Journal of Seismology **6**: 557–570, 2002.

Uncertainties in the estimation of earthquake magnitudes in Greece

B.C. Papazachos[1], V.G. Karakostas[1], A.A. Kiratzi[1], B.N. Margaris[2], C.B. Papazachos[1] & E.M. Scordilis[1]
[1]*Geophysical Laboratory, University of Thessaloniki, P.O. Box 352-1, GR-54006, Thessaloniki, Greece;* [2]*Institute of Engineering Seismology and Earthquake Engineering (ITSAK), P.O. Box 53, GR-55102 Finikas, Thessaloniki, Greece*

Received 9 July 2001; accepted in revised form 8 January 2002

Key words: Magnitude scales, Aegean area

Abstract

Instrumental magnitudes in Greece have been reported as: a) M magnitudes based on the records of the Wiechert or Mainka seismographs, b) M_{LGR} magnitudes based on the records of the Wood-Anderson (WA) seismographs (T_o = 0.8 sec, $V_{effective} \sim 1000$) or other short period seismographs calibrated against WA records and, c) M_{LSM} magnitudes based on strong motion records (accelerograms). Comparison of such magnitudes with moment magnitudes, M_w, for 329 earthquakes, with epicenters in the broader Aegean area, performed in this study, showed that M, M_{LGR}+0.5 and M_{LSM} are practically equal to M_w, with a small overall standard error (σ = 0.23). Therefore, equivalent moment magnitudes, M_w^*, estimated from these magnitudes and reported in the catalogues of the Geophysical Laboratory of the University of Thessaloniki are equal to moment magnitudes for all practical purposes with reasonable uncertainties. It has been further shown that surface wave magnitudes, M_s, for M_s<6.0, can be also transferred into moment magnitudes, M_w^*, but the larger uncertainties encountered make its use rather problematic.

Introduction

Accuracy and homogeneity in magnitudes of earthquakes included in earthquake catalogues are of importance for solving practical problems (seismic hazard assessment, etc.), as well as theoretical ones (calculation of seismic deformation, etc.). Calculations of magnitudes, however, are based on measurements of seismic records from several types of seismographs at various epicentral distances. For this reason several types of magnitudes are often reported for the same event, such as local magnitude, M_L (Richter, 1935), surface–wave magnitude, M_s (Gutenberg, 1945), body wave magnitude, moment magnitude, M_w (Hanks and Kanamori, 1979), among others. Magnitudes, however, must be transferred to the same scale, preferably to the moment magnitude scale and their uncertainties must be estimated, before being included in a catalogue to be used e.g. for seismicity studies.

The Geophysical Laboratory of the University of Thessaloniki has published two catalogues for earthquakes in Greece and surrounding area. The first includes the parameters of the earthquakes of the period 1901–1985 (Comninakis and Papazachos 1986), while the second, published recently (Papazachos et al., 2000), includes the parameters of the earthquakes for the instrumental period (1901–2000) as well as the parameters of the historical earthquakes (550 BC–1900 AD). The magnitude reported in these catalogues is the 'equivalent' moment magnitude, M_w^*, calculated by relations that transfer magnitudes of locally used scales to moment magnitudes (Papazachos et al., 1997). Many scientists extensively use these catalogues and for this reason their homogeneity and accuracy in respect to other magnitudes in use must be further checked. The purpose of the present paper is to test the hypothesis that the magnitudes included in these catalogues are equivalent to moment magnitudes, and to determine the uncertainties of these magnitudes.

Local magnitude scales used in Greece

Three kinds of magnitudes have been calculated in Greece by local data. The first magnitude is symbolized by M and is calculated by the maximum ground amplitude on the Mainka or Wiechert seismographs of the Geodynamic Institute of the National Observatory of Athens (NOA). The second one is the local magnitude, M_{LGR}, which is calculated by the maximum amplitude recorded on the Wood-Anderson (WA) seismograph operated by the National Observatory of Athens (NOA) or by other short period seismographs calibrated on the Athens WA instrument. Finally, a local magnitude, M_{LSM}, calculated by the use of strong motion records (accelerograms) has also been recently used.

