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Earthquake magnitudes revision from early instrumental records: Greece and southern Balkans, 1900-1910

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Abstract

Records from five Agamennone-type mechanical seismographs have been used for the first time to recalculate earthquake magnitudes in Greece and the southern Balkans from 1900 to 1910. Mainka and Wiechert seismometers were used for the Greek seismicity monitoring and the surface-wave magnitude, M_S, determination of hundreds of earthquakes occurring for several decades after 1910. Since the intermediate natural period (3.5-9.0 s) was a common feature of Agamennone, Mainka, and Wiechert instruments, we used Agamennone trace amplitudes recorded from 1900 to 1910. After calibration with post-1910 magnitudes, we recalculated magnitudes for 52 shallow and intermediate-depth earthquakes, with proxy-M_s ranging from 4.7 to 7.4 For some earthquakes the epicentral coordinates were also improved with the use of *P-S* travel-time curves and macroseismic information. The method is promising for magnitude determination of many small earthquakes recorded in Greece in the early instrumental period.

Keywords: Early instrumental earthquakes; Agamennone seismographs; Surface-wave magnitude redetermination; Greek seismicity; Southern Balkans earthquakes

1. Introduction

The reliable determination of earthquake magnitudes is of great importance for studies on seismicity and seismotectonics as well as for earthquake hazard and risk assessment purposes. This issue, however, is quite challenging particularly as regards the early instrumental era of seismology, i.e. around the transition from the 19th to the 20th century. The reasons are the sparsity of seismic stations and the low quality of records. Therefore, earthquake catalogues of that era are vastly incomplete, heterogeneous and of low accuracy. The region of Greece and the surrounding areas (Fig. 1) is characterized by the highest seismic activity in Europe (e.g., Båth, 1983). Shallow earthquakes occur in the entire region while intermediate-depth earthquakes, with focal depths up to ~200 km, take place only in the southern side of the region due to the active subduction of the Mediterranean lithosphere from about SSW to NNE (Fig. 1) (e.g. Bocchini et al., 2019, Le Pichon et al., 2019, and references therein). In the instrumental period of seismology, i.e. from 1900 onwards, large magnitude earthquakes have been recorded, such as the tsunamigenic earthquake of 9 July 1956 ($M_w = 7.7$; ISC-GEM, 2024) that ruptured the south Aegean Sea back-arc area.

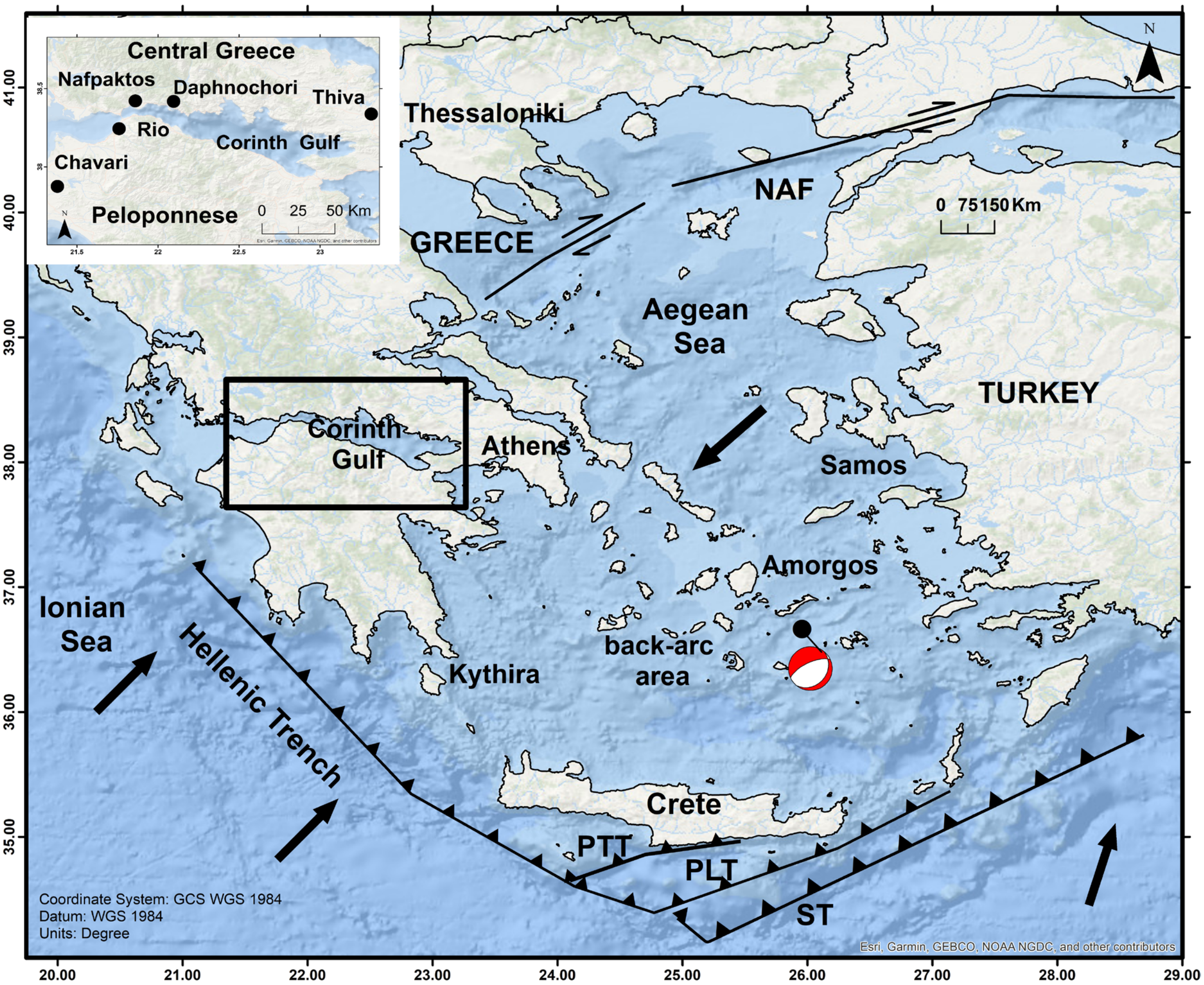


Figure 1. Seismotectonic features of Greece and the surrounding areas. Arrows show lithospheric plate motions; the African (Nubian) lithosphere is subducting from the southern Eurasian plate margin along the Hellenic Trench beneath the back-arc area of the South Aegean Sea; PTT, PLT and ST stand for Ptolemy, Pliny, and Strabo trenches, respectively. Solid dot and beach-ball illustrate the epicenter and the focal mechanism of the large 9 July 1956 (M_w 7.7) earthquake. Localities referred to in the text are also plotted; NAF shows one of the main branches of the North Anatolian Fault and its continuation along the north Aegean Sea trough.

Determinations of instrumental seismicity parameters for Greece in the time interval from 1900 up to the present are listed in various earthquake catalogues as analyzed in the next section. The very early era of instrumental seismology in Greece started in June 1899 when a mechanical Agamennone-type instrument was installed by the National Observatory of Athens (NOA) at Athens (ATH) station. Another four seismograph stations equipped with Agamennone instruments were gradually established by NOA in other cities of the country by January 1903 (Table 1). According to Eginitis (1905a) the Agamennone instruments used are of the type described by Agamennone (1895). These instruments operated until a Mainka-type, two-horizontal component seismometer was installed at ATH station in November of 1910 (Table 1). Reliable earthquake records were systematically obtained for several years thanks to the operation of the Mainka instrument.

In September 1924, a two-horizontal component Wiechert seismometer (Table 1) was installed at ATH station. The instrumentation in Greece was further enriched with a vertical Wiechert seismometer, which operated since March 1928. More instruments were gradually added until 1965 when the modern national seismograph network was established in the frame of the World-Wide Standardized Seismograph Network (WWSSN). Today the Hellenic Unified Seismological Network (HUSN) incorporates the national network of NOA, and regional networks operated by Greek university departments. These developments in the seismographic coverage of Greece gradually improved both the accuracy of the earthquake parameters determinations and the completeness of the seismicity catalogues.

Existing catalogues list several earthquakes, as a rule strong ones, that occurred in the time interval from 1900 to 1910. Although such earthquakes were recorded by distant stations operating mainly in Europe, the overall instrumental earthquake record in the Greek region during that interval remained quite poor. On the other hand, the completeness level in the various catalogues for that time interval is variable. Earthquakes listed in a catalogue are missing in others, while magnitude determinations for an earthquake often are much different in different catalogues. Besides, it is not always clear how magnitudes and other earthquake focal parameters have been determined, while focal parameters of some large earthquakes have been reassessed (e.g. Ambraseys, 2001a).

Table 1. Constants and other technical characteristics of the horizontal components of Agamennone, Mainka and Wiechert seismographs operated in Greece (Eginitis, 1905b, 1910, 1912, Comninakis et al., 1987). Very likely Agamennone instruments had no double-speed system. For the CH Agamennone station specification details are not available.

