, as well as the restless behavior of animals in the earthquake-affected area as precursors to the earthquake. Since the first testimony did not include further information, it was not taken seriously into account by Schmidt [25]. As for the restless behavior of the animals in the area, it is mentioned that a horse in Argostoli broke the lead rope shortly before the earthquake and ran around with fear [25,58].

Vergotis [29] described testimonies of residents according to which, in the afternoon hours of the day before the earthquake, they observed flashes from the sea towards the Gerogobos area, at the southwestern end of the Paliki Peninsula. Both before and after the earthquake, sea disturbances called “ρηχίλες” (in Greek)/richies were observed [29].

Partsch [35] mentioned that before the earthquake in Cephalonia, various events occurred in the Eastern Mediterranean. An hour before the Cephalonia main shock, four strong seismic events occurred in Algeria, which had already been affected by a devastating earthquake that had occurred two days earlier. Half an hour before the earthquake in Cephalonia, seismic events occurred in Albania (Vlorë, Durrës) and in southern Italy (Otranto, Messina).

Tsitselis [38] stated that the 4 February 1867 earthquake was preceded by the occurrence of the July–October 1866 earthquakes.

6.1.5. Aftershock Sequence

According to the scientific reports and newspaper articles, the aftershock sequence was intense, as expected for a main earthquake with a magnitude greater than $M_w = 7.0$.

Schmidt [25] mentioned that one hour after the main shock, at 07:00 (local time), as well as at 11:00 (local time), aftershocks were generated. Particularly, during the first 48 h after the main earthquake, the aftershocks were constant. During the occurrence of both the main earthquake and the aftershocks, deep sounds were perceived and sounded similar to gunshots from a distance.

From the occurrence of the main shock until the end of April of the same year, not a day passed without an earthquake, while there was not a week without a strong earthquake until July [25,30,35,39].

Schmidt [25] reported that during the first 14 days many large earthquakes were generated, mainly on 31 January/12 February and 1/13 February 1867. A total of 50 earthquakes occurred from 19/31 March to 2/14 April. In particular, on 25 March/6 April 1867, 03:00 (local time), an earthquake occurred, accompanied by deep sounds resembling thunder.

Vergotis [29] mentioned a strong aftershock an hour after the main shock that completed the destruction.

Partsch [35] noted that countless smaller aftershocks occurred, the most intense of which occurred 15 min (06:15 local time), 75 min (07:15), and 5 h (11:00) after the main shock.

Tsitselis [38] described that two strong aftershocks followed the main shock, at 07:15 and 11:00, respectively. After these earthquakes, the sequence of aftershocks included smaller events.

During the aftershock sequence, no noteworthy damage was caused in the earthquake-affected area (“Anamorphosis” and “Avgi” newspapers on 11/23 February 1867).

Regarding the spatial distribution of the aftershocks, the activity was continuous, and the earthquakes were felt for the first two months after the main destructive earthquake in the western part of Cephalonia and especially in the fault block of the Paliki Peninsula [44], where the epicenter of the main earthquake had been located. In the adjacent island of Ithaki, on the day after the main shock (24 January/5 February 1867), another aftershock was felt, while from 2/14 February onwards no other event was felt (“Omonoia” newspaper on 28 January/9 February 1867, “Avgi” newspaper on 11/23 February 1867).

Many smaller aftershocks were felt in Lefkada until 26 January/7 February according to information from the “Omonoia” newspaper of Zakynthos, which republished the information from “Anamorphosis” and “Lefkada” dated 28 January/9 February 1867.

6.1.6. Directivity and Rotational Phenomena

Schmidt [25] discussed the 1867 earthquake’s directivity, intensity, and rotational ground motion. In Agia Thekli, roofs, chimneys, and columns were displaced. The Maitland Monument and an obelisk in Argostoli experienced minor rotation. At Kouvalata, a church roof collapsed 15 m north. The damage in Delaportata, Skineas, and Agia Thekli revealed the earthquake’s severity, with seismic waves moving NW to SE, parallel to the major axis of the affected area.

6.2. Impact on Public Health

6.2.1. Direct Public Health Effects

Many sources refer to the fatalities caused by the 4 February 1867 earthquake, including Schmidt [25], Vergotis [29], Lombardos [70], Fouqué [28], Miliarakis [34], and Partsch [35]. The reports by Schmidt [25] and Fouqué [28] provided a detailed list of the affected villages, along with fatalities per settlement and in total. The total number reached 224. The same number is mentioned in the official report by Lombardos [70], who was the Minister of Justice of that time, and by Partsch [35]. Vergotis [29] stated in his earthquake

report that the number of fatalities was more than 200. Miliarakis [34] refers to about 200 fatalities. The reports by Schmidt [25], Lombardos [70], and Fouqué [28] are considered the most reliable in terms of the earthquake's direct health effects on the local population, with the reported number of fatalities being widely accepted today. The total numbers of human losses per settlement are presented in Table 4, while the spatial distribution of residential areas that suffered human losses is illustrated in Figure 7. As regards Ithaki, there were no casualties [40].

Table 4. Residential areas (villages and towns) on the Cephalonia Island with human losses from the 4 February 1867 earthquake according to the data presented by Schmidt [25]. The classification is in descending order of fatalities. The earthquake-affected residential areas are also presented in Figure 7. PP: Paliki Peninsula; AMEC: the Aenos Mt and Eastern Cephalonia; AP: Argostoli Peninsula.

Earthquake-Affected Fault Block/Province	Earthquake-Affected Residential Areas	Fatalities
PP/Paliki	Damoulanata and Rifi	63
	Agia Thekli	41
	Lixouri town	35
	Kouvalata	19
	Agonas	9
	Skinaeas	9
	Mantzavinata	7
	Kaminarata	6
	Dellaportata	5
	Illaroi (present Soullaroi)	4
	Vouni	4
	Chavriata	4
Transition from PP to AMEC/Thinia	Kontogourata	3
PP/Paliki	Monopolata	3
PP/Paliki	Kontogenata	2
AMEC/Sami	Rissa	2
AMEC/Sami	Sami	2
AP/Livathos	Korianna	1
PP/Paliki	Vlychata	1
PP/Paliki	Chavdata	1
AMEC/Potamiana	Kourouklata	1
Transition from PP to AMEC/Thinia	Kardakata	1

The most affected residential areas were the villages of Rifi and Damoulanata, with 63 fatalities in total; Agia Thekli, with 41; the town of Lixouri, with 35; and Kouvalata, with 19, all located in the Paliki Peninsula [25]. Based on the distribution of fatalities in Cephalonia, the most affected province was Paliki, with 213 casualties, followed by the Kranaea province, located east of Argostoli Bay, Sami, in the eastern part of Cephalonia, and the Erissos Peninsula, with 6, 4, and 2 casualties, respectively [25]. These casualties were attributed not only to strong ground motion and building collapse, but also to the triggered effects, particularly rockfalls and soil slides [25,35].

The newspapers “Anamorphosis”, initially (11/23 March 1867), and “Kefallinia”, subsequently (22 May/3 June 1867), published a report and submitted it to the Prefect of Kefallinia. The report was from two doctors who visited the affected Cephalonia and voluntarily provided their services, treating more than 100 patients and providing food and medicine for the relief of the affected population. The earthquake victims examined by doctors Metaxas and Livieratos [45] suffered fractures, effusions in various body parts, fractures of the arms, ribs, and legs, dislocations, injuries to the head, face, arms, legs, and other parts of the body. Many of these injuries resulted in disabilities and deformities, as many patients did not strictly follow the instructions and treatment recommended

by the doctors. Due to the unfavorable conditions after the earthquake, intrathoracic injuries, gastric fever, rheumatic pains, and other diseases were found [45]. Based on the observations of the above doctors, the patients were divided into those who (i) were in recovery, (ii) could recover on the spot, (iii) needed constant medical supervision because of their serious condition. The first two categories required medical aid and assistance until full recovery, while the third category required transport to health facilities for continuous health monitoring and medical assistance until final recovery.

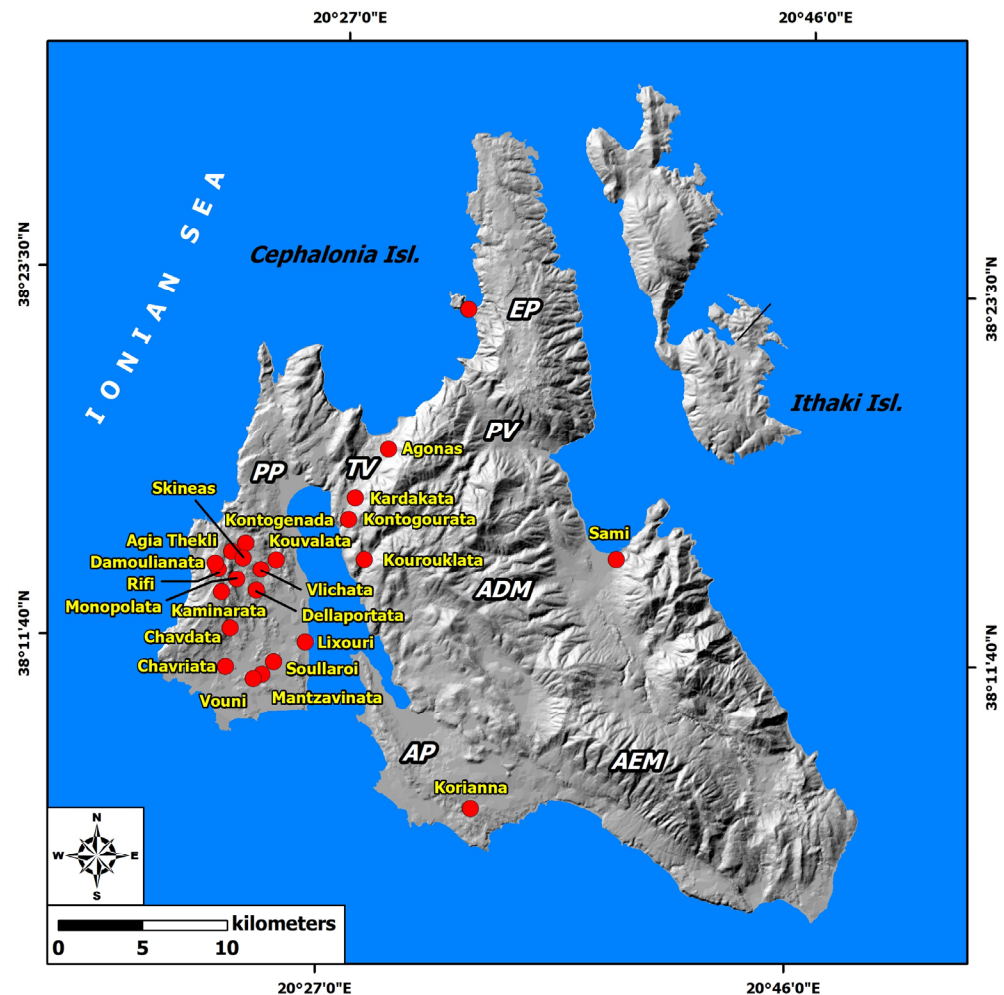


Figure 7. Spatial distribution of the villages in Cephalonia that suffered casualties from the 4 February 1867 earthquake. PP: Paliki Peninsula, TV: Thinia Valley, EP: Erisos Peninsula, KM: Kalon Mt, ADM: Agia Dynati Mt, AEM: Aenos Mt, AP: Argostoli Peninsula.

6.2.2. Indirect Public Health Effects

Metaxas and Livieratos [45] noted the harsh conditions for the earthquake survivors. Most were homeless and living in makeshift tents from collapsed houses, which were cramped, humid, and unhealthy. The lack of food, medicine, doctors, and nurses worsened the situation. In the Municipalities of Anogi, Katogi, and Mesochoria, the residents had no access to medical care for several days (“Kefallinia” newspaper on 22 May/3 June 1867). The arrival of volunteer doctors in early March improved conditions somewhat, but many still suffered disabilities or lost their lives due to the lack of medicine and hospitalization.

Furthermore, the bad weather conditions (rain, cold, strong winds) that prevailed in the earthquake-affected area during the aftershock period aggravated the adverse conditions already caused by the main shock [43,44].

Another public health risk after the earthquake was the deterioration of sanitary conditions due to waste accumulation and the spoilage of perishable goods. The newspaper “Anamorphosis” (25 March/6 April 1867) reported that Lixouri’s market was heavily affected, with merchants setting up disorderly huts in the market square. This led to significant waste and increased the risk of infectious disease outbreaks.

