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A catalogue of seismicity in Greece and the adjacent areas for the twentieth century

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Abstract

A magnitude homogeneous earthquake catalogue spanning the twentieth century has been assembled for Greece and adjacent areas. Data assemblage had to consider all of the common magnitude scales: M_W, M_S, m_b, and M_L (including M_L(ATH) of the National Observatory of Athens (NOA)). Fourteen different correlation equations between magnitude scales were considered in order to approach magnitude homogeneity in the final catalogue. This catalogue contains an estimate of both M_W and M_S, for each earthquake, and the actual reported values of m_b, M_S, M_W, and M_L. The final catalogue includes 5198 earthquakes after having been truncated at 4 M_W to eliminate large numbers of patchily reported microearthquakes. These 5198 earthquakes during 1900–1999 are within the area 33–43°N, 18–30.99°E, focal depths 1.0–215 km, and magnitude range $4.0 \leq M_W \leq 7.7$. The surface wave magnitude M_S is always estimated for each earthquake to facilitate application of the catalogue to seismic hazard assessment, since seismic attenuation laws are more often expressed in terms of M_S rather than M_W. Alongside this new catalogue, the data of Papazachos and Papazachou for the period 550 BC–1899 then provide a full picture of the known seismicity of Greece.

Keywords: Earthquakes; Seismicity; Magnitude; Seismic hazard; Greece

1. Introduction

Greece is the country of highest seismicity in Europe and as such, a homogeneous account of its earthquake record and history is of great interest. The interest in creating a homogeneous earthquake catalogue is not merely academic but of great practical concern when applied to underpin analyses of seismic hazard and ensuing seismic risk, and for seismic zonation and land use regulation and planning. Many high quality and relatively uniform data have accumulated since 1964 through the International Seismological Centre (ISC) that supplements earlier, less clear periods. The task of earthquake catalogue compilation is an ongoing research task in which

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previous attempts are occasionally revisited and improved on, in light of new information, to update the old. A further driving force for this study is to provide a homogeneous catalogue from which resulting strategic seismic hazard analyses will assist the design of an earthquake early warning system to be deployed near Athens. The final driving force to this study is the aim to make available the catalogue on disk or file transfer to those interested in the seismicity of Greece, along with a clear statement of the methods that were use to homogenize the catalogue. It is expected that this will assist researchers and responsible decision-taking organizations alike.

Thus two slightly different targets are addressed:

- Preparation of a researched earthquake catalogue that is sufficiently homogeneous to enable a spatial (geographic distribution) analysis of earthquake magnitude frequency and of earthquake strong ground shaking frequency. This will span the period 1900–1999.
- Inclusion of an inventory of the size and position of the larger damaging earthquakes known in Greece prior to 1900.

The first target requires a catalogue that is homogeneous and carefully researched, is highly numerate and technically complete above some reasonable magnitude threshold, of reasonable duration, and spans beyond Greece (to avoid "edge effects" in any ensuing seismic hazard analysis intruding into the primary region). It is also essential that this catalogue can be used easily in conjunction with a regression equation expressing the attenuation of earthquake strong ground vibration with distance from the earthquake source. The second need implies a historical catalogue that reaches as far back in time as possible in order to span all catastrophic earthquake occurrences (or as many as possible—there will always be the possibility of "rogue" earthquakes and surprises). The first target is researched substantially herein whereas the second need draws entirely on the extant work of others and is included briefly herein to provide a full account of Greek seismicity.

At first sight, it may seem best to prepare the whole catalogue homogeneously using one earthquake magnitude scale, moment magnitude M_W, to describe the size of an earthquake consistently. However, as desirable as this may appear, inspection of earthquake strong motion attenuation laws demonstrates that much practical work still necessarily uses the surface wave magnitude scale M_S. Nevertheless, a catalogue for the entire period will be rendered onto the moment magnitude scale, viz. a pseudo moment magnitude as most entries are of necessity not actual direct measurements of moment magnitude on an earthquake.

Greece is the country of highest seismicity in Europe (Bath, 1983), and as such, its earthquakes have been extensively studied. The major sources available to and used in this study are the catalogues and bulletins of the International Seismological Centre (ISC), and the researched catalogues of Makropoulos and Burton (1981), Makropoulos et al. (1989), and Papazachos and Papazachou (1997). The catalogue of Baba et al. (2000) was also consulted but not used.

The major published catalogue available that studies damaging earthquakes through historical times in Greece, 550 BC–1995 AD, is that of Papazachos and Papazachou (1997). This catalogue has clearly assimilated much macroseismic data and evidence of destruction in Greece through the centuries and lends itself well to the second need listed above. The first target is served best by exploiting the instrumental data of the 20th century. This is another reason why it was decided to provide two catalogues spanning two periods.

The geographical area loosely described as "Greece" is taken as 33–43°N, 18–31°E.