Station/ Instrument	φ [N°]	λ [E°]	m [kgr]	T [sec]	V	DS [mm/min]	Recording status
Station Athens (ATH) **Instruments** Agamennone Mainka Wiechert	37.973	23.717	200 136 1000	5.2-6.0 3.5-6.0 5.0-9.2	12 60-80 160-175	6.4 15-30 12-30	Very Good: June 1899-1910 Very Good: 1911-1963 Very Good: 1924-1963
Station Chalcis (CH) **Instrument** Agamennone	38.482	23.584					Interruptions: 1900-1908 No operation: 1909-1910
Station Egion (E) **Instrument** Agamennone	38.233	22.072	200	6.5	12	5.4	Occasionally: 1903-1908 Good: interruptions in 1910
Station Zante (Z) **Instrument** Agamennone	37.877	20.663	200	4.2	12	5.3	Occasionally: 1902-1908 Occasionally:1909-1910
Station Calamata (CA) **Instrument** Agamennone	37.035	22.096	200	5.8	12	6	Occasionally: 1900-1907 Normal operation: 1908 Interruptions: 1908-1910
Symbol key: φ = geographical latitude; λ = geographical longitude; m = pendulum mass, T = natural period; V = static magnification; DS = drum speed.							
Notes: for Mainka T = 6, V = 80 and DS = 15 for the period 1911-1956, T = 3.5, V = 60 and DS = 30 for the period 1957-1963; for Wiechert horizontal components T = 5.0-9.2, V = 160-175 and DS = 12-30 for the period 1924-1963.							

Revision of earthquake magnitudes in the Greek region for the period 1900-1910 is of importance since it may improve the seismicity catalogue with more transparent and homogeneous determinations. Additionally, large and disastrous earthquakes occurred during that period, making revised magnitudes particularly relevant. For example, a sequence of high magnitude earthquakes ruptured the area of SW Bulgaria close to the northern Greek borders on 4 April 1904, the two largest (n. 13, 14 in Fig. 2) being of re-calculated moment magnitudes of $M_w = 6.93$ and $M_w = 7.21$ (Ambraseys, 2001a) or of $M_w = 6.84$ and $M_w = 7.02$ (Dineva et al., 2002). Other examples (n. 7, 32 in Fig. 2) are the northern Greece earthquakes of 5 July 1902 with $M_w = 6.38$ (Ambraseys, 2001b) or $M_w = 6.50$ (Papazachos and Papazachou, 2003) and of 8 November 1905 with magnitude estimations ranging from surface-wave magnitude $M_s = 6.8$ (Abe and Nogushi, 1983) or $M_s = 7.5$ (Kárník, 1969) to moment magnitude $M_w = 7.24$ (ISC-GEM, 2024) (see review in Triantafyllou et al., 2020). Large intermediate-depth earthquakes also occurred in the period 1900-1910. For example, the earthquake of 11 August 1903 with source in the SW Aegean Sea, near Kythira island (n. 12, Fig. 2), was of magnitude as high as $M_s = 6.6$ (Ambraseys et al., 1994) or proxy-M_w equal to 6.7 (±0.2) (Papadopoulos, 2011), although higher magnitude estimates can be found in earlier publications.

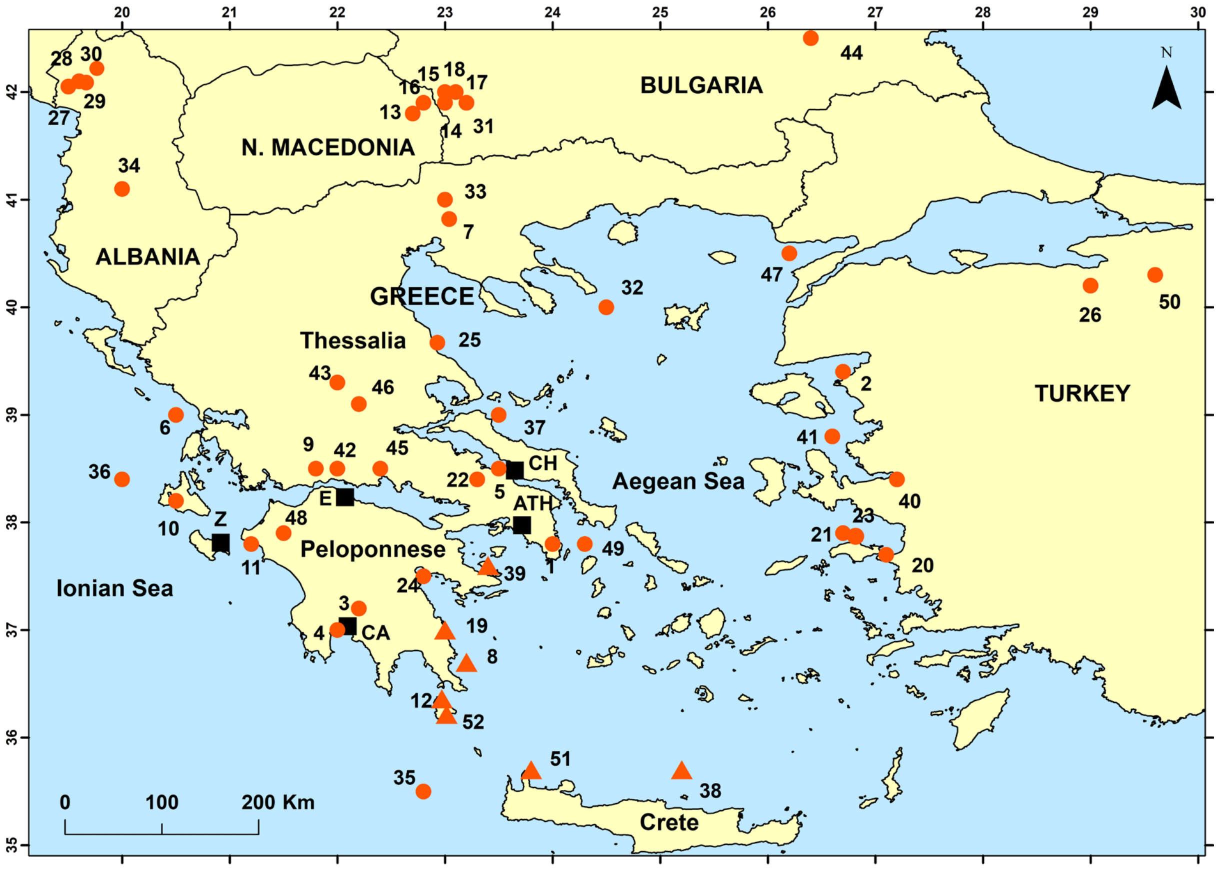


Figure 2. Locations of the five Agamennone seismograph stations (squares) operated in Greece from 1900 to 1910. Epicenters of the shallow (dots) and intermediate-depth (triangles) earthquakes listed in Table 3, along with the respective code numbers, are also plotted.

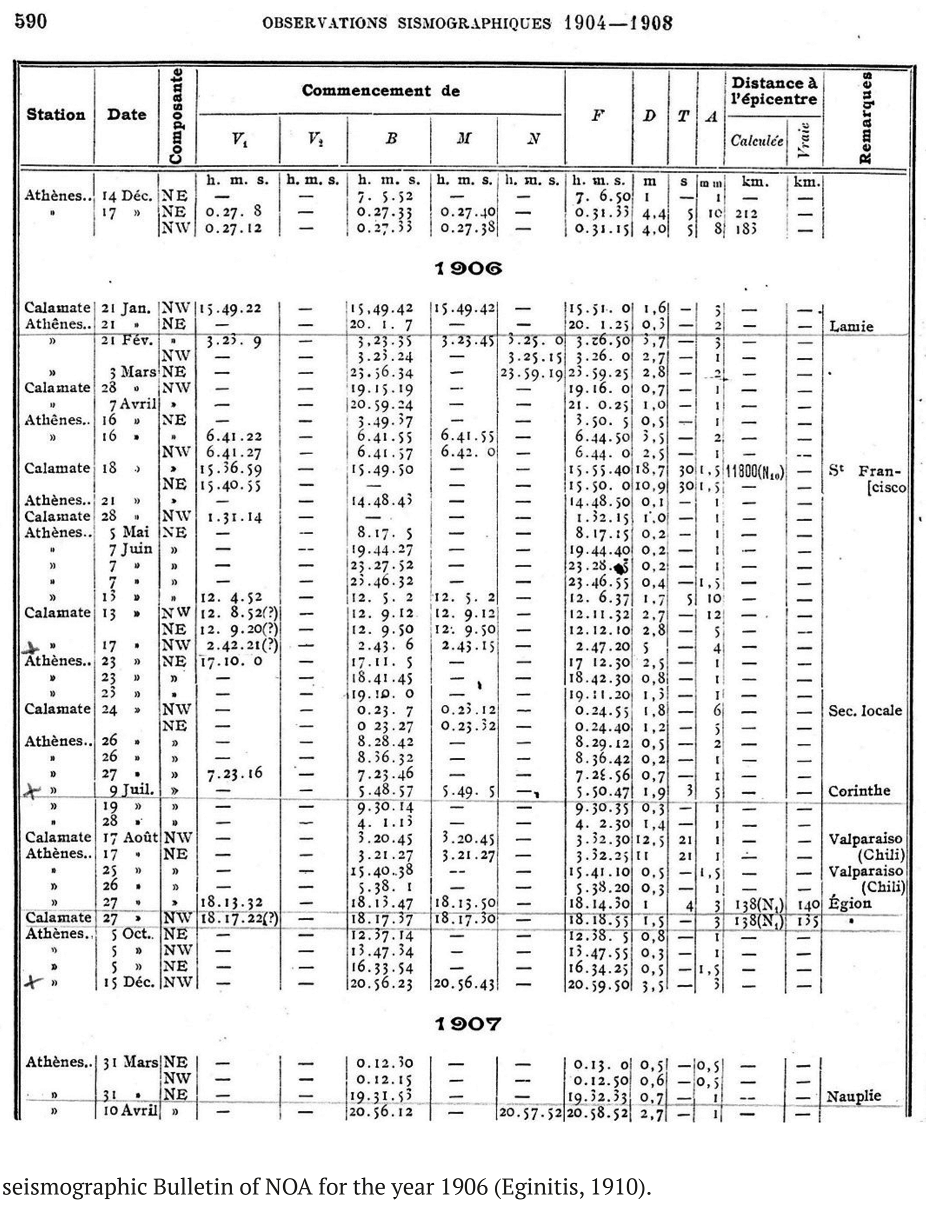
The purpose of the present paper is to improve the early instrumental earthquake catalogue in the Greek region by re-calculating magnitudes of earthquakes occurring in the time interval from 1900 to 1910. To this aim we utilized trace amplitudes recorded by the five Agamennone-type instruments operated by NOA in that time interval. The utilization of such records for the determination of focal parameters has been very limited so far. For example, a record from the ATH station was used for the determination of focal parameters of the strong earthquake occurring in SW Bulgaria (n. 14, Fig. 2) on 4 April 1904 (Dineva et al., 2002). Therefore, the systematic use of records by Agamennone instruments is attempted for the first time in Greece. Ultimately, it has been possible to re-calculate magnitudes for 52 earthquakes of proxy-M_s magnitude ranging from 4.7 to 7.4. For some of these earthquakes new epicentral coordinates were also determined. The majority of these earthquakes occurred in Greece, but others occurred in areas of the southern Balkans, including Albania, Bulgaria, North Macedonia and western Turkey (Fig. 2).