Donations of essential goods and financial aid from the citizens of the Ionian Islands (Kerkyra and Zakynthos), other parts of Greece (Ermoupolis in Syros Island, the Aegean Sea), expatriates, and foreigners, along with volunteer mobilization from Western Greece [Kerkyra and Zakynthos Islands, Patras (Achaia, Peloponnese)], played a significant role in meeting the needs in the earthquake-affected areas [29,37]. Foreign countries also provided significant assistance, sending ships with food and medicine (“Omonoia” newspaper on 4/16 February 1867; “Anamorphosis” newspaper on 11/23 February 1867).

6.2.3. Population Change

Table 5 shows that the population of Cephalonia decreased from 1865 to 1879 by 12,610 inhabitants. Thereafter, there was an increase of a few thousands until 1896 for the prefecture of Cephalonia and until 1907 only for the island of Cephalonia. Ithaki did not follow the same trend as Cephalonia, as the population of the former showed an increasing trend from 1865 to 1896. However, taking into account the fact that a large part of Cephalonia was severely affected by the 1867 earthquake, we can attribute the population decline in Cephalonia to the earthquake’s impact and the adverse conditions that developed not only during the post-earthquake period on the island, but also in the years that followed. Already from the first hours after the earthquake and its first strong aftershocks, many families either fled to other less affected areas of Cephalonia or left the affected island, mainly for Kerkyra and Zakynthos and for other neighboring areas of mainland Greece to the east, such as Central Greece and the Peloponnese (“Anamorphosis” newspaper on 2/14 February 1867, “Imera” newspaper on 18 February/2 March 1867; [38]).

Table 5. The population evolution in the 1867 earthquake-affected areas from 1865 to 1920.

Province	1865	1879	1896	1907
Kranaea (east of Argostoli Gulf)	38,649	32,203	33,441	32,437
Pali (Paliki Peninsula)	23,261	19,003	18,928	17,907
Sami (Eastern Cephalonia)	19,021	17,115	17,708	20,891
Ithaki Island	11,950	12,222	13,286	11,715
Total for Cephalonia Island	80,931	68,321	70,077	71,235
Total for Cephalonia Prefecture	92,881	80,543	83,363	82,950

Not only the 1867 earthquake but also other strong earthquakes in the central part of the Ionian Islands were devastating and had the potential to affect the population evolution of the Ionian Islands, along with other fields of daily life. A typical example of such an effect was observed after the devastating August 1953 earthquake sequence, where three of the most destructive earthquakes in the seismic history of the central part of the Ionian Islands led to waves of migration both to the major urban centers of Greece and abroad. Based on population census data of the Hellenic Statistical Authority over a period of 30 years, from 1951 to 1981, the population of the three islands decreased from 92,706 in 1951 to 61,012 in 1981 (a decrease of 34.18%) [4].

7. The Impact of the 1867 Ionian Sea Major Earthquake on the Built Environment

7.1. Architectural and Constructional Characteristics of the Buildings in the Affected Area

The buildings of the central and southern Ionian Islands are either modern or traditional. The period from 9 to 12 August 1953, when three devastating earthquakes completely swept away decades-old buildings that had been carefully constructed by the local builders, is what distinguishes them. The traditional buildings of the 19th century are either public or private ones. The first category of public buildings included large, impressive structures

that were single units with substantial volume. They had two or more floors. They featured Venetian baroque and renaissance elements in simplified form, a fact that resulted from the long Venetian influence in the Ionian Islands from the mid-14th to the end of the 18th century (1386–1797). This fact led to the creation and prevalence of the “Cephalonian” baroque style [71]. The grandeur of their facades was emphasized by pilasters or pilaster strips extending along the height of the buildings. They had numerous openings, symmetrically placed, without shutters, and richly decorated lintels and frames. They were usually topped with a flat roof with intricate decoration and rarely with a pitched roof. Their plan was mostly rectangular, rarely “I”-shaped or “settee”-shaped, as the latter term prevailed.

The churches and monasteries that constitute the religious architecture of the islands are also classified as public buildings. The 19th-century churches of Cephalonia were always single-aisled basilicas with a tiled double roof [72]. They externally retained the morphological elements of the local simplified baroque style, which was most evident in the flat-type bell towers, which followed a neoclassical line with monumental entrances and facades [72].

An important source for Cephalonia’s town planning and architecture is its historical archive, containing numerous documents on 19th-century constructions, especially from 1818 to 1865 [72]. This period marked significant prosperity and construction activity, notably between 1838 and 1849. The documents include applications and plans for new buildings, reconstructions, demolitions, and extensions, covering private houses, temples, mills, and stone walls. They also feature floor plans and facades of buildings in major towns, such as Argostoli and Lixouri, and various villages across the island.

According to this source, the traditional buildings consisted of one, two, or three floors. Each floor had either a single room, which would later be divided into more using false walls (“muro finto” in Italian, or “morofinta”, as they used to be called on the Ionian Islands) or with many rooms on each floor [72].

The roof was almost always tiled, and while flat, single-pitched roofs were rare, two-, three-, or four-pitched roofs, whether pyramidal, scaphoid, or polyclined were most common. The layout of this roof favors the creation of an attic, i.e., a loft which was usually used as a storeroom. The first floor included the kitchen and the sanitary rooms, while on the ground floor there was the entrance, the storerooms, and the auxiliary rooms [72].

Externally, the architectural style of the private houses is simple. The front doors are rectangular or arched, while the windows are rectangular. The openings in the facades are surrounded by stone frames and are sometimes topped with cornices, while the corners of the buildings and the projections of the floor levels on the exterior of the buildings are often emphasized. The front windows are usually short in length and correspond to one or, less frequently, to two doors.

In terms of construction, the main materials included stone, brick, or wood, with a binder, including lime, sand, and other materials [72,73]. Since there was no additional reinforcement or chainage in most cases, all static and seismic rules in force at the time were applied. Thus, as regards openings, the facade had to maintain symmetry and a ratio equal to 1/2 or 1/1.5 had to prevail. For this reason, the “window under window” rule was applied.

The used stone was soft in texture and thus bonded better with the mortars. The corners of the buildings consisted of carved masonry, necessary for decorative and structural reasons. It served to provide the required reinforcement of these points. The window frames were made of wood and less frequently of metal.

The used mortars consisted mainly of red soil, which it was considered to have anti-seismic properties. The use of lime, as in other parts of Greece, was not common in many buildings because of its cost. The ideal mortar in this period comprised red soil with a small portion of lime. In northern Cephalonia, porcelain was also used in coatings and mortars, providing greater strength [73].

The devastating earthquake of 1867 probably wiped out many buildings depicted in the documents of the local historical archive of Cephalonia and described in this section.

Identifying the buildings designed and constructed from this archive, and confirming whether or not they survived to the present day, could be the subject of a special and extensive research on their seismic construction performance and strength.

7.2. Macroseismic Analysis—Impact on the Built Environment of the Ionian Islands

If one takes into account the contemporary sources that included the effects of historical earthquakes, it can be seen in many cases that damage to monumental structures is presented in more detail than damage to houses. This is attributed to two main reasons, as follows [8]:

- These buildings are more important to the authors of such reports because of their social, economic, symbolic, and cultural values.
- Their structural and non-structural complexity is such that they may be more likely to be damaged than ordinary buildings, even though they may be better constructed.

This is not the case for the 1867 earthquake, as there are reports with a detailed list of the total number of houses in each of the residential areas affected by the earthquake, the number of houses that collapsed, and the number of houses that suffered serious structural damage. These sources enabled us to develop a detailed assessment of the damage to the built environment from the historical earthquake. This detailed analysis gave us the possibility to draw useful conclusions about the vulnerability classes of buildings in the earthquake affected area, the damage grades, the percentages of buildings that suffered heavy and very heavy structural damage per settlement, and to assign macroseismic intensities.

In this section, the impact of the earthquake in several parts of Cephalonia will be presented, starting from (a) the fault block of the Paliki Peninsula in the western part of Cephalonia, where the epicenter was located, and continuing in (b) the Thinia valley, along the transition from Paliki to central Cephalonia, (c) the fault block of the Erissos Peninsula, (d) the western end of Agia Dynati Mt (Potamiana area), (e) the fault block of the Argostoli Peninsula (the Talamies and Livathos areas), (f) the southern slopes of the Aenos Mt in southern Cephalonia and (g) eastern Cephalonia (Pyrgi and Sami areas) (Figure 8). Then, the earthquake's impact on the built environment in the surrounding islands of Ithaki, Lefkada, and Zakynthos in the east, north and south of Cephalonia, respectively, will follow.

7.2.1. Fault Block of Paliki Peninsula

The earthquake completely destroyed most villages in the Atheras, Anogi, Mesochoria, and Katogi areas of the Paliki Peninsula (Figure 8a). Complete destruction (100% collapsed buildings) was recorded in 11 of them. Two thirds (66.67%) of the houses had been reduced to a pile of rubble in three of them. Nine-tenths of the houses (90%) were collapsed in one of them. These settlements, along with the related information, are presented in detail in Table S1, while their distribution is shown in Figure 8b. According to the reports by Fouqué [28] and Schmidt [25], in the Mesochoria area, in which Lixouri is located, out of a total of 3396 houses, 1307 collapsed and 1889 suffered significant damage. This shows that this part of Paliki was irreparably affected. In the Anogi area, 587 collapses were recorded out of a total of 666 houses [25,28]. The complete destruction of the villages of the Anogi and Mesochoria areas was initially published in the “Anamorphosis” newspaper of Cephalonia (2/14 February 1867) and republished in the “Merimna” and “I Foni ton Chorikon” newspapers shortly after (7/19 and 11/23 February 1867, respectively).

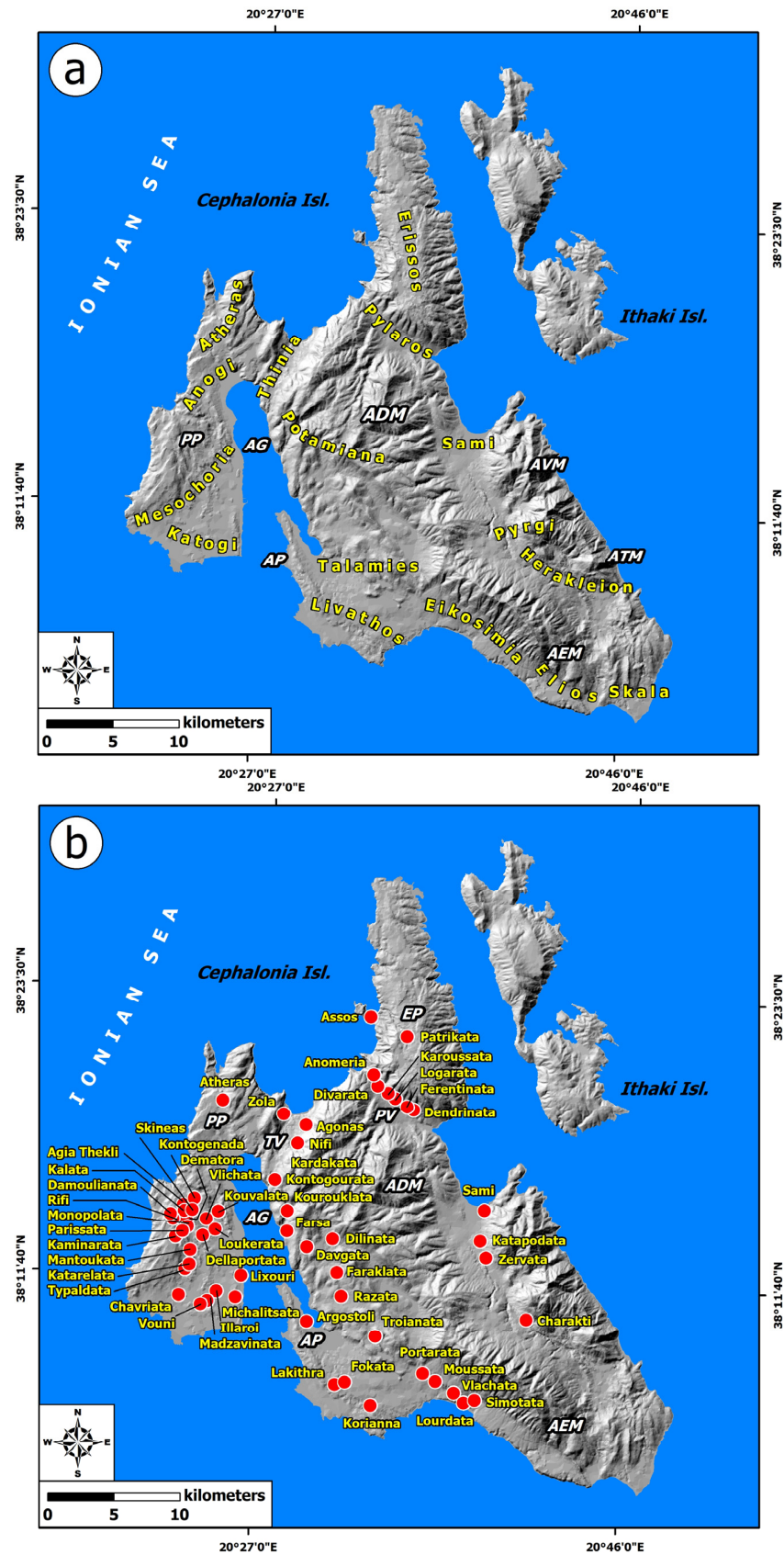


Figure 8. (a) The areas affected by the 4 February 1867 Cephalonia earthquake. (b) The villages and towns that suffered heavy to very heavy structural damage from the 1867 earthquake. They are distributed mainly in the western half of Cephalonia, and more specifically in the central and southern