2. Earthquake catalogue for Greece

The period 550 BC–1899 AD is taken directly from Papazachos and Papazachou (1997) so that a full account of Greek seismicity is provided uniformly. The parameters (year, date, time, latitude, longitude, depth, magnitude) for all earthquakes during this historical period are extracted directly from their book. This book sets out to include all known strong earthquakes in Greece with magnitude $M \geq 6.0$ up to 1995. Previous macroseismic catalogues for Greece include those of Galanopoulos (1960, 1961). Much of the macroseismic data used by Papazachos and Papazachou (1997) are interpreted and summarized as isoseismal maps in the corresponding atlas of Papazachos et al. (1997). Papazachos and Papazachou (P&P) indicate that they have taken into account the recent work of Evagelatou-Notara (1993), Guidoboni et al. (1994), Ambraseys and Finkel (1995), and Papaioannou (various studies in Greek).

The magnitude scale used by P&P (also see the magnitude scale work for Greece of Kiratzi and Papazachos, 1984) is generically labeled "M" and it is held that $M \equiv M_W \equiv M_S$ for practical purposes with the restrictions:

$$M = M_S \quad \ldots 6.0 \leq M_S \leq 8.0 \tag{1}$$

and

$$M = M_W \quad \ldots 5.0 \leq M_W \leq 8.0 \tag{2}$$

and so these historical earthquakes are easily rendered onto the moment magnitude or surface wave magnitude scales.

General summary of P&P Greek Catalogue 550 BC–1899 AD: this catalogue contains a total of 427 earthquakes during 550 BC–1899 AD, within the area 34.80–42.80°N, 18.10–30.00°E and magnitude range $6.0 \leq M_W \leq 8.3$. These epicenters are mapped in Fig. 1.

We now turn our detailed attention to the twentieth century period 1900–1999 AD in order to form a homogeneous Greek Catalogue 1900–1999 AD.

The development of this catalogue relies primarily, during three different periods, on the studies of Makropoulos and Burton (1981) for 1900–1963, Engdahl et al. (1998, essentially ISC data) for 1964–1998, and the National Observatory of Athens for 1999. Complications arise because of the need to reconcile magnitude scales between these three components of the final catalogue. The final catalogue is cut at a moment magnitude threshold of 4.0 M_W. These three components will be considered in turn.

2.1. Subperiod 1900–1963

This subperiod of the catalogue is constructed from the catalogues of Makropoulos and Burton (1981) and Makropoulos et al. (1989). From 1917 to 1963, most of the earthquakes in this catalogue have all of their focal parameters recalculated using the joint epicenter determination method of Douglas et al. (1974), with control earthquakes selected from the larger ones that have both good teleseismic and local macroseismic coverage. For the period 1901–1917, there is much reliance on the UNS catalogue of Shebalin et al. (1974). All magnitudes during the period 1908–1977 were determined using Swedish ground amplitude records in a manner similar to Alsan et al. (1975) and thus consistently rendered on to the surface wave magnitude scale M_S. Every attempt was made to maintain homogeneity. This Makropoulos and Burton and Makropoulos et al. catalogue—referred to here as M&B—is here truncated after 1963 and supplies 1183 earthquakes with magnitudes $4.0 \leq M_S \leq 8.0$. The

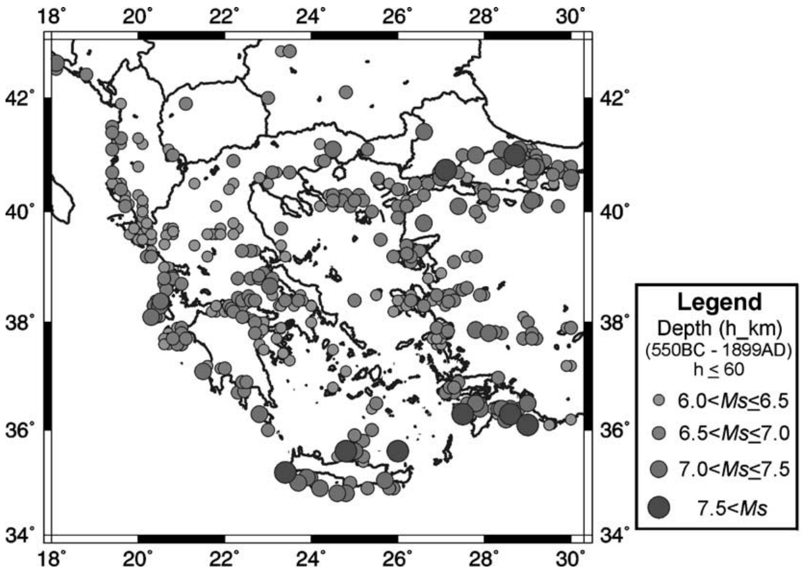

Fig. 1. Earthquake epicenters in Greece during 550 BC–1899 AD with shallow focal depth $h \leq 60$ km (after Papazachos and Papazachou, 1997).

Appendix to Makropoulos et al. supplies a further 1002 smaller magnitude earthquakes during 1900–1947 in the range $4.0 \leq M_S \leq 5.7$.

For events that are listed in the P&P catalogue ($M \geq 6$) that are not in the strong earthquake ($M_W \geq 6$) list of the M&B catalogue, there are two situations. Firstly, two events are missing from the M&B catalogue and so they are added to the updated version of the M&B catalogue as follows in Table 1.