2. Data

2.1 Instrumental records: 1900-1910

Between 1899 and 1903, five mechanical Agamennone-type instruments were installed by NOA in Greece. The first was placed in Athens (ATH) station in June 1899, followed by Chalkis in June 1900, Calamata in September 1900, Zante (modern Zakynthos, in October 1902) and Egion (or Aegion, in January 1903) at stations with working names CH, CA, Z and E, respectively (Fig. 2). Constants of these instruments are listed in Table 1. Of particular importance is that the Agamennone, Mainka and Wiechert seismographs were instruments having as common feature an intermediate natural period, which for horizontal components ranged from 4.2 to 6.5 s for Agamennone, from 3.5 to 6.0 s for Mainka and from 5.0 to 9.2 s for Wiechert (Eginitis, 1910, 1912, Båth, 1983, Comninakis et al. 1987).

Due to instrument malfunction problems the Agamennone network operated with interruptions in several stations (Table 1) except the instrument at ATH station which operated without important interruption in the entire period of 1900-1910. Focal parameters of earthquakes occurring since 1900 onwards and recorded by Agamennone instruments were systematically published in the NOA Bulletins (Eginitis, 1905b, 1910, 1912). These parameters included, among others, the earthquake date, the arrival time of the first wave phase, t_p, the termination time of the pendulum motion, t_f, and the maximum trace amplitude, A (in mm), of the record. For sizable earthquakes of magnitude over ~5.5, the geographic name of the epicentral area as well as the calculated epicentral distance (in km)



590 OBSERVATIONS SISMOGRAPHIQUES 1904—1908

Station	Date	Composante	Commencement de V_1	V_2	B	M	N	F	D	T	A	Distance à l'épicentre Calculée	Vraie	Remarques
			h. m. s.	h. m. s.	h. m. s.	h. m. s.	h. m. s.	h. m. s.	m	s	mm	km.	km.	
Athènes..	14 Déc.	NE	—	—	7. 5.52	—	—	7. 6.50	1	—	1	—	—	
»	17 »	NE	0.27. 8	—	0.27.33	0.27.40	—	0.31.33	4,4	5	10	212	—	
		NW	0.27.12	—	0.27.33	0.27.38	—	0.31.15	4,0	5	8	183	—	
					1906									
Calamate	21 Jan.	NW	15.49.22	—	15,49.42	15.49.42	—	15.51. 0	1,6	—	3	—	—	
Athênes..	21 »	NE	—	—	20. 1. 7	—	—	20. 1.25	0,3	—	2	—	—	Lamie
»	21 Fév.	»	3.23. 9	—	3.23.35	3.23.45	3.25. 0	3.26.50	3,7	—	3	—	—	
		NW	—	—	3.23.24	—	3.25.15	3.26. 0	2,7	—	1	—	—	
»	3 Mars	NE	—	—	23.56.34	—	23.59.19	23.59.25	2,8	—	2	—	—	
Calamate	28 »	NW	—	—	19.15.19	—	—	19.16. 0	0,7	—	1	—	—	
»	7 Avril	»	—	—	20.59.24	—	—	21. 0.25	1,0	—	1	—	—	
Athênes..	16 »	NE	—	—	3.49.37	—	—	3.50. 5	0,5	—	1	—	—	
»	16 »	»	6.41.22	—	6.41.55	6.41.55	—	6.44.50	3,5	—	2	—	—	
		NW	6.41.27	—	6.41.57	6.42. 0	—	6.44. 0	2,5	—	1	—	—	
Calamate	18 »	»	15.36.59	—	15.49.50	—	—	15.55.40	18,7	30	1,5	11800(N_{10})	—	St Fran-
		NE	15.40.55	—	—	—	—	15.50. 0	10,9	30	1,5	—	—	[cisco
Athènes..	21 »	»	—	—	14.48.43	—	—	14.48.50	0,1	—	1	—	—	
Calamate	28 »	NW	1.31.14	—	—	—	—	1.32.15	1,0	—	1	—	—	
Athènes..	5 Mai	NE	—	—	8.17. 5	—	—	8.17.15	0,2	—	1	—	—	
»	7 Juin	»	—	—	19.44.27	—	—	19.44.40	0,2	—	1	—	—	
»	7 »	»	—	—	23.27.52	—	—	23.28.[illegible]	0,2	—	1	—	—	
»	7 »	»	—	—	23.46.32	—	—	23.46.55	0,4	—	1,5	—	—	
»	13 »	»	12. 4.52	—	12. 5. 2	12. 5. 2	—	12. 6.37	1,7	5	10	—	—	
Calamate	13 »	NW	12. 8.52(?)	—	12. 9.12	12. 9.12	—	12.11.32	2,7	—	12	—	—	
		NE	12. 9.20(?)	—	12. 9.50	12. 9.50	—	12.12.10	2,8	—	5	—	—	
»	17 »	NW	2.42.21(?)	—	2.43. 6	2.43.15	—	2.47.20	5	—	4	—	—	
Athènes..	23 »	NE	17.10. 0	—	17.11. 5	—	—	17 12.30	2,5	—	1	—	—	
»	23 »	»	—	—	18.41.45	—	—	18.42.30	0,8	—	1	—	—	
»	23 »	»	—	—	19.10. 0	—	—	19.11.20	1,3	—	1	—	—	
Calamate	24 »	NW	—	—	0.23. 7	0.23.12	—	0.24.55	1,8	—	6	—	—	Sec. locale
		NE	—	—	0 23.27	0.23.32	—	0.24.40	1,2	—	5	—	—	
Athènes..	26 »	»	—	—	8.28.42	—	—	8.29.12	0,5	—	2	—	—	
»	26 »	»	—	—	8.36.32	—	—	8.36.42	0,2	—	1	—	—	
»	27 »	»	7.23.16	—	7.23.46	—	—	7.28.56	0,7	—	1	—	—	
»	9 Juil.	»	—	—	5.48.57	5.49. 5	—	5.50.47	1,9	3	5	—	—	Corinthe
»	19 »	»	—	—	9.30.14	—	—	9.30.35	0,3	—	1	—	—	
»	28 »	»	—	—	4. 1.13	—	—	4. 2.30	1,4	—	1	—	—	
Calamate	17 Août	NW	—	—	3.20.45	3.20.45	—	3.32.30	12,5	21	1	—	—	Valparaiso
Athènes..	17 »	NE	—	—	3.21.27	3.21.27	—	3.32.25	11	21	1	—	—	(Chili)
»	25 »	»	—	—	15.40.38	—	—	15.41.10	0,5	—	1,5	—	—	Valparaiso
»	26 »	»	—	—	5.38. 1	—	—	5.38.20	0,3	—	1	—	—	(Chili)
»	27 »	»	18.13.32	—	18.13.47	18.13.50	—	18.14.30	1	4	3	138(N_1)	140	Égion
Calamate	27 »	NW	18.17.22(?)	—	18.17.37	18.17.30	—	18.18.55	1,5	—	3	138(N_1)	135	
Athènes..	5 Oct.	NE	—	—	12.37.14	—	—	12.38. 5	0,8	—	1	—	—	
»	5 »	NW	—	—	13.47.34	—	—	13.47.55	0,3	—	1	—	—	
»	5 »	NE	—	—	16.33.54	—	—	16.34.25	0,5	—	1,5	—	—	
»	15 Déc.	NW	—	—	20.56.23	20.56.43	—	20.59.50	3,5	—	3	—	—	
					1907									
Athènes..	31 Mars	NE	—	—	0.12.30	—	—	0.13. 0	0,5	—	0,5	—	—	
		NW	—	—	0.12.15	—	—	0.12.50	0,6	—	0,5	—	—	
»	31 »	NE	—	—	19.31.53	—	—	19.32.33	0,7	—	1	—	—	Nauplie
»	10 Avril	»	—	—	20.56.12	—	20.57.52	20.58.52	2,7	—	1	—	—	

Figure 3. The seismographic Bulletin of NOA for the year 1906 (Eginitis, 1910).

from ATH station frequently were listed too. Since 1904 maximum amplitudes at the two horizontal components (NE, NW) often were reported. For the time interval from 1900 to 1908, times t_p and t_f, in h, min and s, were given for each station in astronomical time. However, since 1909 t_p was given in Greenwich Meridian Time (GMT). A typical page of the seismographic Bulletin of NOA is illustrated in Fig. 3.