part of the Paliki Peninsula (PP), within the Thinia and Pylaros valleys (TV and PV, respectively), in a zone between the western ends of the Agia Dynati Mt (ADM) and the eastern coastal part of Argostoli Gulf (AG), in the Argostoli Peninsula (AP), south of the southern slopes of the Aenos Mt (AEM) and in Eastern Cephalonia, from Sami to Riza, along the western slopes of the Avgo and Atros Mts (AVM and ATM, respectively). Lighter damage was reported in the Erissos Peninsula (EP).

Lixouri was the town most severely impacted by the 1867 earthquake. According to Fouqué [28] in his earthquake report, the town had 2000 buildings, half of which were completely destroyed. This was corroborated by Vergotis [29], Partsch [35], and Tsitselis [38]. Schmidt [25] provided more details, citing 1750 damaged buildings and 200 that had collapsed.

Articles in “Anamorphosis”, “Merimna”, and “I Foni ton Chorikon” (on 2/14, 7/19 and 11/23 February 1867, respectively) detailed the earthquake’s impact on Lixouri, noting that almost all buildings were ruined, with only 12–15 heavily cracked and 3–4 intact houses remaining. “Proinos Kirix” (6/18 February 1867) briefly mentioned Lixouri’s destruction without details, likely due to the early publication date. “Omonoia” of Zakynthos (28 January/9 February 1867) emphasized that “no stone was left on stone”.

Vergotis [29] attributed the disaster in Lixouri to three main reasons: (a) the city was close to the earthquake epicenter, (b) its geological structure comprises mainly soft soils, and (c) the majority of the structures in the area included old and fragile buildings.

Despite Lixouri suffering the most structural damage (1950 out of 2000 houses), the highest casualties occurred in Agia Thekli (41 casualties) and Rifi and Damoulanata (63 casualties) due to the total collapse of their smaller number of houses (420 combined) [25,28,35,38]. This is primarily due to the fact that the main shock’s epicenter was in this area, as indicated by the damage and debris patterns. Fouqué [28] and Partsch [35] noted that the shaking was predominantly vertical, especially in Rifi and Damoulanata, where solid stone windmills collapsed vertically due to this motion. It is important to note that these structures were previously founded on soil with excellent properties, and the majority were carefully constructed for the standards and knowledge of the time.

Another element that supports the location of the epicenter between the villages of Rifi and Damoulanata, as well as the prevalence of the vertical component of the earthquake ground motion in the area, is the observed direction of collapses. The buildings between Rifi and Damoulanata collapsed in all directions, indicating vertical ground motion. In contrast, nearby villages, such as Agia Thekli and Skineas, showed a clear E-W collapse direction [28].

As regards the damage intensity in Agia Thekli, the village suffered intensified damage due to its location on a steep slope, which suffered landslides that compounded the earthquake’s impact. The destruction was so total that the village’s buildings, roads, and bell towers were unrecognizable after the main shock [25,28,29,35].

As regards the earthquake’s impact on monumental structures, Fouqué [28] and Partsch [35] reported effects on churches, revealing the direction of propagation of seismic waves. In particular, the bell tower of Pantokrator church in Lixouri tilted to the northeast. Of the 24 churches of the town, most of which were magnificent and spacious, only three remained standing after the earthquake, but even these were on the verge of collapse (“Imera” newspaper, on 25 February/9 March 1867).

Mesoloras [46,47] used the Archive of the Holy Metropolis to detail the impact of the 1867 earthquake on churches and chapels in Cephalonia, as recorded by Metropolitan Spyridon Kontomichalos and priest Panagis Pylarinos. They detailed the damage of three churches and two chapels in Illaroi, three churches and two chapels in Matzavinata, one church and one chapel in Vouni, and one church, one chapel, and one small monastery in Chavriata. The churches suffered (a) the collapse of sanctuary walls, resulting in the partial or total destruction of the Holy Table and the Holy Prosthesis, as well as the interior decoration of the church, (b) extensive cracks of the nave, which occupies the largest surface of the structure and (c) the collapse of the walls of the narthex [46,47]. The chapels collapsed

completely, and the bell towers had extensive cracks or collapsed. The damage is attributed by Typaldos [32] to the use of heavy building stones. The cemetery and courtyard walls collapsed in all cases [46,47].

7.2.2. Thinia and Pylaros Valleys along Transition Zones between Fault Blocks

The impact of the earthquake on the villages in the Thinia valley was published in the newspapers “Proinos Kirix”, on 6/18 February 1867 and “Imera”, on 18 February/2 March 1867. Schmidt [25], Fouqué [28], and Tsitselis [38] also presented data on the destruction in Thinia. The settlements mentioned in most of the above sources are Agonas, Nifio, Kardakata, Riza, Kontogourata, and Zola (Figure 8b). A common feature of the impact in these settlements is the almost complete or complete destruction. More specifically, the percentage of collapsed buildings in each village in Thinia ranges from 75% to 100%. In particular, in two villages, the percentage of collapses reached 100%, in five villages it was more than 80%, and in one village it was 75% (Table S1).

The high percentage of collapses in Thinia is mainly attributed to its geological structure. The valley lies between the fault blocks of the Paliki Peninsula and central Cephalonia [51,55], with the oblique reverse Kontogourata—Agonas fault (KAF in Figure 5b) significantly weakening the geotechnical properties, even of alpine formations. This faulting makes the valley margins highly susceptible to earthquake-triggered landslides, greatly impacting the built environment [3–5].

Similar conditions exist in the Pylaros valley, which was formed along the Agia Efimia fault (AEF in Figure 5b), between central Cephalonia and the Erissos Peninsula (Figure 8b). The northern part of the valley features a blocky and well-interlocked undisturbed rock mass consisting of separate blocks formed by two or locally three discontinuity sets (bedding and two sets of joints), while the footwall block has many open or shear fractures due to its proximity to the Kontogourata—Agonas and Agia Efimia faults [4,5]. This results in an extensive zone of intensively fractured rockmass in the footwall of the Agia Efimia fault, which could be characterized as microcataclasite.

In an article published in “Proinos Kirix” on 6/18 February, it was reported that six settlements in Pylaros were almost destroyed (Anomeria, Divarata, Ligarata, Karousata, Ferentinata, Dendrinata). The newspapers “Anamorphosis”, “Merimna” and “I Foni ton Chorikon” (on 2/14, 7/19 and 11/23 February 1867, respectively), published that Pylaros had suffered considerable damage. Tsitselis [38] also reported major damage in this valley. However, he did not provide further quantitative information on the earthquake’s impact.

7.2.3. Fault Block of Erissos Peninsula

Partsch [35] reported notable damage in the Assos area of the Erissos peninsula (Figure 8). According to the report from “Anamorphosis” on 2/14 February 1867, the damage to the houses in Assos area was extensive. Furthermore, three churches collapsed resulting in a human loss [28]. Schmidt [25] and Fouqué [28] reported that 86 buildings were damaged and 11 collapsed, that is a total of 97 buildings with serious structural damage out of a total of 200 buildings (48.5%). In the village of Fiskardo, located at the northern part of the Erissos Peninsula, six houses collapsed, while many others suffered cracks.

According to “Proinos Kirix” on 6/18 February 1867, even houses in the Assos fortress collapsed. The same newspaper reported that other villages in both the southern and northern part of the Erissos Peninsula were affected (Kothreas, Plagia, Komitata, Neochori and others).

In the Assos province, there were two human casualties in total [28].

7.2.4. Western Front of Agia Dynati Mt (Potamiana Area)

Potamiana is the coastal area that extends between the western front of the Agia Dynati Mt and the Argostoli Gulf (Figure 8). In this area, villages have been founded on the carbonate sequence of the Paxos unit and on scree that has widely formed in this area. The village of Kourouklata (Figure 8b) suffered total destruction, with 100% of the houses

collapsing (65 collapses, one casualty) [25,28] (“Anamorphosis”, “Merimna”, and “I Foni ton Chorikon” on 2/14, 7/19, and 11/23 February 1867, respectively). In the village of Davgata (Figure 8b), out of a total of 150 buildings, 135 were significantly affected by the earthquake, with the majority becoming uninhabitable, as the damage included partial collapse of the masonry. In the same settlement, only 15 buildings remained standing, with no human casualties. The roof of the church collapsed, and many of its walls were cracked (“Anamorphosis”, “Merimna” and “I Foni ton Chorikon”, on 2/14, 7/19, and 11/23 February 1867, respectively). A total of 15 collapsed buildings out of 700 were reported in Dillinata, and 12 buildings out of a total of 80 in Farsa suffered heavy damage but did not collapse [25,28] (“Anamorphosis”, “Merimna”, and “I Foni ton Chorikon”, on 2/14, 7/19, and 11/23 February 1867, respectively). In Faraklata (Figure 8b), out of a total of 400 houses, 25 to 35 collapsed, and 40 were severely damaged [25,28,35]. Razata and Prokopata, suffered no collapse, but only heavy damage to 60 houses [25]. The damage caused in the last three settlements is briefly mentioned in “Proinos Kirix”, on 6/18 February 1867, without providing any further information.

7.2.5. Fault Block of Argostoli Peninsula

Earthquake-induced damage in the Argostoli Peninsula was reported from the Argostoli, Talamies, and Livathos areas (Figure 8a). Argostoli is mentioned first, followed by Talamies and Livathos.

Schmidt [25], Vergotis [29], and Partsch [35] noted that the houses in Argostoli, which had been built along the waterfront and founded on recent deposits, suffered extensive and very heavy damage. This comprised four houses that completely collapsed, while the rest were no longer habitable, except for a few that needed extensive repairs (“Anamorphosis”, “Merimna”, and “I Foni ton Chorikon”, on 2/14, 7/19 and 11/23 February 1867, respectively).

Schmidt [25] and Partsch [35] stressed that these structures were recently and thoroughly constructed. However, their foundation on recent alluvial deposits and the occurrence of secondary EEEs, such as subsidence and liquefaction in the coastal zone [58], affected the performance of the structures against the earthquake and exacerbated the resulted damage.

Apart from the severely affected coastal houses in Argostoli, all the houses and churches in the town were also damaged (“Anamorphosis”, “Merimna”, and “I Foni ton Chorikon”, on 2/14, 7/19, and 11/23 February 1867, respectively). Vergotis [29] reported that one tenth of the houses were significantly damaged, while public buildings such as the courthouse, the customs office, the town hall, the infantry barracks, the bank, and the bridge were also significantly affected [29,35] (“Anamorphosis”, “Merimna”, and “I Foni ton Chorikon”, on 2/14, 7/19, and 11/23 February 1867, respectively).

As regards the special structures, damage, including mainly extensive cracks in the masonry, was also observed in the school facilities of the time, such as the gymnasium, resulting in lessons interruption (“Ephimeris ton Filomathon”, on 20 February/4 March 1867). Furthermore, the only church that suffered serious damage was located at the eastern end of the large bridge that still exists today in Argostoli bay [25].