Secondly, magnitudes in the M&B catalogue tend to be slightly smaller than in the P&P catalogue during the 20th century. If ${}^{P\&P}M - {}^{M\&B}M_W \leq 0.4$, then these differences are regarded as within the standard magnitude uncertainty, especially for the early 20th century. There are five earthquakes for which ${}^{P\&P}M - {}^{M\&B}M_W > 0.4$. For the event in 1939 September 20 in the SW of Cephalonia (5.8 ${}^{M\&B}M_W$, 6.3 ${}^{P\&P}M$), although the difference is 0.5, there is no macroseismic information available for the P&P catalogue (Papazachos and Papazachou, 1997, p. 271), so the M&B magnitude is retained. However, the other four earthquakes, with magnitude difference in excess of 0.4, are all determined at intermediate focal depth in both catalogues (see Table 1b), and the P&P magnitude determination is preferred for these four earthquakes while the M&B determination is retained for the other focal parameters. Karakaisis (personal communication) kindly pointed out additional information substantiating the P&P magnitudes for these four earthquakes, including an isoseismal map drawn by Criticos (1928) for the 1925 July 6 earthquake.

Moment–magnitude correlation in Greece does not necessarily follow the global average. However, conversions between the surface wave magnitude scale used in this catalogue and the moment magnitude scale can be obtained on a good basis using directly pertinent data. The moment–magnitude scaling law determined by Main and Burton (1990) is obtained directly from 50 earthquakes that occurred in the Aegean area in the magnitude range $5.3 \leq M_S \leq 7.2$:

$$\log M_o = 1.5 M_S + 9.198(\pm 0.317) \quad (3)$$

with seismic moment M_o in N m. This is for a constant stress drop model, the average stress drop corresponding to use of Eq. (3) being 25_{-12}^{+25} bar. If the stress drop is allowed to vary, then:

$$\log M_o = 1.206(\pm 0.105) M_S + 10.970(\pm 0.632) \quad (4)$$

There is little difference between Eqs. (3) and (4) at 5.5 M_S. The difference increases slightly with earthquake size, with Eq. (3) exceeding Eq. (4). The moment magnitude defining equation of Kanamori's (1977) is

$$M_W = 2/3 \log M_o - 10.7 \quad (5)$$

with seismic moment expressed in dyn cm. Combining Eqs. (4) and (5), a procedure similar to that followed by Pérez (1999) when producing a world seismicity catalogue for strong shallow earthquakes, provides the required link between moment magnitude and surface wave magnitude scales:

$$M_W = 0.804\ M_S + 1.28 \quad \ldots 5.3 \leq M_S \leq 7.2 \quad (6)$$

Papazachos and Papazachou (1997) are of the view that:

$$M_W = M_S \quad \ldots 6.0 \leq M_S \leq 8.0 \quad (7a)$$

$$M_W = 0.56\ M_S + 2.66 \quad \ldots 4.2 \leq M_S \leq 6.0 \quad (7b)$$

Eq. (6) generates identical $M_W \equiv M_S$ at 6.53 with the difference being only −0.19 at 7.5 M_S, broadly consistent with the Papazachos and Papazachou view

Table 1
Modifications to the M&B catalogue for the subperiod 1900–1963

Event	Date (year-month-day)	Time (h-min-s)	Latitude and Longitude (°N, °E)	Depth (h km)	Magnitude
(a) P&P determinations, including P&P focal depth h2 km and magnitude M; n="normal" depth					
1	1927-02-14	03-43-37	43.0, 18.0	$h2$=n	6.1 ${}^{P\&P}M$
2	1928-05-02	21-55	39.4, 29.5	$h2$=n	6.2 ${}^{P\&P}M$
(b) M&B determinations, including M&B focal depth h1 km and magnitude M_S; P&P h2 km and M					
1	1923-08-01	08-16-34.70	34.67, 23.56	$h1$=91, $h2$=90	5.7 ${}^{M\&B}M_W \rightarrow 6.8\ {}^{P\&P}M$
2	1925-07-06	12-15-54.30	37.79, 21.94	$h1$=70, $h2$=80	5.9 ${}^{M\&B}M_W \rightarrow 6.6\ {}^{P\&P}M$
3	1942-06-21	04-38-44.20	36.05, 26.96	$h1$=88, $h2$=90	5.5 ${}^{M\&B}M_W \rightarrow 6.3\ {}^{P\&P}M$
4	1958-06-30	08-42-47.10	36.44, 27.28	$h1$=112 $h2$=110	5.5 ${}^{M\&B}M_W \rightarrow 6.0\ {}^{P\&P}M$

of equivalence between the two scales at the higher magnitudes, as expressed in Eq. (7a). Obtaining M_W using Eqs. (6) and (7b) over magnitude ranges $4.2 \leq M_S$ in Eq. (7b) $< 5.3 \leq M_S$ in Eq. (6) provides remarkable consistency with very small matching error of order 0.03–0.10 just below magnitude 5.3 (5.3 $M_S \rightarrow 5.54$ M_W using Eq. (6) and 5.2 $M_S \rightarrow 5.57$ M_W using Eq. (7b)). Therefore, all earthquake magnitudes for this period have, in the first instance, consistent surface wave magnitude determinations, and also, secondly, a clear route to rendering all magnitudes systematically on the moment magnitude scale based on the local physical properties of earthquakes determined for Greece.