We examined the NOA Bulletins of the period 1900-1910 and organized a list containing hundreds of earthquakes with recorded trace amplitudes mainly at ATH station and occasionally at other Agamennone stations. Astronomical times, t_p, inserted in the Bulletins before 1909, were converted to GMT taking into account that Greece belongs to a time zone with local time GMT+2h.

2.2 Overview of earthquake catalogues

Calculation of earthquake magnitudes for the period 1900-1910 have been based on the calibration of Agamennone trace amplitudes for M_s determinations listed in existing catalogues that cover the post-1910 period. Therefore, existing catalogues are shortly overviewed in this section.

Of interest to our analysis are mainly catalogues covering Greece and the surrounding areas (geographical latitude 35°-43° N, and longitude 19°-30° E), starting from the beginning of the 20th century, extending to a large time segment of the instrumental period (post-1900 time interval) and not relying on other catalogue(s). A catalogue of interest has been compiled by the Geophysical Laboratory of the Aristotle University of Thessaloniki (AUTH) (https://seismo.auth.gr/wp-content/uploads/2023/03/seiscat.dat) (last access, 08 May 2025). This compilation, named shortly AUTH catalogue, constitutes the last extended version of a long-lasting effort that initially started at the Institute of Geodynamics of NOA, with the compilation of a series of catalogues (e.g. Papazachos and Comninakis, 1971, 1972, Comninakis and Papazachos, 1986). For the time interval 1900-1910 the AUTH catalogue lists 340 earthquakes both shallow and of intermediate depth with magnitude ranging from 4.5 to 7.5 (Table 2).

The catalogue published by Makropoulos et al. (2012) covers the time interval from 1900 to 2009 and was compiled at the University of Athens, hereinafter briefly called UOA catalogue. This is an extended version of the catalogues initially compiled by Makropoulos (1978), Makropoulos and Burton (1981) and Makropoulos et al. (1989). For the time interval 1900-1910 the UOA catalogue lists 58 earthquake events, shallow and of intermediate depth, with magnitudes in proxy-M_s and M_w scales for each event (Table 2). Magnitudes in this catalogue range from 5.0 to 8.0 for M_s and from 5.0 to 7.6 for M_w. The catalogue compiled by Burton et al. (2004) is not considered here since extensively relies on the catalogue by Makropoulos and Burton (1981) for the time interval of interest.

Table 2. Main characteristics of the earthquake catalogues covering the Greek region in the time period from 1900 to 1910. All magnitudes are in proxy-M_w scale except those marked by * which are in proxy-M_s scale.

Catalogue	N	M_{min}	M_{max}	M_c	Time period
AUTH	340 (n + i)	4.5	7.5	5.0	1900-1910
UOA	58 (n + i)	5.0, 5.0*	7.6, 8.0*	5.5	1900-1910
ISC-GEM	21 (n + i)	5.44	7.24	5.8	1904-1910
AM	14 (n)	6.0*	7.24*	6.0	1900-1910

Key: N = number of earthquakes, n = shallow earthquakes, i = intermediate-depth earthquakes; M_{min} = minimum magnitude; M_{max} = maximum magnitude, M_c = magnitude completeness threshold.

The ISC-GEM (2024) global earthquake catalogue, hereinafter denoted simply as ISC-GEM catalogue, is a reference compilation, which starts from the year 1904 and extends up to 2020. The ISC-GEM catalogue lists 21 strong earthquakes occurring in the Greek region up to 1910 with magnitude equivalent to M_w ranging from 5.44

to 7.24 (Table 2). The fourth catalogue of interest in this study is the one organized by Ambraseys (2001a), briefly named AM catalogue, which covers the eastern Mediterranean region. For the Greek region and for the time interval 1900-1910, the AM catalogue contains 14 shallow events truncated by default at lower magnitude $M_s = 6.0$, while the maximum magnitude is $M_s = 7.24$.

The SHARE European Earthquake Catalogue (SHEEC) compiled in the frame of the project SHARE (Stucchi, 2013), as well as the European-Mediterranean Earthquake Catalogue (EMEC; Grünthal and Wahlström, 2012, 2013), covering the time segment from 1901 to 2006, rely at large extent on the AUTH and UOA catalogues. Therefore, these two catalogues are not further considered in this study. The seismicity database of the Institute of Geodynamics of NOA covers only the time window from 1964 up to the present (http://www.gein.noa.gr/el/seismikotita/katalogoi-seismwn).

The previous overview implies that the four catalogues summarized in Table 2 are in principle useful to the present study. The completeness magnitude threshold, M_c, of the catalogues for the time interval 1900-1910 was tested with the use of the z-map toolbox (Wiemer, 2001). The Maximum Curvature Method (MAXC) (Wiemer and Wyss, 2000) was applied for the calculation of M_c, which for the AUTH catalogue was found $M_c = 5.0$ (Fig. 4). However, M_c values found for the rest catalogues are quite unstable due to the low numbers of earthquakes (Table 2).

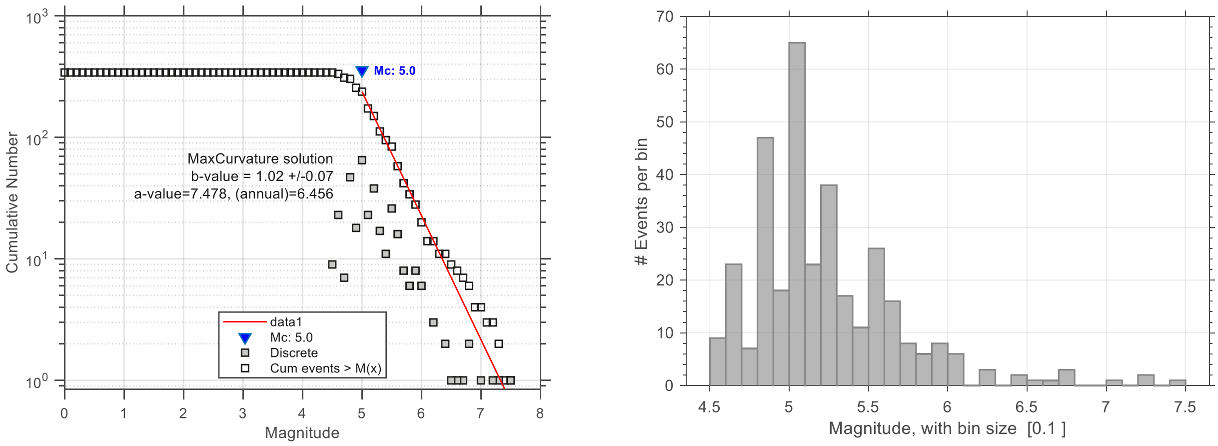


Figure 4. Magnitude-frequency diagram (left) and magnitude distribution (right) for the AUTH catalogue for the period 1900-1910; magnitude completeness threshold $M_c = 5.0$ was determined with the MAXC method incorporated in the z-map toolbox.

2.3 Macroseismic observations

Macroseismic information from the NOA Bulletins has been useful in determining epicentral areas and distances for earthquakes listed in these reports. Further details were investigated in the "Book of Earthquakes", which is a two-volume unpublished manuscript of NOA with a collection of macroseismic material systematically compiled by a network of local observers affiliated to NOA during the time interval 1893-1915. We utilized macroseismic information, which is contained in the second volume covering the time interval 1902-1915 (Anonymous, 1902-1915).

3. Method

Since the Agamenonne, Mainka and Wiechert seismographs have been instruments of intermediate natural period we expect that ground amplitudes, A, recorded by Agamenonne seismographs in the time window 1900-1910 would correlate with magnitudes calculated from ground amplitudes recorded by Mainka and Wiechert instruments for the post-1910 time interval. Then, for magnitude calculation purposes it would be possible to utilize the Agamennone ground amplitudes A recorded for earthquakes of the period 1900-1910 after calibrating these amplitudes for post-1910 magnitudes. To this aim, we first briefly overview the methods used by previous authors to determine magnitudes in the four catalogues overviewed earlier and then we proceed with the Agamennone magnitudes determination.