The magnitude M of the shallow earthquakes (h≤60 km), which occurred in Greece and surrounding area and were recorded by the Wiechert or Mainka seismographs at the National Observatory seismological station in Athens, is calculated by the following relation derived by Papazachos and Vasilicou (1966):

$$M = \log a + 1.42 \log \Delta + 0.20 \quad (1)$$

where α is the average ground amplitude (in μm) as inferred from the maximum recorded amplitude on the two horizontal components and Δ (<600 km) is the epicentral distance from Athens. Furthermore, Papazachos and Comninakis (1971) proposed the following relation to calculate the magnitude M of the intermediate – depth earthquakes (60 km<h≤180 km) in the southern Aegean:

$$M = \log a + 0.18\frac{R}{100} + 3.20 \quad (2)$$

where α (in μm) is the same as in relation (1) and R (in km) is the hypocentral distance from Athens.

The coefficients in relations (1) and (2) were determined from a regression analysis with surface wave magnitudes $M_s \geq 6.0$ calculated from surface waves recorded at distant stations (Uppsala, Pasadena, Berkeley). Although relations (1) and (2) have been derived using data of strong earthquakes, they have been routinely used to calculate magnitude M for smaller events too. In addition, since M was originally calibrated on M_s, it was usually referred to and reported as M_s for these smaller events (Comninakis and Papazachos, 1986). This misidentification is not correct, as it has been shown (Papazachos, 1989; Papazachos et al., 1997) that M is equivalent to moment magnitude (denoted as M_w*) for a wide range of magnitudes, that is:

$$M_w^* = M, \quad 5.0 \leq M \leq 8.0 \quad (3)$$

For large magnitudes (≥6.0) M is also equivalent to M_s.

Recordings of surface waves on long period seismographs at distant seismological stations have been used for the estimation of the surface wave magnitudes, M_s, for many earthquakes in the broader Aegean area (Makropoulos et al., 1989; Ambraseys and Jackson, 1990; Karnik, 1996; Ambraseys et al., 1996; Ambraseys, 2001).

Local earthquake magnitude, M_{LGR}, is based on records of the Wood-Anderson seismograph, which is installed in Athens (NOA) since 1964. Appropriate calibration formulae have also been derived to calculate M_{LGR} magnitudes from records of short period instruments operated by the Geophysical Laboratory of the University of Thessaloniki (Kiratzi, 1984; Kiratzi and Papazachos, 1984; Scordilis, 1985). It has been shown (Papazachos et al., 1997) that:

$$M_w^* = 0.97M_{LGR} + 0.58, \quad 4.5 \leq M_L \leq 6.0 \quad (4)$$

which has been confirmed to also apply for $3.6 \leq M_{LGR} \leq 6.5$ by Margaris and Papazachos (1999). Equation (4) practically gives the same results with the simple formula:

$$M_w^* = M_{LGR} + 0.5, \quad 3.6 \leq M_{LGR} \leq 6.5 \quad (5)$$

which is routinely used to calculate magnitudes in Greece (Kiratzi, 1984; Latoussakis, 1984). This bias of 0.5 between M_w and M_{LGR} estimates in Greece is not expected, since it has been shown (e.g. Heaton, 1986) that $M_w = M_L$ for the magnitude range reported in equation (4), as it is also expected from the definition of M_w through M_L (Hanks and Kanamori, 1979). It has been suggested (Papazachos et al., 1997) and proved by Margaris and Papazachos (1999) that this difference is due to low static magnification (V∼1000) of the Wood-Anderson instrument in Athens (NOA), which is much smaller than the effective static magnification of V∼2080 found for WA instruments (Boore, 1989; Uhrhammer and Collins, 1990)

Recently, strong motion records (accelerograms) have also been used to calculate magnitudes in Greece, following the original proposal of Trifunac (1991). Thus, Margaris and Papazachos (1999) determined strong motion local magnitudes, M_{LSM}, by performing an integration of the equation of motion of the