General summary of Greek subcatalogue 1900–1963: this subcatalogue contains a total of 2187 earthquakes during 1900–1963 AD, within the area 33.00–43.00°N, 18.00–30.13°E, focal depths 2.0–215.0 km, and magnitude range $4.9 \leq M_W \leq 7.7$.

2.2. Subperiod 1964–1998

The international standard data of the International Seismological Centre (ISC) come into its own from 1964 onwards, with standard deviations on origin time, on epicentral coordinates, and on focal depths, all of which indicate a high quality of solution. Also, during M&B catalogue production, it was found that a sample of test relocations on earthquakes of the period 1964–1975 produced relocation shift vectors of less than 10 km between the "old" ISC location and the "new" location to within the 95% confidence limits. M&B therefore accepted ISC epicenters for Greece from 1964 onwards. Much of the required ISC data are readily available in the work and associated web site of Engdahl et al. (1998), and data from this source were accepted. There are a few inevitable perturbations from simplicity towards the end of this period, and these are described next.

ISC data are obtained for the period 1964–1995 inclusive, providing 2097 earthquakes. Data for 1996–1997 inclusive are attributable to Engdahl et al., providing 240 earthquakes. Data for 1998 are attributable to Preliminary Determination of Epicenters (PDE) of the USGS National Earthquake Information Center (NEIC), providing 71 earthquakes. When 18 earthquakes without magnitude are deleted, a total of 2390 earthquakes remain.

In some cases, moment magnitude is a reported magnitude. A systematic rendering onto the moment magnitude scale is achievable for the other earthquakes, which have body wave magnitude m_b reported, albeit with probable wide scatter, using the Papazachos and Papazachou (1997) equation:

$$M_W = 1.28\, m_b - 1.12 \quad \ldots 4.8 \leq m_b \leq 6.0 \tag{8}$$

General summary of Greek subcatalogue 1964–1998: this subcatalogue contains a total of 2390 earthquakes during 1964–1998 AD, within the area 33.16–42.81°N, E18.01–30.99°E, focal depths 1.0–350.0 km, and magnitude range $3.2 \leq M_W \leq 6.9$.

2.3. Subperiod 1999

This 1-year closing period adopts Greek data directly from the web site catalogue of the Institute of Geodynamics, National Observatory of Athens (NOA). This is supplemented by six earthquakes extracted from the CMT Harvard catalogue (see Table 2) associated with the major earthquake at Izmit, Turkey, of 1999 August 17, because this lies within the seismogenic source zones of Papazachos and Papazachou.

Table 2
Data on six earthquakes extracted from the Harvard CMT catalogue for the subperiod 1999

Event	Date (year-month-day)	Time (h-min-s)	Latitude and Longitude (°N, °E)	Depth (h km)	Magnitude
1	1999-08-17	00-01-50.1	41.01, 29.97	17.0	7.6 M_W, 7.8 M_S
2	1999-08-19	15-17-47.3	40.68, 29.10	15.0	5.1 M_W, 4.7 M_S
3	1999-08-31	08-10-51.3	40.43, 30.25	15.0	5.1 M_W, 4.9 M_S
4	1999-09-13	11-55-32.0	40.31, 30.29	15.0	5.8 M_W, 5.8 M_S
5	1999-09-29	00-13-10.9	40.55, 29.69	15.0	5.2 M_W, 4.5 M_S
6	1999-11-11	14-41-30.5	40.95, 30.10	15.2	5.6 M_W, 5.5 M_S

NOA cites local magnitude M_L, whereas CMT cites both moment magnitude and surface wave magnitude. To convert NOA M_L to moment magnitude, the equation of Baba et al. (2000) and Margaris and Papazachos (1999) is adopted:

$$M_W = M_L + 0.43 \tag{9}$$

and the ensuing subcatalogue has 2502 earthquakes with general details below.

General summary of Greek subcatalogue 1999: this subcatalogue contains a total of 2502 earthquakes during 1999 AD, within the area 34.01–41.98°N, 19.05–30.29°E, focal depths 2.0–142.0 km, and magnitude range $2.1 \le M_W \le 7.6$.

The detail of the analysis for 1999 is maintained here, rather than replaced by any recent determinations, so that any user may extract current data from the NOA and update this catalogue using this methodology at any time.

2.4. Period 1900–1999

The three subcatalogues for 1900–1963, 1963–1998, and 1999 combined together form a catalogue for 1900–1999. There is a homogenized moment magnitude value (actual measurement—rare; rendering onto the scale using inter-scale correlation equations—common) for each earthquake entry.

General summary of catalogue 1900–1999 AD: this catalogue contains a total of 7079 earthquakes during 1900–1999 AD within the area 33.00–43.00°N, 18.00–30.99°E, focal depths 1.0–350 km, and magnitude range $2.1 \le M_W \le 7.7$.