3.1 Magnitude determination in Greek catalogues

For the calculation of surface-wave magnitude, Gutenberg (1945) proposed the formula

$$M_s = \log A + 1.656 \log \Delta + 1.818 \quad (1)$$

where A (in μm) is the amplitude of combined horizontal amplitudes of surface waves of period ~20 s and Δ is the epicentral distance in degrees. Equation (1) was designed mainly for records at Pasadena station. Later, a major contribution was the introduction of the widely accepted Prague or IASPEI formula (Vaněk et al., 1962):

$$M_s = \log(A/T)_m + 1.66 \log \Delta + 3.3 \quad (2)$$

In Eq. (2), $(A/T)_m$ is the combined value of the maximum A/T ratios of horizontal components of the surface waves of period T~20 s; Δ and A as in (1). However, using maximum of the quotient (A/T) the validity of the Eq. (2) can be extended from 2 to 60 s (Bormann et al., 2013). For earthquakes occurring in the Greek region in the post-1910-time interval, Papazachos and Vasilikou (1966) suggested that the magnitude of shallow earthquakes (focal depth $h < 60$ km) can be calculated as a function of ground amplitude, a (in microns) and epicentral distance Δ from ATH station for $\Delta < 600$ km:

$$M = \log a + 1.42 \log \Delta + 0.2 \quad (3)$$

In Eq. (3), which is similar to (1) and (2), ground amplitude is taken from the average of maximum amplitudes recorded at the two horizontal components (NS, EW) of Mainka and/or Wiechert instruments operating at ATH station. The parameters in (3) were determined with linear regression utilizing M_s magnitudes calculated from surface waves of Greek earthquakes recorded at distant stations, such as Pasadena and Berkeley. It should be noted that the Mainka and Wiechert seismometers were well calibrated, i.e. their response curves were well known during the whole period of their operation and, therefore, an accurate determination of the maximum ground amplitude in the records on the seismograms was easily obtained (Comninakis et al., 1987).

Starting from early 1970s, magnitudes of intermediate-depth earthquakes ($h > 60$ km) were calculated from the formula

$$M = \log a + 0.18(R/100) + 3.2 \quad (4)$$

proposed by Papazachos and Comninakis (1971), where a as in (3); R (in km) is the hypocentral distance. The validity of M as a magnitude equivalent to M_s and M_w was shown in a series of subsequent publications (Kiratzi and Papazachos, 1984; Papazachos, 1989; Papazachos et al., 2002).

Equations (3) and (4) remained in use at NOA up to mid-1980s. For the time interval from 1911 to mid-1980s the AUTH catalogue lists M_w magnitudes equivalent to M_s determined by the procedure described above. Other procedures were followed for magnitude determinations after that period, but this is not of interest to our analysis. However, magnitudes and other focal parameters listed for the time interval 1900-1910 were mainly based on the collection of magnitudes from other sources including the catalogue by Kárnik (1969, 1996) who utilized records of Greek earthquakes in European stations and developed formulae similar to the Prague formula. Magnitudes equivalent to M_w listed in the AUTH catalogue for the time interval 1900-1910 were calculated with the use of empirical global relations converting M_s and m_b magnitudes to M_w (Scordilis, 2006). In the remaining of our analysis the magnitude inserted in the AUTH catalogue for the time interval 1900-1910 is denoted as M_T.

In the UOA catalogue, magnitude M_s for earthquakes occurring in the time interval 1900-1963 was calculated only under the condition that ground amplitudes in long-period instruments at Uppsala (UPP) and Kiruna (KIR) stations were available. Then, M_s was calculated as the average of M_s values obtained by using the Prague formula. Since 1964, when ISC commenced to publish body-wave magnitude m_b, magnitude M_s was calculated from M_s/m_b regression equation used in the ISC catalogue. Magnitudes M_w were collected from various sources including the GCMT project for the post-1975-time interval. M_s/M_w empirical relationships were developed and used by Makropoulos et al. (2012) to convert M_s to M_w for events occurring in the entire time span covered by the UOA catalogue, including the period 1900-1910.

In the ISC-GEM catalogue, magnitudes M_s and m_b have been re-computed uniformly at large extent and with procedures detailed by Bondar et al. (2015), Storchak et al. (2015) and Di Giacomo et al. (2018). Re-computed magnitudes have provided the basis for deriving new non-linear regression models and conversion relationships to M_w. For the time interval from 1900 to 1975, M_w proxies were inserted instead of the re-computed M_s and m_b values using the derived conversion relationships. However, directly measured M_w values as published by the GCMT project and by a long number of publications were inserted for the post-1975-time interval. Similar was the procedure followed earlier by Ambraseys (2001a) for the compilation of a new catalogue in the eastern Mediterranean region. The AM catalogue is homogeneous at large extent as regards magnitude determination since M_s was calculated from Bulletin readings of long-period phases for each earthquake examined.

Since M_s determinations in the AUTH catalogue are based on Mainka and Wiechert records from 1911 up to the mid 1980's, this catalogue is suitable for the calibration of magnitudes based on Agamennone instruments records for the time interval 1900-1910. Besides, the low number of earthquakes contained in the UOA, ISC-GEM and AM catalogues for that time interval again favors the use of the AUTH catalogue. Nevertheless, the UOA, ISC-GEM and AM catalogues are still useful to the rest of our analysis.

3.2 A/M_T correlation

From the hundreds of earthquakes listed in the NOA Bulletins with trace (ground) amplitudes recorded in at least one out of five Agamennone stations in the time interval 1900-1910, we found 52 earthquakes which are also included in the AUTH catalogue (Table 3). The shallow ($h < 60$ km) earthquakes amount to 45 and their magnitude M_T ranges from 4.8 to 7.5. The remaining seven events is a set of intermediate-depth earthquakes ($h \geq 60$ km) with M_T ranging from 5.8 to 7.2. All the earthquakes selected were recorded by Agamennone instrument at the ATH station. Six out of 52 earthquakes were also recorded at other Agamennone stations (Table 3).

Table 3. List of the earthquakes selected for examination.

No.	Year	mo	d	hr	mi	s	φ°_{N}	λ°_{E}	*h*	M_T	NE/NW	*A*	*Δ*	M_a	M_A
1	1901	11	23	18	30	00	37.80	24.00	*n*	5.0	2	2	**290**	**5.4**	**5.4**
2	1901	12	18	03	51	00	39.40	26.70	*n*	5.9	2	2	**304**	**5.4**	**5.4**
3	1901	12	24	23	18	00	37.20	22.20	15	5.8	8	8	**160**	**5.6**	**5.6**
4	1902	2	09	08	17	00	37.00	22.00	*n*	4.8	1	1	**160**	**4.7**	**4.7**
5	1902	4	11	18	35	30	**38.10**	**23.10**	*n*	5.5	9	9	**40**	**4.8**	
5CH											50	50	**45**	**5.6**	
5CA											3	3	**145**	**5.1**	**5.2**
6	1902	5	26	11	06	00	39.00	20.50	*n*	5.5	1	1	**350**	**5.2**	
6CA											1	1	**320**	**5.2**	**5.2**
7	1902	7	05	14	56	30	40.82	23.04	*n*	6.5	32/40	36	**318**	**6.7**	**6.7**
8	1902	7	29	01	20	00	36.70	23.20	100	5.8	9	9	**180**	**6.0**	**6.0**
9	1902	8	02	05	38	30	**38.50**	**21.80**	*n*	5.5	1	1	**170**	**4.8**	**4.8**
10	1902	11	05	23	50	30	38.20	20.50	*n*	5.5	8	8	**280**	**6.0**	**6.0**
11	1903	3	15	19	03	30	37.80	21.20	*n*	5.5	1	1	**220**	**4.9**	**4.9**
12	1903	8	11	04	32	54	36.36	22.97	80	7.2	70	70	**244**	**7.0**	**7.0**
13	1904	4	04	10	02	55	41.80	22.70	*n*	7.0	100/75	87.5	**428**	**7.3**	**7.3**
14	1904	4	04	10	26	00	41.90	23.00	*n*	7.3	110	110	**434**	**7.4**	**7.4**
15	1904	4	04	11	09	30	42.00	23.00	*n*	5.5	1/1	1	**446**	**5.4**	**5.4**
16	1904	4	10	08	52	46	41.90	22.80	*n*	6.2	11/8	9.5	**438**	**6.3**	**6.3**

Key: No. = event number; mo = month, d = day, hr = hour, mi = minute; s = sec; φ°_{N}, λ°_{E} = epicentral coordinates; *h* = focal depth (km), *n* = shallow earthquake; M_T = magnitude in AUTH catalogue; *Δ* = epicentral distance (km) of the respective station. Epicentral coordinates have been taken from the AUTH catalogues unless recalculated in this study (marked in bold). The initial and final magnitudes, M_a and M_A respectively, were calculated from the maximum wave amplitudes recorded at the horizontal components *NE* and *NW* (in mm, taken from the NOA Bulletins) of Agamennone seismographs operating in Greece from 1901 to 1910; *A* is the average of *NE* and *NW* unless only the value from one component was available (see main text for details).
Parameters marked in bold were calculated in this study.
All records are from the Athens (ATH) station unless otherwise indicated; Working names of other stations: CH = Chalkis, CA = Calamata, E = Egion, Z = Zante.