The casualties in Argostoli amounted to four, with the number of injured being much higher (“Anamorphosis”, “Merimna”, and “I Foni ton Chorikon”, on 2/14, 7/19, and 11/23 February 1867, respectively).

In contrast to the damage within the town of Argostoli and in spite of the destruction along the waterfront, the villages from the Argostoli hilltop up to Pessada and Afrato suffered minor damage [25,35].

The Talamies area was also affected by the earthquake. The villages of Troianata, Demoutsantata (Montesantata before 1940), and Mitakata suffered minor damage (“Anamorphosis”, on 11/23 February 1867) (Figure 8b). Troianata was the worst affected, with 30 collapses [25,28,35], but no human casualties. In the village of Agios Georgios, south of Troianata, 10 houses collapsed [35].

In the Livathos area, the center of the destruction comprised Korianna, Karantinata, and Fokata villages [25,28] (“Anamorphosis”, “Proinos Kirix”, “Merimna”, and “I Foni ton Chorikon”, on 2/14, 6/18, 7/19, and 11/23 February 1867, respectively) (Figure 8b). Korianna village, with a total of 180 buildings, most of which were very well constructed, was completely destroyed, resulting in a casualty. The village of Karadinata, with a total of 70 buildings, and Focata, with a total of 60 buildings, were completely destroyed. In Lakithra village, with a total of 200 buildings, two-thirds of them were completely destroyed.

Partsch [35] reported that the semi-mountainous and mountainous villages of the Livathos area did not suffer significant damage. On the contrary, the villages in coastal areas, such as Korianna, suffered major damage [35] (Figure 8b). A similar pattern of damage distribution was observed in the Potamiana area, mentioned in the previous section.

7.2.6. Southern Slopes of Aenos Mt (Eikosimia Area)

The Eikosimia area is located on the southern slopes of the Aenos Mt (Figure 8a). The aforementioned effect of geology on the distribution of the macroseismic effects is also demonstrated in this area. The semi-mountainous and mountainous villages founded on carbonate formations, more specifically on limestones of the Paxoi unit, remained almost intact after the earthquake [25]. While there were no effects on the carbonate formations, the villages located south of the disrupted front of the Aenos Mt and founded on recent deposits suffered extensive damage [25,28,35].

The percentage of the severely affected buildings reached 100% in all the reported villages [25,28]:

- In Lourdata, out of a total of 52 buildings, 26 had collapsed (50%), and the rest (50%) were severely damaged.
- In Simotata, out of a total of 12 buildings, three had collapsed (25%), and the remaining nine (75%) were severely damaged.
- In Poriarata, out of a total of 24 buildings, 13 had collapsed (54.17%), and the remaining 11 (45.83%) were severely damaged.
- In Moussata, out of a total of 22 buildings, five had collapsed (22.72%), and the remaining 17 (77.27%) were severely damaged.
- In Vlahata, all 43 buildings (100%) were severely damaged.

Despite the significant impact in the Eikosimia area, few casualties and no human losses were reported [28].

7.2.7. East Cephalonia

Earthquake-induced damage in East Cephalonia was reported from the Pyrgi and Sami areas (Figure 8). In Pyrgi, which lies between the Aenos Mt to the west and the Atros Mt to the east, the earthquake caused the almost complete destruction of the village of Charakti (“Anamorphosis”, “Merimna”, and “I Foni ton Chorikon” on 2/14, 7/19, and 11/23 February 1867, respectively), with many ruined houses after the earthquake [28]. The other villages in the area suffered minor damage (“Proinos Kirix”, on 6/18 February 1867).

As in other coastal areas that were significantly affected by the earthquake, great damage was also caused to the town of Sami, in the eastern part of Cephalonia (“Anamorphosis”, “Merimna”, and “I Foni ton Chorikon”, on 2/14, 7/19, and 11/23 February 1867, respectively, “I Imera”, on 18 February/2 March 1867), resulting in two casualties [25,28]. Apart from Sami, the earthquake also destroyed the villages of Zervata, Katapodata, and Mouzakata (Figure 8b), which were founded close to the Ionian thrust over the Paxoi unit [35] (“Proinos Kirix”, on 6/18 February 1867). The other villages of Sami suffered less (“Proinos Kirix” on 6/18 February 1867).

7.2.8. Ithaki Island

Papazachos and Papazachou [58] and Ambraseys [59] noted minimal damage in Ithaki, primarily on its western coastal area, facing Cephalonia. According to reports

from “Proinos Kirix” and “Avgi”, on 6/18 February and 11/23 February 1867, respectively, and from Kallinikos [40], the 4 February 1867 earthquake affected all structures in Ithaki, rendering many uninhabitable. Approximately 30 houses collapsed, causing three injuries (two men and an elderly woman). The residents sought refuge in the countryside and on boats for ten days, as aftershocks caused minimal additional damage. Additionally, on 5 February, a strong earthquake destroyed Dragamesto village in neighboring Aetoloakarnania (“Omonoia”, on 28 January/9 February 1867 and “I Foni ton Chorikon”, on 11/23 February 1867).

7.2.9. Zakynthos Island

Schmidt [25] and Partsch [35] reported the collapse of a small and old house in Zakynthos and cracking in the masonry walls of several houses due to the main shock, especially to the northernmost part of the island (Skinari area). In terms of seismic intensity, this earthquake was more severe than the 1840 event in Zakynthos.

7.2.10. Lefkada Island

Papazachos and Papazachou [58] noted that two settlements were destroyed in Lefkada, while Ambraseys [59] described some damage only from the southernmost part of the island, around the village of Vassiliki (Figure 9).

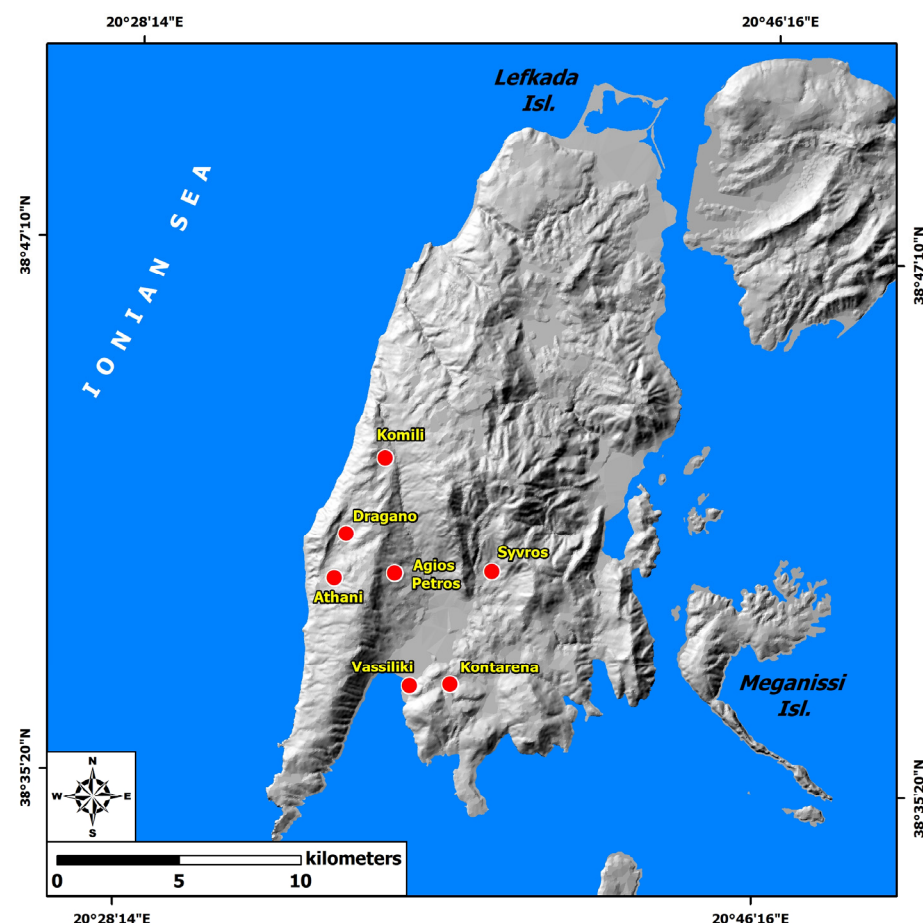


Figure 9. The spatial distribution of Lefkada villages affected by the 4 February 1867 earthquake. They were mainly distributed in the south and southwestern part of the island.

Various newspapers reported briefly on the effects of the Cephalonia earthquake on Lefkada, including “Avgi”, on 26 January/7 February, “Phos” and “Paligenesia”, on 27 January/8 February, “Proinos Kirix”, on 30 January/11 February and “Elpis”, on 31 January/12 February 1867. However, the most extensive reference to the impact of the

1867 main shock on Lefkada was made by the “Lefkada” newspaper on 28 January/9 February and the “Omonoia” newspaper of Zakynthos, on 4/16 February 1867, which essentially republished the information of the former. The greatest impact was reported from the villages of Agios Petros, Kontarena, Syvros, Vassiliki, Athani, Dragano, and Komilio (Figure 9), where many houses completely collapsed.

In Vassiliki, major impact occurred in olive oil warehouses, with about 90 barrels spilled due to the collapse of the warehouses. Fortunately, due to the time, casualties were limited. In the town of Lefkada, several masonry houses suffered cracking, and the old structures collapsed completely. As a result, many valuable fragile objects were destroyed. Many families were left homeless and exposed to cold weather conditions and severe hunger.

7.2.11. Impact on the Built Environment of the Surrounding Island and Mainland Areas

In Central Greece and the northwestern Peloponnese, e.g., in Messolonghi and Patras, respectively, the damage caused by the earthquake was insignificant [25].

However, no further details were available to Schmidt to provide a full picture of the impact on these areas. All available sources, both scientific reports and newspapers, were therefore examined, in order to identify and highlight the effects on the mainland areas east of Cephalonia. Ambraseys [59] reported that the seismic events were felt over a relatively large area, causing minor damage to vulnerable rural houses in places: an empty single-story structure in the swamps of Messolonghi (present Aetolia–Akarnania regional unit in mainland Greece) collapsed, an old dome of a central and ancient church in Agrafa (present Evrytania regional unit in mainland Greece) collapsed, and some ceilings cracked in Astros (Arcadia regional unit in the Peloponnese) and Patras (Achaia regional unit in the Peloponnese). The collapse of the house in Messolonghi was also reported by the newspaper “Paligenesia” on 27 January/8 February 1867. In Kerkyra, where the earthquakes lasted for some time and caused concern, there was no reported damage [59].

7.3. Application of the European Macroseismic Scale 1998 (EMS-98)

7.3.1. Vulnerability Class

According to the available information on the dominant building types and their construction method in the 19th century earthquake-affected Cephalonia, it can be concluded that the private and public buildings affected by the earthquake were masonry buildings with load-bearing walls. Their main structural element is mainly simple or massive stone, respectively, which exists in abundance in the natural environment of the island due to its geological structure. Considering only this information about the construction material, the structures in Cephalonia at the beginning of the second half of the 19th century could be classified into vulnerability class B, according to the guidelines of EMS-98.

If, however, we take into account the way they were constructed, as is evident from the available sources [32,71–73], then it is easy to understand that the application of antiseismic rules was common practice in Cephalonia, which had been previously affected by seismic events, with devastating effects on its structural fabric. Therefore, it is more appropriate to classify private buildings in vulnerability class C according to the EMS-98 guidelines.

Similar practices regarding the construction of masonry buildings in historical periods have been identified in other areas in Greece, which have been affected by destructive earthquakes from antiquity to present. Typical examples are the masonry buildings on the Lefkada Island [54], which is located in the same geotectonic environment as Cephalonia, but also in other parts of Greece, such as the Lesbos Island [74]. Lesbos may be located in the northeastern part of the Aegean Sea, with different geotectonic properties, but is also characterized by high seismicity, with frequent occurrence of destructive earthquakes recorded since antiquity [74].

In the Lefkada case, one- to three-story traditional buildings with dual structural system designed to withstand earthquakes were first constructed before the 19th century. These structures were primarily made of wood frames with diagonal braces, covered

by planks or filled with clay bricks [75,76]. The primary ground level support system consisted of stone masonry walls, while the secondary wooden frame system, reinforced with diagonal trusses and brick infills, supported the upper floors. In the event of masonry wall damage, the wooden frame could sustain the building's vertical load, preventing collapse and providing time for safe evacuation and subsequent repairs.