2.5. Greek catalogue 1900–1999 AD

The above catalogue 1900–1999 AD provides a uniform record of seismicity with all magnitudes expressed on the moment magnitude scale. It is compatible with the historical P&P Greek catalogue 550 BC–1899 AD, also expressed on the moment magnitude scale, and these two catalogues can be united easily to span 550 BC–1999 AD. This provides a very lengthy record of seismicity in Greece.

However, there are practical difficulties in using this catalogue for other purposes than representing seismicity on a uniform magnitude scale. A minor difficulty is the proliferation of small magnitudes, in some parts of the catalogue, that will not be of significant value to a seismic hazard analysis. However, the major practical difficulty arising in relation to seismic hazard analysis is that most regression equations describing the attenuation of earthquake strong ground vibration with distance from the earthquake source still relate to the surface wave magnitude scale, and not to the moment magnitude scale. Because of this it was decided that the final catalogue would (a) in addition to M_W also associate an M_S with each earthquake entry, and (b) record the values of M_W, M_S, m_b, and M_L that are actually reported in the constituent catalogues (subject to the few specific examples of individual magnitude values that have been preferred with reasons described above). This produces the need, in some circumstances, for additional correlation equations between the different magnitude scales—and a hierarchy of preferred original magnitude scales when converting to M_S.

There is no difficulty for the P&P catalogue 550 BC–1899 AD because M_W, M_S, and M of Papazachos and Papazachou are considered synonymous for magnitudes greater than 6, which this catalogue represents. Similarly, there is no difficulty with the M&B catalogue for the subperiod 1900–1963 because all magnitudes were originally made systematically as M_S determinations.

The period 1964–1998 requires attention. This is largely the period of production by the ISC of internationally accepted earthquake catalogues. The magnitudes reported include M_W, M_S, and m_b scale entries, but not all scale values for each earthquake. Body wave magnitudes are reported in practically all cases, surface wave magnitudes are often reported, and occasionally moment magnitude is reported. Most necessary scale conversion equations are in place above, except one from body wave to surface wave magnitude scales. Note that there are 591 earthquakes during 1964–1998 for which paired observations of M_S and m_b are available. Six equations linking M_S and m_b were considered:

$$M_S = 1.306(\pm 0.070)m_b - 2.037(\pm 0.32) \tag{10a}$$

resulting from a standard linear regression of M_S on m_b using the 591 paired data points available during 1964–1998;

$$M_S = 3.05(\pm 0.10)m_b - 10.22(\pm 0.47) \tag{10b}$$

resulting from a York double-error regression on the data used to derive Eq. (10a);

$$M_S = (1.8782 \pm 0.0222)m_b - (4.6046 \pm 0.1102) \quad (10c)$$

derived by Rezapour and Pearce (1998) using ISC global data for 13,903 earthquakes and assuming the same variance in M_S and m_b;

$$M_S = 1.31m_b - 1.41 \quad (10d)$$

derived by Makropoulos and Burton (1981) using ISC data for Greece for the 126 earthquakes with paired M_S and m_b available during 1964–1975 (note standard deviation on M_S of ± 0.41);

$$M_S = 1.55m_b - 2.49 \quad (10e)$$

of Alsan et al. (1975) derived from 110 earthquakes; and

$$m_b = 0.287(\pm 0.015)M_S + 3.522(\pm 0.063) \quad (10f)$$

derived from the same data as Eq. (10a) but with m_b regressed on M_S for comparison. Eq. (10c) from Rezapour and Pearce (1998), although for a global rather than Greek data base, appears superior and is adopted.

The hierarchy and conversion scheme then adopted is:

(1) If M_S is reported:
$\Rightarrow$ accept the value of M_S.
(2) If M_S is not reported, but both M_W and m_b are reported:
$\Rightarrow$ prefer the M_W value
$\Rightarrow$ use Eqs. (6) or (7b) to calculate M_S.
(3) If neither M_S nor M_W is reported:
$\Rightarrow$ accept the m_b value
$\Rightarrow$ use Eq. (10c)
to calculate M_S.

The year 1999 also requires attention. The six earthquakes extracted from the CMT Harvard catalogue all have M_S values reported (see Table 2). All other entries, from the NOA catalogue, are reported with the local magnitude M_L(ATH). Kiratzi and Papazachos (1984) suggest that M_S is greater then M_L by 0.5, whereas Papazachos and Papazachou provide:

$$M_L = (0.58 \pm 0.02)M_S + (2.14 \pm 0.07) \quad \ldots 3.0 \leq M_S \leq 6.0 \quad (11a)$$

which inverts to:

$$M_S = 1.72M_L - 3.69 \quad \ldots 3.9 \leq M_L \leq 5.6 \quad (11b)$$

although inversion of such a regression is dubious practice. However, also available is the result (Burton et al., 1991) obtained from correlating ISC M_S values for Greek earthquakes that occurred during the period 1969–1981, and NEIC M_S values, with NOA Monthly Bulletin M_L(ATH) values:

$$M_S = 1.70(\pm 0.05)M_L(ATH) - 3.59(\pm 0.22) \quad (11c)$$

The agreement between Eqs. (11b) and (11c) is remarkable in the circumstances. Eq. (11c) is adopted to convert M_L(ATH) values to M_S.