No.	Year	mo	d	hr	mi	s	φ°_N	λ°_E	*h*	M_T	NE/NW	*A*	*Δ*	M_a	M_A
17	1904	4	19	18	14	30	42.00	23.10	*n*	5.9	2	2	**444**	**5.7**	**5.7**
18	1904	4	25	20	02	00	42.00	23.00	*n*	5.7	1	1	**446**	**5.4**	**5.4**
19	1904	7	09	00	50	00	37.00	23.00	100	5.9	7/1	4	**162**	**5.6**	**5.6**
20	1904	8	11	06	08	30	**37.70**	**27.10**	*n*	6.8	18/9	13.5	**310**	**6.3**	**6.3**
21	1904	8	18	20	07	30	**37.90**	**26.70**	*n*	5.9	24/18	21	**255**	**6.3**	**6.3**
22	1904	9	13	09	30	00	38.40	23.30	16	5.5	22/16	19	**54**	**5.3**	**5.3**
23	1904	10	10	17	40	30	**37.90**	**26.70**	20	5.8	10	10	**255**	**6.0**	**6.0**
24	1904	12	28	06	15	00	37.50	22.80	*n*	5.0	11/14	12.5	**96**	**5.5**	**5.5**
25	1905	1	20	02	32	30	39.67	22.93	13	6.4	55/54	54.5	**200**	**6.6**	**6.6**
26	1905	4	15	05	36	30	40.20	29.00	*n*	5.5	4	4	**520**	**6.1**	**6.1**
27	1905	6	01	04	42	15	42.05	19.50	*n*	6.6	30	30	**566**	**7.0**	**7.0**
28	1905	6	03	05	10	43	42.10	19.60	*n*	5.6	3/3.5	3.25	**568**	**6.0**	**6.0**
29	1905	8	04	05	09	00	42.10	19.60	*n*	5.9	2	2	**568**	**5.8**	**5.8**
30	1905	8	28	05	30	00	42.10	19.60	*n*	4.8	0.5	0.5	**568**	**5.2**	**5.2**
31	1905	10	08	07	27	00	41.90	23.20	*n*	6.4	10	10	**432**	**6.3**	**6.3**
32	1905	11	08	22	06	30	40.00	24.50	*n*	7.5	110	110	**230**	**7.1**	
32CA									*n*		77	77	**385**	**7.2**	**7.2**
33	1905	11	18	00	19	00	41.00	23.00	*n*	5.6	2	2	**338**	**5.5**	**5.5**
34	1906	3	03	21	46	30	41.10	20.00	5	5.6	2	2	**464**	**5.7**	**5.7**
35	1906	6	17	01	11	00	35.50	22.80	*n*	5.5	4	4	**290**	**5.7**	**5.7**

Key: No. = event number; mo = month, d = day, hr = hour, mi = minute; s = sec; φ°_N, λ°_E = epicentral coordinates; *h* = focal depth (km), *n* = shallow earthquake; M_T = magnitude in AUTH catalogue; *Δ* = epicentral distance (km) of the respective station. Epicentral coordinates have been taken from the AUTH catalogues unless recalculated in this study (marked in bold). The initial and final magnitudes, M_a and M_A respectively, were calculated from the maximum wave amplitudes recorded at the horizontal components *NE* and *NW* (in mm, taken from the NOA Bulletins) of Agamennone seismographs operating in Greece from 1901 to 1910; *A* is the average of *NE* and *NW* unless only the value from one component was available (see main text for details).
Parameters marked in bold were calculated in this study.
All records are from the Athens (ATH) station unless otherwise indicated; Working names of other stations: CH = Chalkis, CA = Calamata, E = Egion, Z = Zante.

No.	Year	mo	d	hr	mi	s	φ°_{N}	λ°_{E}	h	M_T	NE/NW	A	Δ	M_a	M_A
36	1906	12	15	19	21	00	38.40	20.00	*n*	5.4	3	3	**326**	**5.6**	**5.6**
37	1907	5	15	23	30	00	39.00	23.50	*n*	5.3	2	2	**110**	**4.8**	**4.8**
38	1908	5	17	12	30	42	35.70	25.20	80	6.7	25/21	23	**309**	**6.6**	
38Z											80/62	71	**445**	**7.4**	
38E											20/25	22.5	**400**	**6.8**	**6.9**
39	1908	5	30	15	00	00	37.60	23.40	150	5.8	20	20	**158**	**6.3**	
39E											20	20	**197**	**6.4**	
39CA											15	15	**170**	**6.2**	
39Z											15	15	**260**	**6.3**	**6.3**
40	1908	6	23	14	18	00	38.40	27.20	*n*	5.5	2/3	2.5	**310**	**5.5**	**5.5**
41	1908	6	23	16	03	00	38.80	26.60	*n*	5.3	1/1	1	**268**	**5.0**	**5.0**
42	1909	1	01	21	40	00	38.50	22.00	*n*	4.8	3/5	4	**158**	**5.3**	**5.3**
43	1909	1	20	19	57	00	39.30	22.00	33	5.0	1/3	2	**206**	**5.2**	**5.2**
44	1909	2	15	09	34	30	42.50	26.40	*n*	5.9	1/1.5	1.25	**645**	**5.7**	**5.7**
45	1909	5	30	06	14	30	**38.50**	**22.40**	20	6.2	42/65	53.5	**130**	**6.3**	
45E											100	100	**45**	**5.9**	**6.1**
46	1909	6	15	23	30	30	39.10	22.20	*n*	5.7	20/18	1.1	**176**	**6.1**	**6.1**
47	1909	6	19	17	45	54	40.50	26.20	*n*	5.5	0.5	0.5	**350**	**4.9**	**4.9**
48	1909	7	15	00	34	42	37.90	21.50	3	5.7	39/68	53.5	**192**	**6.6**	**6.6**
49	1909	9	22	03	48	00	37.80	24.30	14	5.0	8	8	**58**	**5.0**	**5.0**

Key: No. = event number; mo = month, d = day, hr = hour, mi = minute; s = sec; φ°_{N}, λ°_{E} = epicentral coordinates; h = focal depth (km), n = shallow earthquake; M_T = magnitude in AUTH catalogue; Δ = epicentral distance (km) of the respective station. Epicentral coordinates have been taken from the AUTH catalogues unless recalculated in this study (marked in bold). The initial and final magnitudes, M_a and M_A respectively, were calculated from the maximum wave amplitudes recorded at the horizontal components *NE* and *NW* (in mm, taken from the NOA Bulletins) of Agamennone seismographs operating in Greece from 1901 to 1910; A is the average of *NE* and *NW* unless only the value from one component was available (see main text for details).
Parameters marked in bold were calculated in this study.
All records are from the Athens (ATH) station unless otherwise indicated; Working names of other stations: CH = Chalkis, CA = Calamata, E = Egion, Z = Zante.

No.	Year	mo d hr mi s	φ°_{N}	λ°_{E}	h	M_T	NE/NW	A	Δ	M_a	M_A
50	1909	10 29 17 38 00	40.30	29.60	*n*	5.7	0.5	0.5	**570**	**5.2**	**5.2**
51	1910	2 18 05 09 18	35.70	23.8	90	6.8	43/43	43	**271**	**6.8**	**6.8**
52	1910	6 03 04 28 00	36.30	23.00	100	5.8	2/2	2	**219**	**5.4**	
52E							2/3	2.5	**255**	**5.6**	**5.5**

Key: No. = event number; mo = month, d = day, hr = hour, mi = minute; s = sec; φ°_{N}, λ°_{E} = epicentral coordinates; h = focal depth (km), n = shallow earthquake; M_T = magnitude in AUTH catalogue; Δ = epicentral distance (km) of the respective station. Epicentral coordinates have been taken from the AUTH catalogues unless recalculated in this study (marked in bold). The initial and final magnitudes, M_a and M_A respectively, were calculated from the maximum wave amplitudes recorded at the horizontal components *NE* and *NW* (in mm, taken from the NOA Bulletins) of Agamennone seismographs operating in Greece from 1901 to 1910; A is the average of *NE* and *NW* unless only the value from one component was available (see main text for details).
Parameters marked in bold were calculated in this study.
All records are from the Athens (ATH) station unless otherwise indicated; Working names of other stations: CH = Chalkis, CA = Calamata, E = Egion, Z = Zante.

Before the calculation of magnitudes from trace amplitudes recorded by the Agamennone instruments we investigated if the amplitude A, which is the average of the maximum amplitudes at the two horizontal components *NE* and *NW* at ATH station, is correlated with magnitude M_T. However, if amplitude from only one component was available then that amplitude was taken into account. Plotting trace amplitudes, A, against the respective magnitudes M_T of the 52 earthquakes we found good correlation (Fig. 5). The best-fit relationships reached after regression for the sets of 45 shallow earthquakes and of seven intermediate-depth earthquakes are expressed by the Eqs. (5) and (6), respectively:

$$A = 20.9M_T^2 - 220.7M_T + 585.4, \qquad r^2 = 0.76 \tag{5}$$

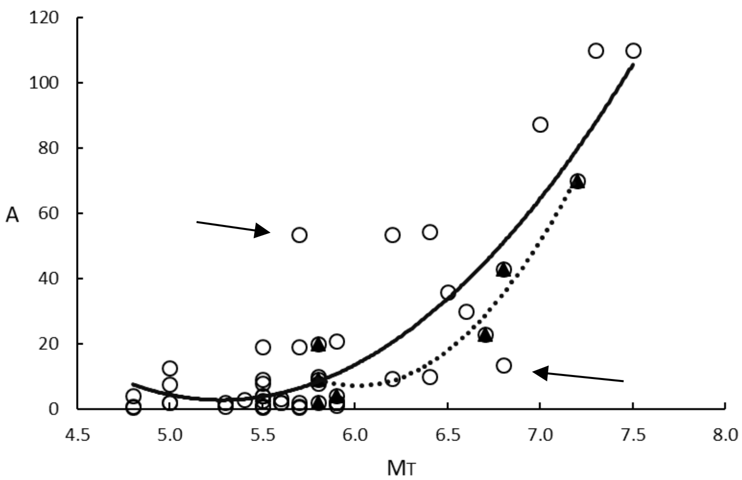


Figure 5. Plot of magnitude M_T for shallow (open circles) and intermediate-depth (solid triangle) earthquakes against trace amplitude A (in mm) recorded by the Agamennone instrument at ATH station. Best-fit is illustrated by solid and dashed line for shallow and intermediate-depth earthquakes, respectively. Arrows show the outliers of 11 August 1904 (M_T = 6.8) and 15 July 1909 (M_T = 5.7) (n. 20 and 48 in Table 3, respectively).