Following damaging earthquakes in the mid-1800s in the Ionian Islands, timber-framed houses, introduced by the British Navy carpenters using ship-building techniques, including dove-tailed wooden elbows, became prevalent in Lefkada [59]. Their effectiveness during earthquakes in the early 1820s led to their widespread adoption in the region. Many structures built under these specifications have shown reduced vulnerability to earthquakes and are still inhabited today. To protect against humidity, the walls of the upper floors were often plastered or clad with timber or metal sheets. These buildings with the dual structural system are classified as vulnerability class D according to the EMS-98 scale guidelines [54].

In the aftermath of the 2017 Lesvos earthquake, Mavroulis et al. [74] conducted a building-by-building inspection in the affected village of Vrissa, revealing the implementation of anti-seismic construction techniques differing from traditional practices in the Northeastern Aegean. Many buildings featured a dual structural system, incorporating autonomous masonry walls alongside timber frames with extensive "X" bracing. This design ensured roof stability in the event of partial masonry collapse during earthquakes.

7.3.2. Structural Damage and Damage Grades

In terms of damage grades based on the EMS-98, the main structural damage recorded in most of the villages affected by the 4 February 1867 earthquake included: (a) partial or total collapse, corresponding to damage grade 5 and (b) heavy structural damage, including serious failures of walls resulting partial failures of roofs and floors, excluding collapse, corresponding to damage grade 4 (Figure 10).



Figure 10. Typical views of structural damage caused by the 4 February 1867 earthquake to houses with load-bearing masonry walls in the town of Lixouri, located in the Paliki Peninsula. The photographs were first published by Fouqué [28], in his report on the 1867 earthquake. Partial collapse of the masonry is visible (damage of grades 4 and 5 according to the EMS-98 guidelines).

Typaldos [32], in his report, presented not only the building construction deficiencies in Lixouri and Argostoli that led to disaster, but also the advantages of architecture and construction practices that resulted in better performance of buildings during the strong ground motion. He observed that the structures whose walls were made of heavy stones and whose roofs were supported throughout the thickness of walls and gables remained intact after the earthquake. In his view, the great weight of the stones also saved many of the church bell towers.

Considering the destructive repair and reconstruction of many houses, Typaldos [32] proposed measures to limit earthquake damage. He recommended building houses with heavy stones and great height, avoiding pole-supported roofs, and ensuring roofs occupy wall thickness and are supported by building timbers. He also advised against using bricks, particularly in stone-abundant areas like Cephalonia, as they were pointless, unregulated, costly, and weak. During the 1867 earthquake, brick walls were the weakest parts, with most damage occurring at their connections. Typaldos [32] argued that the iron in structures is harmful due to oxidation, calcification, and flexibility during earthquakes, and opposed house coloring due to fading and weathering. In contrast, Vergotis [29] recommended well-designed buildings using wood or metal to limit the earthquake's impact.

7.3.3. Macroseismic Intensities

The spatial distribution of the villages affected by the 1867 earthquake shows that most of them are located in the Paliki Peninsula, more specifically in the Atheras, Anogi, Mesochoria, and Katogi areas, from N to S (Figure 11).

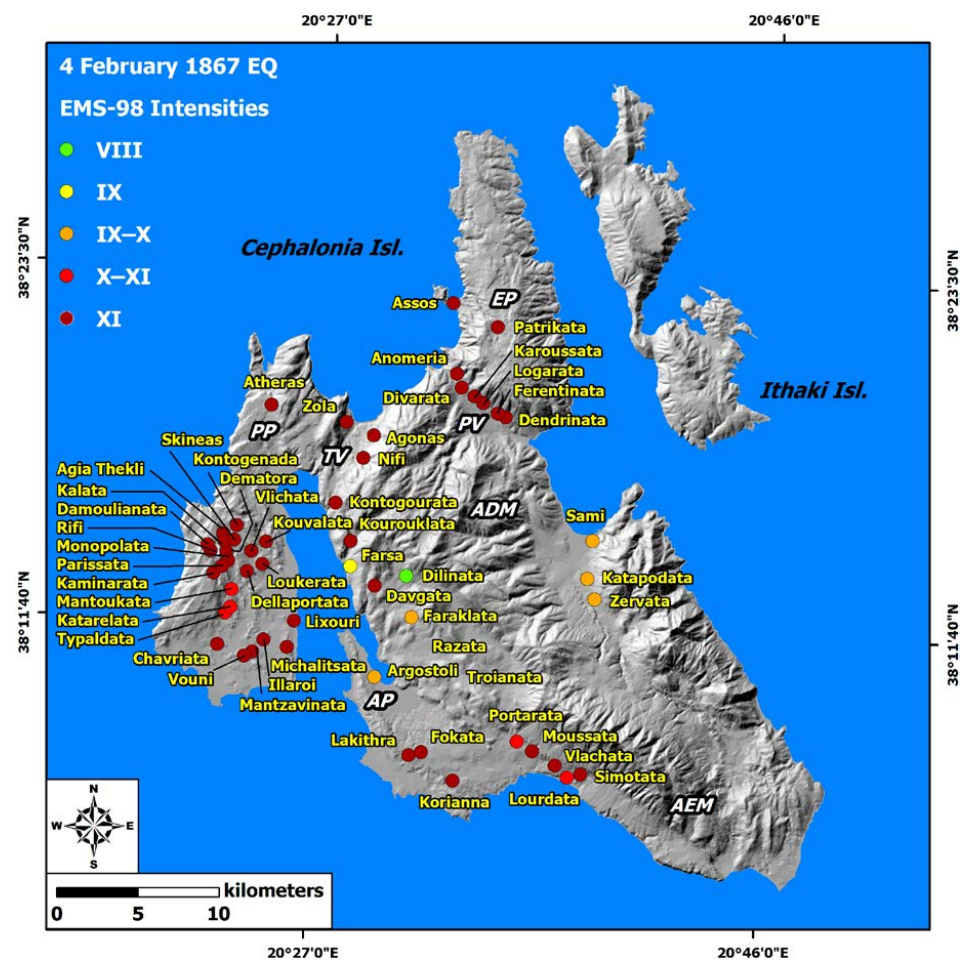


Figure 11. The EMS-98 intensity map of the 4 February 1867 Cephalonia earthquake.

More specifically, 25 of the 54 studied affected settlements are located in the central and southern part of Paliki (Figure 11). A common feature of these villages is the almost complete or complete destruction, with very high percentages of very heavy structural damage (damage grade 5) and heavy structural damage (damage grade 4) in each settlement.

Taking into account the recorded damage, the earthquake can be classified from heavily damaging (intensity VIII_{EMS-98}) to devastating (intensity XI_{EMS-98}) (Figure 11). The maximum intensity XI_{EMS-98} was initially assigned to villages in the fault block of the Paliki Peninsula, in particular in the Anogi, Mesochoria, and Katogi areas. However, XI_{EMS-98}

was not only assigned to Paliki, but also to other fault blocks and transition zones between the fault blocks further east, such as along the transition from Paliki to central Cephalonia (Thinia valley) and from Erissos to Central Cephalonia (Pylaros valley), in the western front of Agia Dynati, in the Argostoli Peninsula, in the area south of the Aenos Mt, and in eastern Cephalonia. Lower intensities (X–XI, X, IX, and VIII_{EMS-98}) were mainly assigned east of Paliki. The assigned EMS-98 intensities are presented in the Table S1 with more details.

8. The Impact of the 1867 Ionian Sea Major Earthquake on the Natural Environment

8.1. Primary Earthquake Environmental Effects

Spanopoulos [44], in his report in the “Ephimeris ton Pilomathon” newspaper on 20 February /4 March 1867, stated that uplift was observed in northeastern Paliki. However, there is no further information on how this phenomenon was perceived in the countryside, nor is there any further reference in any of the other available sources. Information regarding primary effects comes also from Ambraseys [59] and the references therein, which stated that, according to the press reports of the time, seismic activity caused the uplift of the coast of Lixouri [77]. However, this observation was later proven to be untrue [29,39].

8.2. Secondary Earthquake Environmental Effects

From the re-evaluation of the available sources, it was found that the 1867 earthquake triggered the following secondary effects in Cephalonia: (i) ground cracks, (ii) landslides, (iii) liquefaction, (d) hydrological anomalies, and (e) sea disturbances (Figure 12).

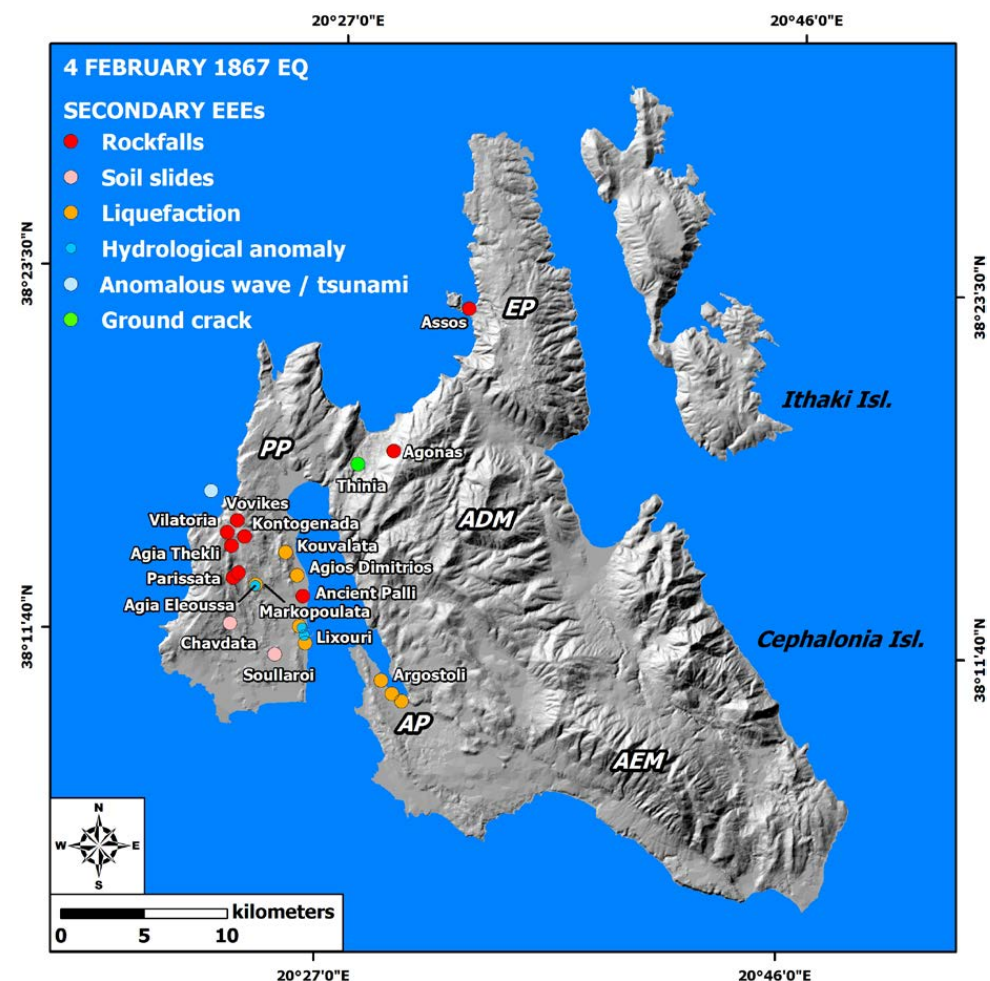


Figure 12. The type and the spatial distribution of the secondary environmental effects triggered by the 4 February 1867 earthquake in Cephalonia were mainly observed or reported in the Paliki Peninsula, with the Argostoli and Erissos peninsulas following with very few affected localities.

8.2.1. Ground Cracks

According to the reports by Schmidt [25], Patsch [35], and the newspapers “Ephimeris ton Filomathon” on 20 February/4 March 1867 and “Imera” on 25 February/9 March 1867, the main shock created ground cracks in various sites in the affected area, especially in the Paliki Peninsula (Figure 12). Many cracks developed very close to stream banks, i.e., in areas that are more unstable during earthquake shaking and susceptible to the occurrence of such phenomena. The ground cracks also had an impact on the vegetation, as many trees growing along these cracks fell.