With these conversions in place, a catalogue for the period 1900–1999 AD can now be produced. This contains magnitudes for all earthquakes, on both moment magnitude and surface wave magnitude scales, whether reported observed or converted values; also included are any reported observed magnitudes on any of the scales M_W, M_S, m_b, and M_L. This catalogue contains a total of 7079 earthquakes during 1900–1999 AD within the area 33.00–43.00°N, 18.00–30.99°E, focal depths 1.0–350.0 km, and magnitude range $2.1 \leq M_W \leq 7.7$. This working catalogue should be truncated to accept magnitudes $M_W \geq 4.0$ as explained below.

The final step for the catalogue period 1900–1999 is to truncate the magnitude range accepting only those earthquakes with $M_W \geq 4.0$. Truncation at 4.0 M_W, rather than at 4.0 M_S, is preferred because Eq. (7b) suggests 4.0 $M_W \cong 2.4$ M_S while 4.0 $M_S \cong 4.9$ M_W and it was held preferable not to eliminate earthquakes in the magnitude range 4.0–4.9 no matter what scale or conversion generated them, i.e., 4.0 $M_W < 4.0$ M_S.

General summary of Greek catalogue 1900–1999 AD: this catalogue contains a total of 5198 earthquakes during 1900–1999 AD within the area 33.00–43.00°N, 18.00–30.99°E, focal depths 1.0–215.0 km, and magnitude range $4.0 \leq M_W \leq 7.7$. These epicenters are all mapped in Fig. 2 regardless of focal depth. Epicenters of earthquakes with shallow focal depth ($h \leq 60$ km) are shown in Fig. 3 and those with focal depth $h > 60$ km in Fig. 4.

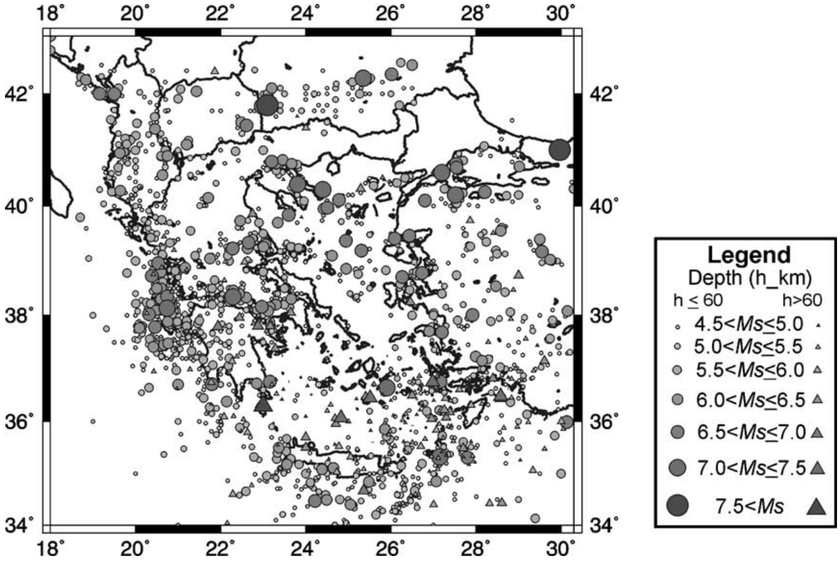

Fig. 2. Earthquake epicenters in Greece during the twentieth century (all focal depths).

Technical note: the format for P&P catalogue 550 BC–1899 AD and Greek catalogue 1900–1999 AD in which they can be provided is:

YR(F4.0)
MON(F3.0)
DATE(F3.0)
HR(F4.0)
MIN(F3.0)
SEC(F7.2)
LAT(F8.2)
LONG(F8.2)

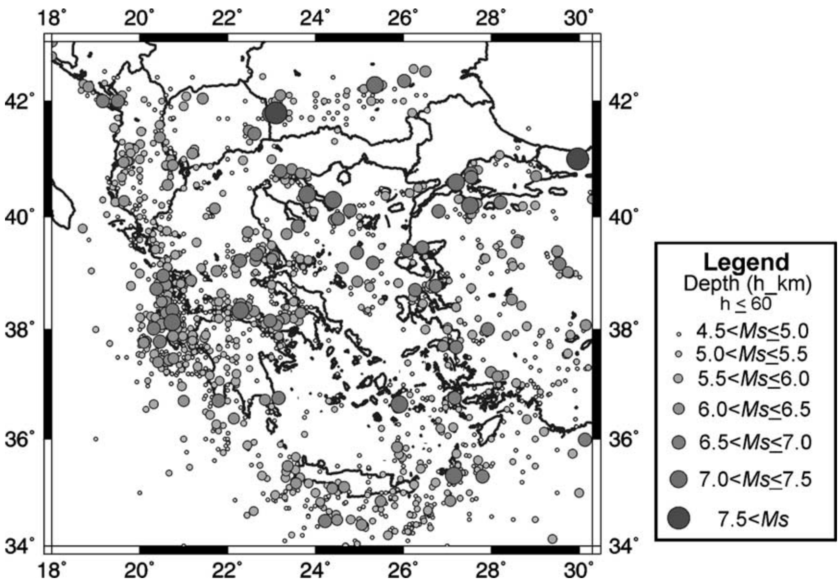

Fig. 3. Earthquake epicenters in Greece during the twentieth century with shallow focal depth $h \leq 60$ km.