$$A = 45.8M_T^2 - 550.5M_T + 1662.4, \qquad r^2 = 0.92 \tag{6}$$

In the diagram of Fig. 5 two shallow earthquakes could be considered as outliers. The first is the 11 August 1904 strong earthquake of $M_T = 6.8$ (n. 20 in Table 3) that ruptured near the island of Samos, Greece, in the east Aegean Sea (Fig. 2). A low average amplitude $A = 13.5$ has been found for this earthquake. The second outlier is the 15 July 1909 earthquake of $M_T = 5.7$ (n. 48 in Table 3) with estimated epicenter near Chavari village in NW Peloponnese (Fig. 3). This earthquake was recorded at the ATH station with average trace amplitude $A = 53.5$ mm, which is an overestimated value. The outliers of 1904 and 1909 are recalled in the Results section. Correlation in relationship (5) was improved after removing the two outliers.

$$A = 22.3M_T^2 - 235.4M_T + 623.2, \qquad r^2 = 0.85 \tag{7}$$

3.3 Agamennone magnitude determination

Three magnitude types were sequentially produced for each earthquake event examined: (a) M_a = initial magnitude calculated from amplitude A by applying the relationships (3) and (4) for shallow and intermediate-depth earthquakes, respectively, and for epicentral distances Δ (in km) listed in Table 3. The respective average magnitude misfit, DA, involved in each one of the two M_{ac}/M_T relationships for shallow and intermediate-depth earthquakes were also calculated, i.e. $DA = D/n$ where $D = |M_T - M_a|$, i.e. is the absolute value of the difference $M_T - M_a$ for each one of the earthquakes examined, and n is the number of earthquakes involved in each one of the two M_a/M_T relationships; (b) $M_{AT} = M_a + DA$, which is the magnitude obtained after calibrating M_a for M_T separately for shallow and intermediate-depth earthquakes; (c) M_A = final Agamennone magnitude, which is the average of the M_{AT} values if trace amplitudes (in mm) were available from more than one station for a single earthquake; otherwise we simply considered $M_A = M_{AT}$.

For the 45 shallow earthquakes we calculated epicentral distances, Δ, from the Agamennone stations by adopting epicentral coordinates listed in the AUTH catalogue (Table 3). In a few cases, however, significant magnitude misfit was initially found and, therefore, we investigated for improved epicenter solutions. In such cases, macroseismic information has been helpful in revising epicenters. A trial-and-error method was applied for the selection of a new epicentral solution until to obtain the minimum magnitude misfit. For earthquakes recorded by more than one Agamennone instruments the new epicenters were controlled with the first arrival times in the Agamennone stations as well as with *P-S* travel-time curves.

4. Results

4.1 Shallow earthquakes

To calculate M_a for shallow earthquakes, amplitudes A (in mm) from Agamennone records at ATH station and respective epicentral distances Δ (in km) (Table 3) were inserted in Eq. (3). The best-fit relationship between M_a and M_T (Table 3) is expressed by the next linear formula:

$$M_A = 0.91M_T - 0.88, \qquad r^2 = 0.74 \tag{8}$$

Average magnitude misfit $DA = 1.4 \pm 0.4$ was found. Then, Agamennone magnitude, M_{AT}, was calculated as $M_{AT} = M_a + 1.4$ and eventually the final Agamennone magnitude M_A was obtained. The M_A/M_T relationship (Fig. 6) is expressed by the Eq. (9). The magnitude misfit involved in (9) was found equal to 0.3 ± 0.2.

$$M_a = 0.93M_T + 0.41, \qquad r^2 = 0.72 \tag{9}$$

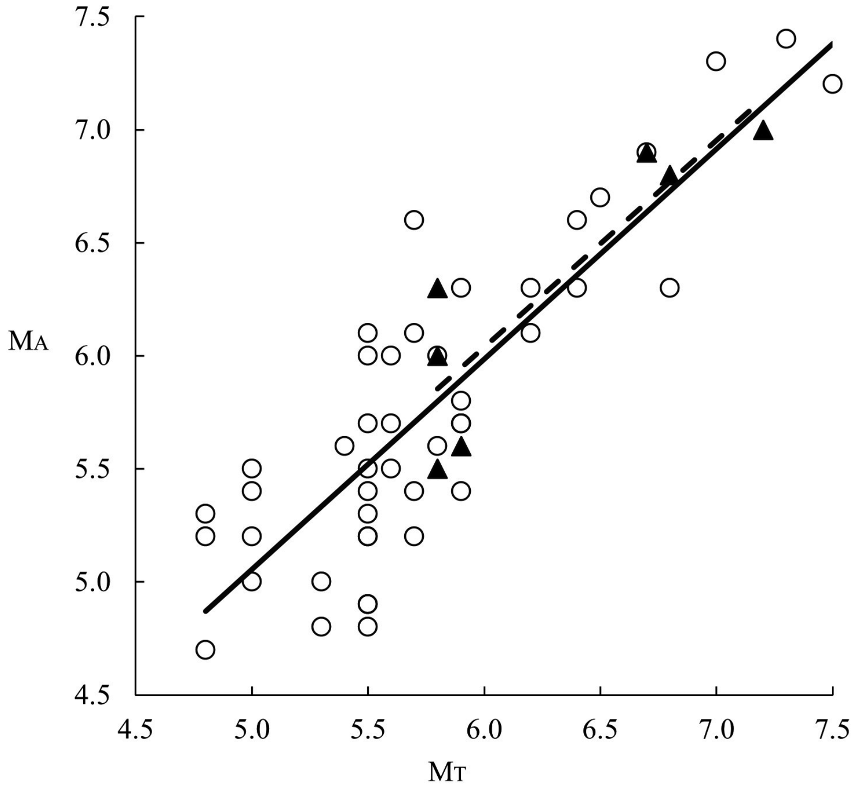


Figure 6. Agamennone magnitude, M_A, against magnitude M_T. Best-fit is illustrated by solid and dashed line for shallow (open circle) and intermediate-depth (solid triangle) earthquakes, respectively.

Four out of 45 shallow earthquakes examined were recorded not only at the ATH station but also at other stations (Table 3). Utilizing records from more than one station consistent magnitudes M_A were calculated for each one of the four earthquakes. A characteristic example is the earthquake of 8 November 1905 (n. 32, Table 3). Magnitudes 7.0 and 7.2 were calculated from records at the ATH and CA stations. The $M_T = 7.5$ listed in the AUTH catalogue is overestimated not only with respect to the magnitude found here ($M_A = 7.1$) but also as compared to magnitude $M_w = 7.24$ calculated independently in the ISC-GEM and AM catalogues. Macroseismic magnitude of 7.2 was estimated by Triantafyllou et al. (2020).

4.2 Intermediate-depth earthquakes

To determine magnitude M_a for intermediate-depth earthquakes (Table 3) we used epicentral distances listed in Table 3, calculated hypocentral distances, R (km), from the ATH station and inserted amplitudes A and respective distances R in Eq. (4). The best-fit M_a/M_T relationship is expressed by the Eq. (10), which is nearly identical to (8):

$$M_a = 0.89M_T - 0.87, \qquad r^2 = 0.76 \tag{10}$$

The magnitude misfit was found equal to 1.5 ± 0.3. Then, we calculated Agamennone magnitude as $M_{AT} = M_a + 1.5$ and magnitude M_A by following the procedure described earlier. The M_A/M_T best-fit relationship is shown in Fig. 6 and expressed by the Eq. (11):

$$M_A = 0.92M_T + 0.54, \qquad r^2 = 0.77 \tag{11}$$

Three out of seven intermediate-depth earthquakes (code numbers 38, 39, 52 in Table 3) have been recorded not only in ATH station but also in other Agamennone stations. The magnitudes M_{AT} found from records in more than one station for each one of the three earthquakes are in general consistent. In these cases, the magnitude misfit was found equal to 0.2 ± 0.1. For the earthquake of 17 May 1908 ($M_T = 6.7$), the magnitude $M_{AT} = 7.4$ calculated from the record at station Z is overestimated with respect to $M_{AT} = 6.6$ and $M_{AT} = 6.8$ found from the records at stations ATH and E, respectively. This inconsistency is recalled and discussed in the next section.

5. Discussion

The Agamennone seismographs operated in Greece during the early instrumental period remain of unknown damping characteristics but most likely they were undamped instruments. Amplitudes of records from such instruments are not suitable for direct magnitude estimation without calibration against magnitudes determined by damped instruments. However, mechanical instruments with low magnification, as this is the case, and with elements subject to dry friction can be calibrated for surface – wave magnitude as discussed by Abe (1988) for Milne seismographs that operated during the early instrumental period.