The widest ground crack was formed in Lixouri, near a large church and the stream [25]. It passed through the cobbled road, and many houses collapsed [25]. Patsch [35] reported that the ground cracks along the stream were 1 m wide and 100 m long. Similar phenomena occurred at other sites and were attributed to the instability of the Pliocene strata [35]. The “Ephimeris ton Filomathon” newspaper on 20 February/4 March 1867 reported that the width of these cracks, which affected the soil of the destroyed town of Lixouri, was about 20 cm.

According to an article published by the “Imera” newspaper on 25 February/9 March 1867, large cracks were created in Thinia valley, without further information on the location and on the quantitative and qualitative characteristics of the effect.

8.2.2. Landslides

According to Schmidt [25], rock fragments were detached from hills during the earthquake and crashed as they rolled downhill. Such phenomena were observed in the acropolis of Paliki, north of Lixouri, and on a hill near Assos (Figure 12).

According to the “Paligenesia” newspaper on 30 January/11 February 1867, stones were ejected from the cracks near Agia Thekli, in the location of Paleon Oros, likely indicating a landslide rather than liquefaction, given the non-existing liquefaction potential of the alpine formations. This view is also supported by the “Avgi” newspaper on 31 January/12 February 1867, which also reported a landslide in Agia Thekli, causing devastation and fire.

Patsch [35] noted that near Agios Stefanos (Figure 12), a large clay volume of several thousand cubic meters and 200 m in length detached from a hill, creating an 8 m deep, 3 m wide gap. Similar landslides occurred during the 2014 earthquake sequence [55,78], which included two quakes ($M_w = 6.1$ and $M_w = 5.9$), on 26 January and 3 February. The first quake caused a landslide that created a gap between the main scarp and the head of the landslide. It was up to 100 m long, 3 m deep, and 5 m wide. The second quake, along with heavy rainfalls, reactivated the landslide, further splitting the clay block and enlarging the gap [55].

According to an article published in the “Imera” newspaper on 25 February/9 March, an almost 4 m wide gap was created from Mothonata to Ernikata (a distance of about 3 km), located in the Chavdata area, in the central part of the Paliki Peninsula. If we take into account the morphology and lithology of the formations in this area [51] and the triggered historical and recent effects [3,5], it is obvious that this effect occurred within an instability zone related to the occurrence of slope failures. Similar phenomena, but of smaller magnitude, were triggered in neighboring areas, such as in Soullaroi, after the 1867 and 2014 earthquakes.

Tsitselis [38] also reported that rock fragments detached from slopes and small ground subsidence occurred after the main shock. However, he does not provide any further information on the exact location and qualitative and quantitative data to determine the intensity of the generated phenomena in the affected localities.

In “Ephimeris ton Filomathon”, on 20 February/4 March 1867, it was reported that at the western end of Paliki, a rock was detached and fell into the sea, along with a small monastery that stood on it.

Landslides occurred in Thinia valley (Figure 12), where unstable rocks were detached from slopes [29]. The valley, 6 km long and up to 2 km wide, lies between the Agia Dynati Mt and the Paliki Peninsula, with steep, fault-controlled marginal slopes that make them

prone to earthquake-triggered landslides [4,5,55]. Similar landslides occurred during the 1953 and early 2014 earthquakes in Cephalonia [4,5].

Papazachos and Papazachou [58] also reported that the earthquake triggered rockfalls. However, they have not provided additional information on the exact location of the phenomena and their qualitative and quantitative characteristics.

In the context of research on earthquake-triggered landslide susceptibility, Mavroulis et al. [5] compiled an inventory of historical and recent phenomena. They found that the 1867 earthquake also triggered debris slides and rockfalls in the villages of Parissata, Monopolata, Vilatoria, Vovikes, and Kontogenada (Figure 12), in the central western part of the Paliki Peninsula, without causing structural damage [35,79].

8.2.3. Liquefaction Phenomena

In Markopoulata of Delaportata, in a vineyard located at a height of 100 m above sea level, ground cracks were formed and cyan silt was ejected. The deposition of the silt created a cone six feet high [25,38]. From this cone, a mixture of silt and water continued to be ejected even after the cone was partially drained. Schmidt [25] attributed the triggered phenomena to the compression of geological formations, which had been deposited on clay layers saturated with water.

Partsch [35] mentioned the occurrence of liquefaction in the Kouvalata and Agios Dimitrios areas (Figure 12). In particular, near Kouvalata, liquefied material ejected in the middle of a field, and a deep basin was formed. Clay liquefied material was also observed. In Agios Dimitrios, a blue-green clay cone resembling a crater 1 m wide and 0.5 m deep was observed a short distance from the sulfur spring of Agia Eleoussa [26]. Its creation was then attributed to the deformation of a clay layer that slid over a very steep formation. On his visit to this site, Schmidt found the cone submerged, with a diameter of 16 feet and a height of 1 foot.

Ground cracks were also observed on the western and southern coast of the Koutavos lagoon, south of the port of Argostoli [25] (Figure 12), which can be attributed to lateral spreading phenomena along or close to the coastline.

Papazachos and Papazachou [58] and Ambraseys [59], in the context of describing the effects on the built environment of the 4 February 1867 earthquake, attributed the type, intensity, and distribution of the building damage in Argostoli waterfront to soil subsidence and liquefaction, but they did not provide additional qualitative and quantitative information and data to determine the exact location of these phenomena. Schmidt [26] also mentioned that these coastal structures were flooded in mud, a fact that reveals extensive liquefaction close to the waterfront of Argostoli.

8.2.4. Hydrological Anomalies

The 4 February 1867 earthquake caused hydrological anomalies in springs in the most affected fault block of the Paliki Peninsula. In particular, it triggered turbidity in the water of sulfur springs gushing from gypsum and limestone in Agia Eleoussa [25]. This hydrological anomaly lasted for 2 months, extending from 23 January/4 February to 23 March/4 April 1867. On the contrary, no change was observed at Kounopetra, nor in the sea current at the mill of Argostoli, areas with susceptibility to such phenomena.

Lixouri residents noticed a strong smell of sulfur in the town after the earthquake ("Aeon" newspaper on 30 January/11 February 1867), while the waterflow in the stream crossing Lixouri decreased after the earthquake ("Ephimeris ton Filomathon" on 20 February/4 March 1867) (Figure 12). However, Partsch [35] contradicted what is described above and reported that the groundwater level did not exhibit any anomalies, neither upward nor downward movement.

8.2.5. Tsunami

According to the “Syntagma” newspaper on 25 February/9 March 1867, the epicenter of the earthquake should be offshore west of Cephalonia, as a sea recession occurred there during the earthquake.

Papazachos and Papazachou [58] reported that the 4 February 1867 earthquake resulted in a subtle tsunami and a phenomenon known in the Ionian Islands as “ρηχίες” (in Greek)/richies, which correspond to the sea withdrawal before and after the earthquake. Vergotis [29] gave more details on these effects, revealing that when the earthquake struck, the sea level rose and fell three times. He also noted that sea disturbances were observed both before and after the earthquake. However, no further information was provided on these phenomena and no spatial data to determine their location.

Ambraseys [59] noted that there is no evidence that the 1867 earthquake was associated with a seismic sea wave. This is initially supported by Schmidt [25], Partsch [35], and Tsitselis [38]. Schmidt [25] claimed that, fortunately for Cephalonia, either no disturbance in the sea occurred or if it did, it was imperceptible. If it had occurred shortly after the earthquake, the lowland area of Lixouri and the narrow bay of Argostoli would have been affected by the relative phenomena of the withdrawal of the sea and the subsequent inundation of the coastal zone. Partsch [35] reported that the sea, as long as the earthquake lasted, remained calm, and the operation of the mills continued with a normal inflow of the sea. Tsitselis [38] reported that no sea disturbance (an increase or decrease in the sea level) occurred that could have destroyed the coastal area of the eastern part of the Paliki Peninsula, including Lixouri and the areas around Kranaea.

8.3. Application of the ESI-07 Scale

The first place in the list of earthquake-triggered environmental effects is occupied by landslides, accounting for 45.83% (11 out of 24 cases), liquefaction phenomena, at 29.17% (7 out of 24), and hydrological anomalies, at 12.50% (3 out of 24), occupying the second and third places, respectively. Marine anomalies (8.33%, 2 out of 24) and soil cracks (4.17%, 1 out of 24) are the lowest percentages.

The vast majority of the secondary EEs in Cephalonia were generated in Paliki (Figure 12). According to the available sources, it can be concluded that almost all categories of secondary effects that an earthquake can trigger in the natural environment of an affected area occurred in Paliki. Outside of Paliki, the only fault blocks affected by the earthquake were the Erissos and Argostoli peninsulas and the Thinia valley (Figure 12). The effects on these fault blocks included ground cracking and subsidence in the Thinia valley, subsidence in the Erissos Peninsula, and liquefaction phenomena in the Argostoli Peninsula (Figure 12).

The study of the available sources enabled us to derive not only qualitative and quantitative information and data on their location, but also to apply the ESI-07 scale by assigning corresponding intensities to 24 cases of effects (Figure 13), which are presented in detail in the Table S2. The only case for which it has been impossible to determine the location of the effect is the case of ρηχίες/richies.

The maximum intensity VIII–IX_{ESI-07} was attributed to extensive earthquake-triggered landslides with impact on the built environment (detachment of scree and the subsequent destruction of the village of Agia Thekli) in Paliki (Figure 13). Intensity VIII_{ESI-07} was attributed to landslides, liquefaction, and hydrological anomalies in Paliki (Figure 13). Smaller intensities, such as VI–VII_{ESI-07}, were attributed to subsidence in eastern Paliki (Figure 13).

In the other fault blocks and in the transition zones, the assigned intensities were lower, such as VI–VII_{ESI-07} in Thinia and Erissos and VIII_{ESI-07} in the northeastern coastal part of the Argostoli Peninsula (Figure 13). This fact supports the view that Paliki suffered the most from the 1867 earthquake.

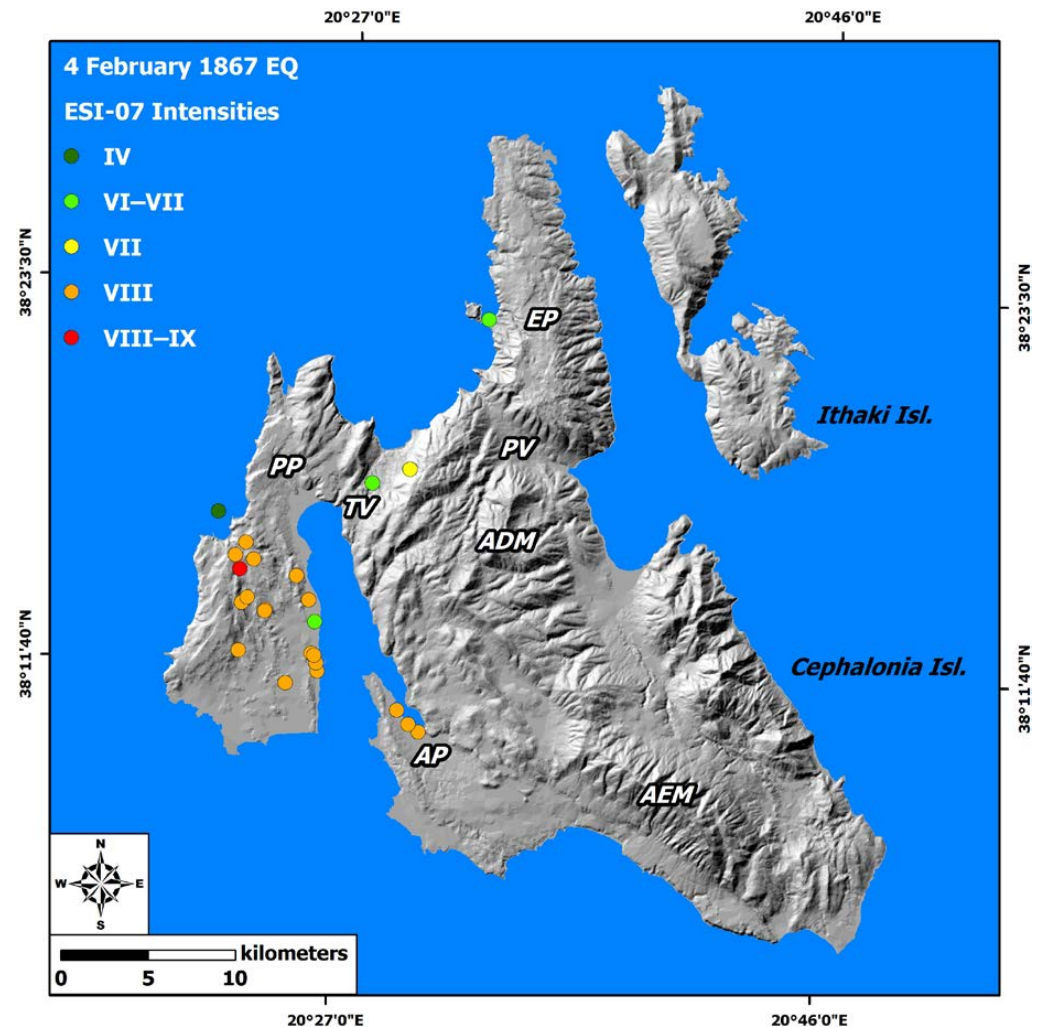


Figure 13. The environmental seismic intensities for the 4 February 1867 earthquake. The maximum intensity VIII–IX_{ESI-07} was assigned to the Paliki Peninsula (PP), with the intensity VIII_{ESI-07} assigned to both Paliki and the neighboring Argostoli Peninsula (AP). In the Thinia valley (TV) and the Erisos Peninsula (EP), the lowest intensity VI–VII_{ESI-07} was assigned. In the Agia Dynati Mt (ADM) and the Aenos Mt (AEM), no intensities were assigned due to the absence of triggered effects.