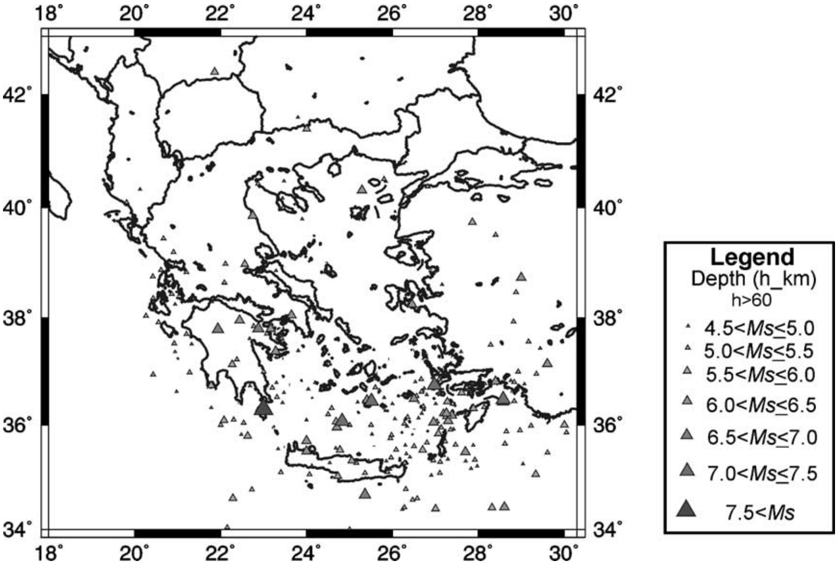

Fig. 4. Earthquake epicenters in Greece during the twentieth century with focal depth h>60 km.

DEPTH(F7.1)
MAG_MW(F8.1)
MAG_MS(F8.1)
MB REPORTED(F8.1)
MS_REPORTED(F8.1)
MW_REPORTED(F8.1)
ML_REPORTED(F8.1)

where MAG_MW and MAG_MS are the homogenized values of M_W and M_S, respectively, being the result of magnitude scale conversion except when reported values of M_W and M_S exist.

3. Conclusions

This new earthquake catalogue spanning the twentieth century for Greece is sufficiently homogeneous in magnitude to facilitate application to probabilistic seismic hazard assessment and seismic zoning for Greece. Combined with the data of Papazachos and Papazachou (1997) for 550 BC–1899 AD, it provides a clear picture of the known seismicity of Greece. These epicenters are mapped in Figs. 1 and 2.

Consideration of three separate periods of data provision was fundamental to catalogue evaluation and preparation: largely the International Seismological Centre since 1964 (1964–1998 after Engdahl et al., 1998), Makropoulos and Burton (1981) redetermination work prior to 1964 (1900–1963), and the National Observatory of Athens for 1999.

The heart of the new work centers around appropriate correlation equations between the various magnitude scales, M_W, M_S, m_b, and M_L (including M_L(ATH) of the NOA), on which Greek earthquakes have variously been reported. Fourteen different magnitude correlation equations were scrutinized in preparation of the twentieth century catalogue. Three of these link M_S to M_W, one m_b to M_W, one M_L to M_W, six m_b to M_S, and three M_S to M_L. The principal equations developed or adopted for catalogue preparation are: Eqs. (6), (7b), (9), (10c), (11c), viz., for M_S to M_W (6, this paper),

$$M_W = 0.804\ M_S + 1.28 \quad \ldots 5.3 \le M_S \le 7.2,$$

and below 5.3 M_S (Papazachos and Papazachou, 1997),

$$M_W = 0.56\ M_S + 2.66 \quad \ldots 4.2 \le M_S \le 6.0,$$

for M_L to M_W (Baba et al., 2000; Margaris and Papazachos, 1999),

$$M_W = M_L + 0.43,$$

for m_b to M_S (Rezapour and Pearce, 1998),

$$M_S = (1.8782 \pm 0.0222) m_b - (4.6046 \pm 0.1102),$$

and for M_L(ATH) to M_S (Burton et al., 1991),

$$M_S = 1.70(\pm 0.05)M_L(ATH) - 3.59(\pm 0.22).$$

The procedure for homogenizing NOA data for 1999 into the catalogue for the twentieth century is maintained herein so that a procedure is always available to update the catalogue rapidly, at any time, by drawing on the data freely provided by NOA prior to the issue of definitive ISC determinations.

The final Greek catalogue 1900–1999 AD is truncated at 4 M_W rather than 4 M_S because (1) at this level 4.0 $M_S \cong 4.9$ M_W and it is preferable not to eliminate earthquakes in the range 4.0–4.9 no matter what magnitude scale was used to derive them, and (2) this eliminates a large number of microearthquakes (M_W<4.0) that have been patchily reported.