The correlation between trace amplitudes A, recorded by the Agamennone instrument at ATH station in the time interval 1900-1910, and magnitudes M_T determined in the AUTH catalogue for the post-1910-time interval, is of particular importance for magnitude calculation from amplitudes A. However, in the relevant diagram (Fig. 5) two shallow earthquakes could be considered as outliers which are in need of explanation. The first is the 11 August 1904 strong earthquake of $M_T = 6.8$ (n. 20 in Table 3) that ruptured near the island of Samos, Greece, in the east Aegean Sea (Fig. 2). A low average amplitude $A = 13.5$ has been found for this earthquake. The second outlier is the 15 July 1909 earthquake of $M_T = 5.7$ (n. 48 in Table 3) with estimated epicenter near Chavari village in NW Peloponnese (Fig. 2). This earthquake was recorded at the ATH station with average trace amplitude $A = 53.5$ mm, which is an overestimated value.

The earthquake of 11 August 1904 (n. 20 in Table 3, Fig. 2) hit the island of Samos and caused damage to many buildings, the collapse of about 60 houses in several villages of the island, 10 fatalities and 20 injuries (Anonymous, 1902-1915, Press reports of 16.8.1904, Old Style Calendar). Very likely the earthquake had its epicenter close to the island. Our calculation returned $M_A = 6.3$ for the revised epicenter solution of 37.7°N/27.1°E, which is slightly shifted with respect to the epicenters of 37.66°N/26.93°E and of 37.7°N/26.9°E adopted in the catalogues of AUTH and of Kalafat et al. (2007), respectively. A reasonable explanation of this difference is that the $M_T = 6.8$ is an overestimation. With the adoption of the new epicenter for this earthquake the outlier is eliminated.

The 15 July 1909 earthquake of $M_T = 5.7$ (n. 48 in Table 3, Fig. 2) caused extensive destruction but in a limited area, with the macroseismic epicenter located at the village of Chavari in NW Peloponnese (Triantafyllou et al., 2022). The NOA Bulletin lists amplitudes of 39 mm and 68 mm in the A_{NE} and A_{NW} components of the Agamennone seismograph at ATH station, respectively. The magnitude $M_A = 6.6$, calculated by adopting the epicenter in the AUTH catalogue (Table 3), is an overestimation as compared to previously instrumentally calculated magnitudes, which range from $M_s = 5.7$ to $M_w = 5.92$, and to the proxy-M_s magnitude 5.9 found from macroseismic observations (see review in Triantafyllou et al., 2022). Re-calculation of magnitude M_A with the adoption of alternative epicenters placed not far away from the macroseismic epicenter proved not effective in reducing M_A. A plausible explanation for the inconsistency is that either the reading of the trace wave amplitudes or the registration of them in the NOA Bulletin have been erroneous (Triantafyllou et al., 2022). Based on this suggestion we performed a simple numerical experiment with the adoption of hypothetical amplitudes of 3.9 mm and 6.8 mm, in replacement of 39 mm and 68 mm, and found $M_A = 5.6$, which eliminates the outlier.

For a few earthquakes some misfit was initially found between the magnitudes M_A and the respective magnitudes M_T. The first case concerns the earthquake ($M_T = 5.5$) that occurred in Central Greece near Chalkis city on 11 April 1902 (n. 5 in Table 3, Fig. 2) and was recorded at the ATH, CH and CA stations with P-wave arrivals at 18:37:21, 18:37:32 and 18:37:35 GMT, respectively. In the AUTH catalogue the epicenter is 38.5°N/23.5°E (Fig. 2). An improved epicentral solution was adopted as 38.1°N/23.1°E, which shifted the epicenter by a few km to the southwest with respect to the AUTH epicenter. This solution yields the smallest magnitude misfit ($M_T = 5.5$, $M_A = 5.2$) and is consistent with that the earthquake was reported as strongly felt in Athens as well as in Chalkis and Thiva cities (Fig. 1) (Anonymous, 1902-1915, Press reports of 30 and 31 March 1902 O.S., Eginitis,1905b). The epicenter is also controlled well by P-S travel-time curves particularly for the most distant CA station, which is lying at $\Delta \sim 145$ km.

The second case of misfit is associated with the earthquake ($M_T = 5.5$) that occurred in the northwestern Corinth Gulf on 2 August 1902 (n. 9 in Table 3, Fig. 2). This event caused fissures to the fortress of Rio town and the collapse of three old houses in Nafpaktos city (Anonymous, 1902-1915, Press reports of 3 August 1904 O.S.) (Fig. 3). Based on these macroseismic observations we selected an improved epicenter (38.5°N/21.8°E), which is shifted by a few km to the north with respect to the one listed in the AUTH catalogue (38.3°N/21.8°E). This choice caused the smallest misfit between $M_T = 5.5$ and $M_A = 4.8$.

Other misfit cases concern three strong earthquakes (n. 20, 21, 23 in Table 3, Fig. 2) belonging to the 1904 seismic sequence that was recorded in the eastern Aegean Sea, near Samos Isl. The first shock, that was destructive and occurred on 11 August 1904, has already been discussed above. No important damage was reported after the subsequent strong shocks, implying that their epicenters were lying away from the island. For both the strong shocks of 18 August 1904 ($M_T = 5.9$, $M_A = 6.3$) and 10 October 1904 ($M_T = 5.8$, $M_A = 6.0$) we adopted epicentral coordinates 37.9°N/26.7°E in replacement of the AUTH epicenters of 38.0°N/27.0°E and 38.4°N/27.2°E, respectively. The three epicenters determined in this study are controlled well by *P-S* travel-time curves.

The 30 May 1909 earthquake of $M_T = 6.2$ (n. 45 in Table 3, Fig. 2) was recorded at the Agamennone stations ATH and E, respectively. It caused damage in several villages on the northwestern side of Corinth Gulf. Based on various sources (Anonymous, 1902-1915; Press reports of June 1909; Eginitis, 1912) we assigned maximum epicentral intensity I_o = VII-VIII (MM) at Daphnochori village (Fig. 1) at 38.42°N/22.10°E; intensity I_o = VIII (MM) was assigned by Comninakis and Papazachos (1986). The most consistent magnitudes of $M_A = 6.3$ and $M_A = 5.9$ for the ATH and E stations were found for an epicenter at 38.5°N/22.4°E. The final magnitude calculated is $M_A = 6.1$. The epicenter adopted falls within the meizoseismal area but is shifted to the northeast with respect to the AUTH epicenter which is placed at 38.44°N/22.14°E. The epicenter is also controlled well by *P-S* travel-time curves for the most distant ATH station, which is situated at epicentral distance $\Delta \sim 130$ km.

For the earthquake of 17 May 1908 ($M_T = 6.7$) (n. 38 in Table 3, Fig. 2), an inconsistency has been noted between the magnitude $M_{AT} = 7.4$ calculated from the record at station Z and the magnitudes $M_{AT} = 6.6$ and $M_{AT} = 6.8$ found from the records at stations ATH and E, respectively. To explain this deviation, one should consider that body waves, particularly *S*-waves, produced by intermediate-depth earthquakes have larger amplitudes at sites situated along the fore-arc domain, e.g. in Z station, as compared to wave amplitudes recorded at about equal epicentral distances in the back-arc domain, e.g. in ATH and E stations. This feature is very likely due to efficient seismic energy propagation towards the fore-arc domain, as compared to propagation towards the back-arc domain, rather than to site soil conditions (Galanopoulos, 1953; Papazachos and Comninakis, 1971). A plausible geophysical interpretation is that seismic energy, particularly of *S*-waves, is strongly absorbed when the waves travel through the warm asthenospheric wedge existing beneath the back-arc area and, therefore, small wave amplitudes are recorded at stations in that area. On the contrary, good propagation is expected for waves traveling through the cool and dense subducting lithosphere and directed towards fore-arc sites.

6. Conclusions

Agamennone-type seismographs have been primitive instruments operated in some seismogenic countries around the turn of the 20th century. The utilization of records by such seismographs has been quite limited so far.

Agamennone instruments have been the first seismographs operated in five stations in Greece during the time interval 1900-1910. Those instruments had intermediate natural period ranging from 3.5 to 9.0 s as a common feature with Mainka and Wiechert seismographs operated in Greece for several decades after 1910. Based on this commonality, ground wave amplitudes, *A*, recorded by Agamennone instruments and listed in the Bulletins of the National Observatory of Athens, are suitable to revise magnitudes of earthquakes occurring in Greece and in the southern Balkans during 1900-1910.

Wave amplitudes *A* for 52 shallow and intermediate-depth earthquakes were found to correlate well with proxy surface-wave magnitudes, M_s, which were independently determined by others for the same earthquakes and listed in the AUTH (Aristotle University of Thessaloniki) catalogue. Agamennone magnitudes, M_A, equivalent to M_s have been determined for the 52 earthquakes after calibrating amplitudes *A* for magnitudes M_s determined by other authors from Mainka and Wiechert seismographs for post-1910 earthquakes and listed in the AUTH catalogue.

The calculated magnitudes M_A range from 4.7 to 7.4 against 4.8 to 7.5 listed in the AUTH catalogue for the same 52 earthquakes. Magnitude misfit between M_s (AUTH) and M_A was found equal to 0.3 ± 0.2 and 0.2 ± 0.1 for shallow and intermediate-depth earthquakes, respectively. For a few earthquakes magnitude misfit was reduced after the adoption of revised epicentral coordinates as compared to the ones listed in the AUTH catalogue. The successful redetermination of magnitudes from Agamennone records contributes to the improvement of the Greek seismicity catalogue for the time interval 1900-1910. At the same time, it provides prospects for the determination of magnitudes of more earthquakes, which are not listed in the AUTH or other existing catalogues but have known Agamennone ground wave amplitudes published in the NOA Bulletins.

Data availability statement. All data and relevant references are included in the text.

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