9. Discussion

A common but significant feature of the 25 affected villages in Paliki is that they were founded on Pliocene and Quaternary deposits (Figure 14). The Pliocene–Calabrian marine sequence, 200–500 m thick, is found in an elevated coastal area, 2–10 km wide in eastern and western Paliki [51]. The lower part of the sequence is composed of conglomerates, breccia, calcarenites, and the limestones of the Lower Pliocene. The intermediate part includes yellowish marls with siltstones, sandstone intercalations, sands and conglomerates of the Middle–Upper Pliocene and the upper part consists of marls with intercalations of sands and coarse-grained calcarenites [51].

The heavily affected part of the Paliki Peninsula is also formed by the Middle Miocene–Lower Pliocene clay–clastic series of the Paxoi unit (Figure 14), which includes alterations of marls, clays, and pebbles [51]. These mixed-phase deposits show heterogeneity, lateral evolution, and weathering, leading to an uneven and anisotropic behavior and rapid variation in mechanical properties [80]. The formation’s cohesion varies due to primary (initial lithological composition, diagenesis, type of matrix and grain size composition) and secondary factors (alteration and weathering). The synergy of factors, such as the above adverse characteristics of the formations in the central, eastern, and southern part

of Paliki, combined with the strong ground motion, the inland location of the earthquake epicenter and the building properties contributed to the total destruction and levelling of many settlements in Paliki.

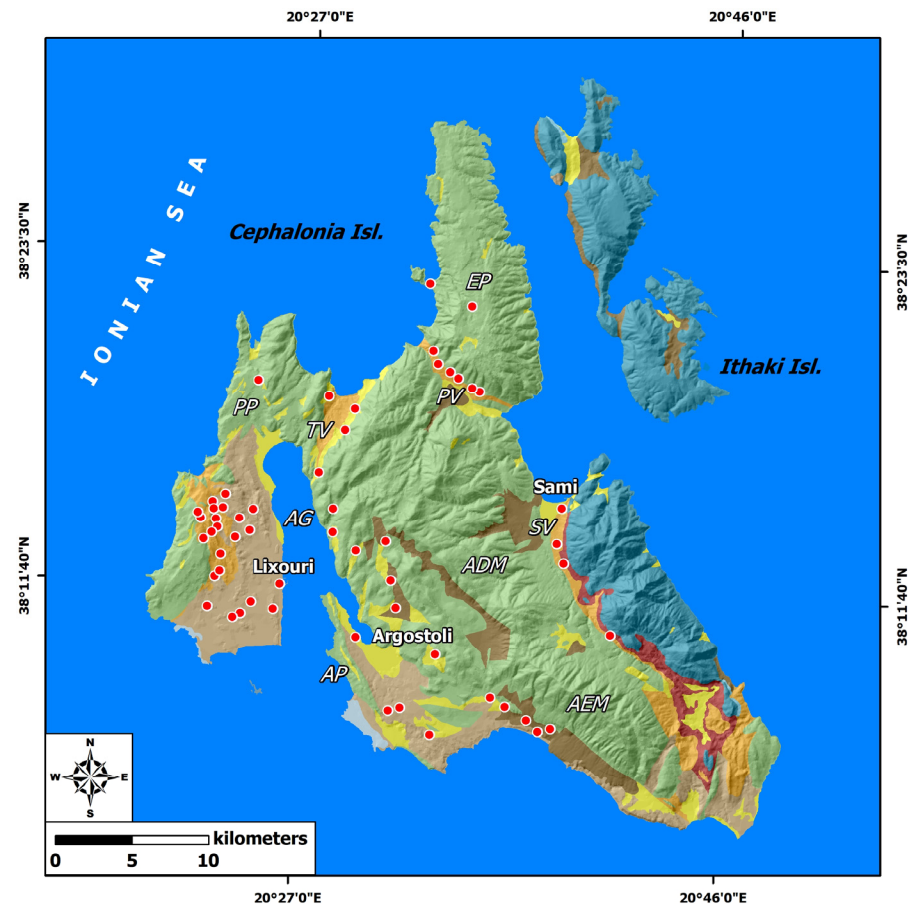


Figure 14. Map showing the spatial distribution of residential areas (red dots) in Cephalonia affected by the 4 February 1867 earthquake, in relation to the geological structure. It is clear that the affected towns and villages are located exclusively in areas composed of post-alpine deposits and clay–clastic alpine formations (details of the geological formations are provided in the neotectonic map shown in Figure 5b), with the properties that make them susceptible to failure. Almost all settlements founded on alpine formations of the Ionian and Paxoi geological units remained intact after the earthquake. PV: Pylaros Valley, TV: Thinia valley, AG: Argostoli Gulf, ADM: Agia Dynati Mt, AEM: Aenos Mt.

If we observe the geological structure of the affected areas outside Paliki, it is concluded that they are also built by recent deposits (Figure 14), with mechanical properties that can contribute to the amplification of the earthquake ground motion and the aggravation of building damage. Starting from the Thinia valley, all the affected villages along its eastern margin are founded on recent Quaternary deposits, including scree (Figure 14), which, in combination with the existence of the oblique-reverse Kontogourata–Agonas fault form conditions ideal for the occurrence of slope failures and serious structural damage to the adjacent villages. The earthquake-affected village of Zola on the western boundary of the Thinia valley was founded on similar deposits.

In terms of geological structure, the same applies to the western front of Agia Dynati Mt, to the Argostoli Peninsula and to the area south of the Aenos Mt (Figure 14). The presence of extensive scree on the western front of the Agia Dynati Mt and the southern slopes of the Aenos Mt [51] have contributed to the instability, the occurrence of slope failures during the earthquake, and the destructive impact on adjacent villages.

In eastern Cephalonia, most of the affected villages were founded on the clay–clastic sequence of the Paxoi unit, forming a zone arranged parallel to the Ionian thrust on the Paxoi unit formations (Figure 14) and characterized by high susceptibility to landslides. Along the same zone, extensive landslides were triggered during the August 1953 earthquake sequence, and in particular during the second and third earthquakes, which occurred on 11 and 12 August, respectively [4,5].

In summary, heavy structural damage and collapses in Cephalonia were observed only in areas with recent Pleistocene–Quaternary deposits, the Pliocene–Calabrian series, and the clay–clastic sequence of the Paxoi unit, which have unfavorable mechanical properties. Other geological formations, such as the carbonate sequence in the northern part of the Paliki Peninsula’s fault block, the Erisos Peninsula’s fault block, the central part of Cephalonia, and the Ionian unit in Eastern Cephalonia, experienced slight damage (Figure 14). This underscores the significant influence of the geological structure, particularly the distribution of alpine and post-alpine deposits, on the building damage distribution.

The same view was supported by Schmidt [25], who stated that structures founded on carbonate formations, particularly limestones, did not suffer damage, unlike those founded on recent deposits, even if they were better designed and constructed, as was the case with the houses destroyed along the Argostoli waterfront.

A similar effect is observed in the southern part of Lefkada. Most of the affected settlements were founded on alluvial deposits, molassic formations, and the clay–clastic sequence of the Paxoi unit (Figure 15). The molassic formations comprise different lithologies and phases, which implies a strong heterogeneity and anisotropy in the behavior of the mixed formations that vary considerably at individual horizons, depending on the lithological composition and the physical state of the formation [80]. Moreover, certain affected villages are situated within a smaller fault block (Dragano–Athani Graben, presented as DAG in Figure 15), composed of limestone. This alpine formation is significantly altered due to the presence of active faults along the graben margins and intense tectonic deformation. Consequently, the limestone in these areas appears nearly pulverized and is highly susceptible to failure, exacerbating the impact of earthquakes on adjacent villages. A prime example of this impact is the damage observed in southern Lefkada during the November 2015 earthquake. Villages such as Dragano, Athani, Agios Petros, and Vassiliki suffered extensive damage from both strong ground motion and secondary EEEs, such as rockfalls in Agios Petros, leading to casualties, and liquefaction in Vassiliki, causing significant damage to port facilities [54] (Figure 15).

Based on recent studies on the impact of hydrometeorological hazards on buildings [81,82], storms are characterized by a high potential to affect various building elements. These are mainly non-structural and include flat roofs, terraces and balconies, connections between steep roofs and other parts of the building, basement walls in contact with the ground, as well as windows and exterior doors [81,82]. The storm that occurred before the 1867 earthquake could have acted locally (in Lixouri and Argostoli) as a factor increasing building vulnerability by subjecting their exterior to water and moisture loads, partially shaping the type and degree of damage triggered by the earthquakes.

Regarding the distribution of the EEEs, by comparing the earthquake-triggered landslide susceptibility zones compiled by Mavroulis et al. [5] with the locations of landslides caused by the 1867 earthquake in Cephalonia, it becomes clear that their distribution is not random. The 1867 landslides were generated in zones of high, very high, and critically high susceptibility (Figure 16). Something similar applies to the triggered liquefaction. By comparing the liquefaction susceptibility zones presented by Mavroulis and Lekkas [4] for Cephalonia and the locations of the 1867 phenomena, it is obvious that all occurred in coastal areas with recent sandy deposits. They are characterized by high liquefaction potential, mainly attributed to the lithology and the age of these deposits among other favorable factors (Figure 16). The hydrological anomalies were triggered in water bodies, and mainly in the rivers and springs of the most affected Paliki fault block. The generated sea disturbances could be classified as mild and are usually reported in the central and

southern Ionian Islands from both historical and recent earthquakes [83]. The mild nature of the effects and the limited to non-existent impact on the coastal zone could be attributed to the fact that the earthquake epicenter was located onshore and to the prevalence of strike-slip motion [83], as is the case for the vast majority of earthquakes occurring in the central part of the Ionian Sea.