This Greek catalogue 1900–1999 AD summarizing seismicity in Greece for the twentieth century contains 5198 earthquakes within the geographical area contained by 33–43°N, 18–30.99°E, focal depths 1.0–215 km, and moment magnitude range $4.0 \leq M_W \leq 7.7$ (Fig. 2). For every earthquake, alongside each actual or scale-converted moment magnitude estimate is an estimate (actual or scale-converted) on the surface wave magnitude scale M_S. This is to facilitate application of the catalogue to seismic hazard assessment, since seismic attenuation laws are still more often expressed in terms of M_S than M_W.

This earthquake catalogue describing twentieth century seismicity in Greece is available on request.

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References

Alsan, E., Tezucan, L., Bath, M., 1975. An earthquake catalogue for Turkey for the interval 1913–1970. Common Rep. 75 Kandilli Turkey Obs., Seism. Inst. Uppsala, Sweden.

Ambraseys, N.N., Finkel, C.F., 1995. Seismicity of Turkey and Adjacent Areas, A Historical Review, 1500–1800. Publ. Muhittin Salih EREN, Istanbul. 240 pp. [not seen].

Baba, A.B., Papadimitiou, E., Papazachos, B.C., Papaioannou, C.A., Karakostas, B.G., 2000. Unified local magnitude scale for earthquakes of south Balkan area. Pure Appl. Geophys. 157, 765–783.

Bath, M., 1983. Earthquake frequency and energy in Greece. Tectonophysics 95, 233–252.

Burton, P.W., Makropoulos, K.C., McGonigle, R.W., Ritchie, M.E.A., Main, I.G., Kouskouna, V., Drakopoulos, J., 1991. Contemporary seismicity in eastern Greece from the Volos network (VOLNET): fault parameters of major and minor earthquakes. Rep. Br. Geol. Surv., Seismology Series, WL/91/29, 106 pp.

Criticos, N.A., 1928. Le tremblement de terre du Peloponnese central du 6 Juillet 1925. Ann. de l'Observ. Nat. d'Athenes 7, 39–46. [not seen].

Douglas, A., Young, J.B., Lilwall, R.C., 1974. Computer programs for epicentre determination. AWRE Rep. O 28/74. HMSO, UK.

Engdahl, E.R., Hilst, R.V.D., Buland, R., 1998. Global teleseismic earthquake relocation with improved travel time and procedure for depth determination. Bull. Seismol. Soc. Am. 88, 722–743.

Evagelatou-Notara, Fl., 1993. The earthquakes in Byzantium, from the 13th till 15th century, historic examination. Parousia, Spec. Issue 24 184 pp. (in Greek) [not seen].

Galanopoulos, A.G., 1960. A Catalogue of shocks with $I_o \geq$VI or M≥5 for the years 1801-1958. Seismological Laboratory, Athens University. 119 pp.

Galanopoulos, A.G., 1961. A Catalogue of shocks with $I_o \geq$VII for the years prior to 1800. Seismological Laboratory, Athens University. 18 pp.

Guidoboni, E., Comastri, A., Traina, G., 1994. Catalogue of ancient earthquakes in the Mediterranean area up to the 10th century. SGA Storia Geofisica Ambiente, Bologna. 504 pp. [not seen].

Kanamori, H., 1977. The energy release in great earthquakes. J. Geophys. Res. 82, 2981–2987.

Kiratzi, A.A., Papazachos, B.C., 1984. Magnitude scales for earthquakes in Greece. Bull. Seismol. Soc. Am. 74, 969–985.

Main, I.G., Burton, P.W., 1990. Moment–magnitude scaling in the Aegean area. Tectonophysics 179, 273–285.

Makropoulos, K.C., Burton, P.W., 1981. A catalogue of seismicity in Greece and adjacent areas. Geophys. J. R. Astron. Soc. 65, 741–762.

Makropoulos, K.C., Drakopoulos, J.K., Latousakis, J.B., 1989. A revised and extended earthquake catalogue for Greece since 1900. Geophys. J. Int. Res. Note 98, 391–394.

Margaris, B.N., Papazachos, C.B., 1999. Moment–magnitude relations based on strong-motion records in Greece. Bull. Seismol. Soc. Am. 89, 442–455.

Papazachos, B., Papazachou, C., 1997. The Earthquakes of Greece. P. Ziti and Co, Thessaloniki, Greece. 304 pp.

Papazachos, B.C., Papaioannou, Ch.A., Papazachos, C.B., Savvaidis, A.S., 1997. Atlas of isoseismal maps for strong (M ≥ 5.5) shallow (h < 60 km) earthquakes in Greece and surrounding area 426BC–1995. University of Thessaloniki, Geophysical Laboratory Publication No. 4, Thessaloniki, Greece, 176 pages.

Prérez, O., 1999. Revised world seismicity catalog (1950–1997) for strong ($Ms \geq 6$) shallow ($h \leq 70$ km) earthquakes. Bull. Seismol. Soc. Am. 89, 335–341.

Rezapour, M., Pearce, R.G., 1998. Bias in surface-wave magnitude M_S due to inadequate distance corrections. Bull. Seismol. Soc. Am. 88, 43–61.

Shebalin, N.V., Karnik, V., Hadzvieski, D. (Eds.), 1974. Balkan Region—Catalogue of Earthquakes. UNESCO Project Office, Skopje.