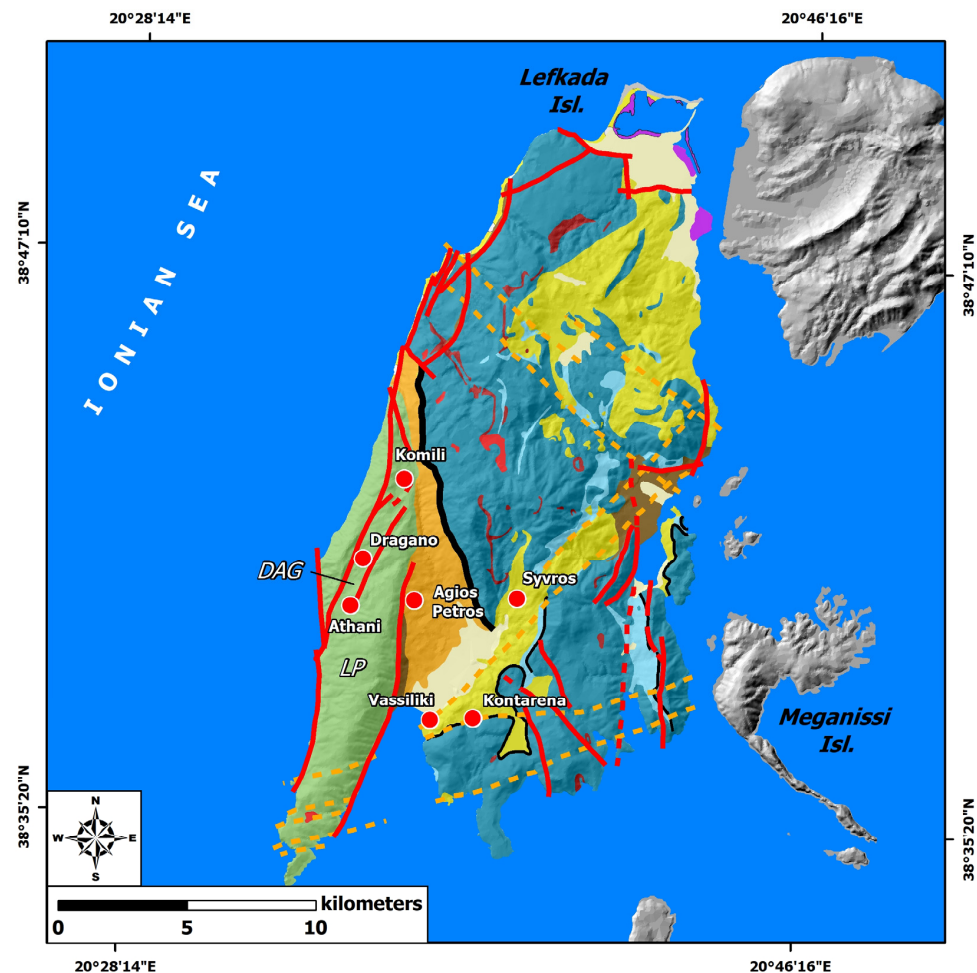


Figure 15. Map showing the spatial distribution of the residential areas in Lefkada affected by the 4 February 1867 earthquake, in relation to the geological structure. It is clear that the majority of the settlements affected in the southern and southwestern part of the island are located in areas structured by post-alpine and clay-clastic alpine deposits (details of the geological formations in Figure 5a), with characteristics that make them prone to failure and earthquake-induced building damage. The affected villages in southwestern Lefkada are located within a small part (Dragano—Athani Graben, DAG) of the fault block of the Lefkada Peninsula (LP). The observed damage is attributed to the active tectonics and the highly disrupted formations within and along the margins of the DAG.

From the comparison of the EMS-98 and ESI-07 intensities of the 1867 Cephalonia earthquake, it is observed that differences occur in several sites, with the EMS-98 intensities being higher than the ESI-07 ones. This can be attributed to the occurrence of previous strong earthquakes in the study area, which had certainly weakened the buildings, many of which were either not fully restored or poorly repaired. One such event, close in time to the 1867 earthquake, which could have had such an effect on the built environment of the study area, is the 1862 Cephalonia earthquake ($M_w = 6.5$, $I_{max} = IX$). As mentioned in the historical seismicity section, the earthquake caused destruction in Argostoli and heavy damage in Lixouri [57]. Apart from this destructive earthquake, seismic events with smaller magnitude but with high potential for damaging structures, such as the July–October 1866

earthquakes mentioned by Tsitselis, certainly occurred before the 1867 event in the study area, resulting in the deterioration of buildings [38].

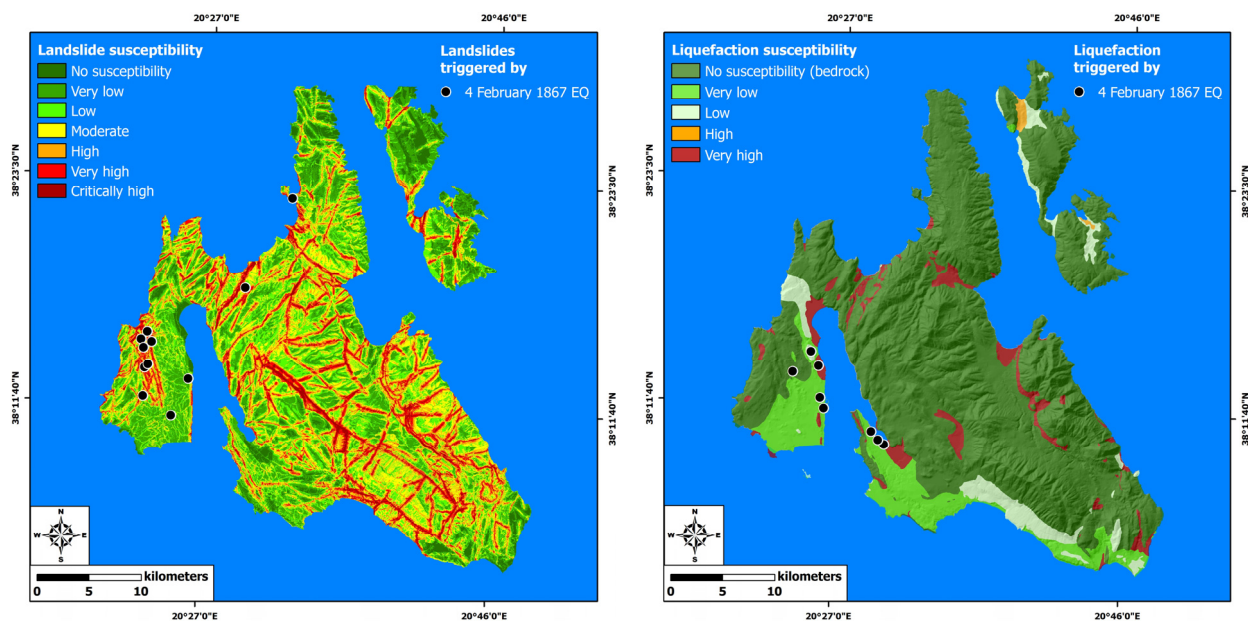


Figure 16. Comparison of the 4 February 1867 earthquake-triggered landslides and liquefaction inventory, with the relevant susceptibility maps of Cephalonia presented by Mavroulis et al. [5] and Mavroulis and Lekkas [4].

Similar differences between traditional macroseismic intensities and environmental seismic intensities were also detected in recent cases. Typical examples are the 1997 Umbria-Marche earthquake in central Italy [84] and the 2008 Andravida earthquake in the northwestern Peloponnese, Greece [85]. Guerrieri et al. [84] attributed the detected differences between the MCS and ESI-07 intensities to the poor maintenance of buildings due to inconstant occupation. In addition, Mavroulis et al. [85] recorded the building damage and environmental effects in the northwestern Peloponnese, applied the EMS-98 and ESI-07 scales, and detected EMS-98 intensities higher than the ESI-07 ones. This fact was attributed to the occurrence of several previous earthquakes in the study area, which had certainly weakened the masonry buildings constructed with fluvial stones and a low-quality matrix and reconstructed either poorly or incompletely after the earthquakes [85]. In all the above cases of recent earthquakes [84,85], but also in the case of the historical earthquake of 1867, an overestimation of the earthquake's strength and shaking in the study area is evident if we take into account only the observed building damage.

Another important element that emerges from this research has to do with the importance of the observation of the effects of a historical earthquake on the built environment and their interpretation, at a time when there were no instrumental recordings and monitoring. The importance of the approach used by Fouqué [25] with only field observations and the effects on buildings to reveal the 1867 earthquake parameters (epicenter location, directivity, focal depth etc.) has been highlighted and exploited in recent years in the context of studies on parameters of either historical or recent earthquakes, for which no instrumental data exist. In a similar way, Mavroulis et al. [86], by utilizing the macroseismic results of their post-event filed surveys conducted in earthquake disaster fields around the world, found and recorded damage which can be more easily attributed to the prevalence of the vertical component of the seismic motion than to the horizontal one. This damage can be used as an indication, and the affected buildings can serve as seismoscopes to draw important conclusions on the properties of the seismic motion of historical earthquakes, where instrumental data are not available. A typical case of non-usable data for a recent seismic event comes from Turkey, where an $M_w = 7.8$ earthquake devastated Eastern Anatolia in

early February 2023. A large part of the recorded near-fault earthquake ground motions exhibited early termination due to instrument malfunction and power failure during ground shaking [87]. This fact did not prevent further studies for detecting earthquake parameters and interpreting the observed damage. Mavroulis et al. [88], relying only on post-event field surveys and the mapping of building damage in Eastern Anatolia, highlighted not only the characteristics of the seismic motion, but also the factors controlling the type, grade, and spatial distribution of damage in the earthquake-affected area.

10. Conclusions

The 1867 earthquake is the largest recorded in the Ionian Islands, being significant for both Greece and the Eastern Mediterranean. Despite its importance, it was understudied until recently. This research gathered information on the earthquake's impact on public health, population, buildings, and the natural environment, using contemporary scientific reports, newspapers, scholars' reports, religious sources, and recent historical accounts. Searching Greek newspapers of local and national circulation to capture the properties and the impact of the 1867 earthquake was conducted for the first time for a historical earthquake and for the second time for an earthquake in the Ionian Sea after Mavroulis and Lekkas [4] applied a similar approach for the relatively recent destructive earthquake sequence in Cephalonia in August 1953.

By searching for new sources in Greek and presenting them in this research for the first time, non-Greek speakers are given the opportunity to discover details about the parameters and consequences of an important historical earthquake. Furthermore, the reevaluation of contemporary sources, including earthquake reports conducted by authors from different disciplines and fields of knowledge (e.g., geologists, doctors, teachers, historians, churchmen, etc.) made it possible to obtain information not only on the effects of the earthquake on the built environment, as is usually the case with historical earthquakes, but also on the effects on the natural environment and the population. In this way, it is possible to highlight the overall impact of the earthquake, based on the existing sources and the available information.

This approach enabled us to obtain a great deal of information about the main types of structures of the period, their vulnerability, and the grades of damage caused by the 1867 earthquake. These data proved useful for assigning macroseismic intensities to residential areas whose building stock had suffered severe structural damage. A similar possibility was given for the EEZs. The available spatial, qualitative and quantitative information was important for mapping the affected locations, identifying areas susceptible to their occurrence and assigning environmental seismic intensities in the affected area.

The results of this research led to the most complete description of the characteristics of the 1867 earthquake, given the historical nature of the phenomenon, and the effects of the first earthquake after the incorporation of the Ionian Islands into the newly established Greek state. This research has not only highlighted the benefits of using such sources and information for the reconstruction of a historical destructive earthquake, but it also reveals that there are still independent sources to be sought and new perspectives from which new data on historical earthquakes could emerge. Furthermore, this research emphasizes that understanding the historical seismicity of both the Ionian Islands and any other seismic active region worldwide is an open challenge for the global scientific community.

Historical earthquake data provide valuable insights into the potential impact of future earthquakes. By analyzing past events, several stakeholders can better prepare for future seismic activity. This is vital for urban planning, infrastructure development, and disaster management. Government agencies should rely on historical earthquake data to formulate policies, regulations, and emergency response plans aimed at minimizing the impact of earthquakes on society. Urban planners and engineers have the opportunity to update the codes for designing and constructing resilient infrastructure, such as buildings, bridges, and transportation networks, capable of withstanding seismic loads, based on historical earthquake information. Through the examples of the past, emergency managers and

disaster relief organizations are able to develop and adopt preparedness and response strategies, allocate resources efficiently, and coordinate relief efforts during earthquake emergencies. Local communities can benefit from historical earthquake information by gaining insights into their region's seismic history and understanding the importance of earthquake preparedness and resilience-building initiatives. The dissemination of information about historical earthquakes and their impact contributes to raising public awareness about seismic risk and the importance of earthquake preparedness. Education and outreach initiatives based on historical data can empower individuals and communities to take proactive measures to reduce their vulnerability to earthquakes.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/geosciences14080214/s1>, Table S1: The residential areas (villages and towns) affected by the 4 February 1867 Cephalonia earthquake, percentages of damage degrees (DD) 4 and 5, based on the available contemporary sources, and EMS-98 intensities based on the available sources and the provided geographic, quantitative, and qualitative information; Table S2: Environmental effects triggered by the 4 February 1867 Cephalonia earthquake and intensities based on the Environmental Seismic Intensity (ESI-07) Scale.

Author Contributions: Conceptualization, S.M.; methodology, S.M.; formal analysis, S.M.; investigation, S.M. and M.M.; resources, E.L.; data curation, S.M. and M.M.; writing—original draft preparation, S.M. and M.M.; writing—review and editing, S.M., M.M., E.L. and P.C.; visualization, S.M.; supervision, S.M.; project administration, S.M. All authors have read and agreed to the published version of the manuscript.

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