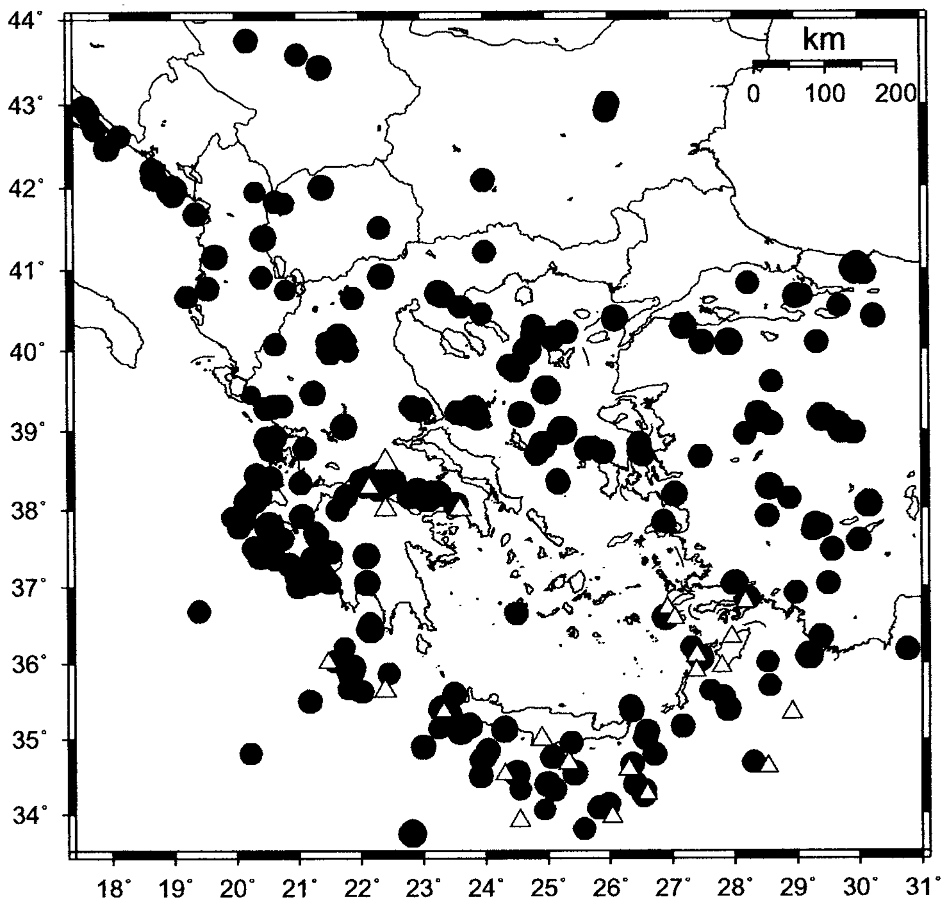

Figure 1. Epicenters of the earthquakes listed in Table 1. Circles and triangles depict shallow and intermediate depth earthquakes, respectively.

Wood-Anderson seismograph subjected to an input acceleration. They have further shown that M_{LSM} is equal to moment magnitude for a relatively wide range of magnitudes:

$$M_w^* = M_{LSM}, \quad 3.9 \leq M_{LSM} \leq 6.6 \tag{6}$$

Several scientists (e.g. Ambraseys, 2001) still consider the magnitudes calculated by relations (1), (2) and (5) as equivalent to M_s for smaller magnitudes (<6.0) too although it has been repeatedly shown (Papazachos et al., 1997; Margaris and Papazachos, 1999) that these magnitudes are equivalent to moment magnitudes, M_w, and that only for $M \geqslant 6.0$ are also equivalent to surface wave magnitudes, M_s. This result is strongly supported by a large sample of data presented later in the present paper.

Data

Data of 329 earthquakes that have occurred in Greece and the surrounding areas (33°N–44°N, 17°E–31°E) since 1959 have been used in the present study. Moment magnitudes, M_w, of these earthquakes have been calculated by using the seismic moment, M_o, measurements and applying the Hanks and Kanamori (1979) relation. For 121, 297, 37 and 227 of these earthquakes the magnitudes M, M_{LGR}, M_{LSM} and M_S were also available, respectively.

Table 1 gives information on the parameters of the earthquakes used, while their epicenters are plotted in Figure 1. The first five columns of Table 1 include information on the date, origin time, epicenter and depth. Moment magnitudes, ranging from 3.3 to 7.6, are listed in the sixth column. These magnitudes, as previously mentioned, were calculated from seismic

Table 1. Parameters of the earthquakes used to check the uncertainties of the magnitude scales applied in Greece

Date	Time	Lat N	Lon E	h(km)	M_w	Ref M_o	M	M_{LGR}	Ref	M_{LSM}	M_S	r
1959/11/15	170843	37.78	20.53	0	6.8	1	6.8	0.0	–	0.0	0.0	–
1963/07/26	041712	42.00	21.40	0	6.0	2	6.1	0.0	–	0.0	0.0	–
1963/09/18	165808	40.67	29.00	0	5.9	3	6.3	0.0	–	0.0	0.0	–
1963/12/16	134753	37.00	21.00	0	5.5	4	5.9	0.0	–	0.0	0.0	–
1964/04/11	160043	40.30	24.80	33	5.6	2	5.5	0.0	–	0.0	0.0	–
1964/04/29	042105	39.20	23.70	20	5.5	2	5.6	0.0	–	0.0	0.0	–
1964/07/17	023427	38.00	23.60	155	6.2	2	6.0	0.0	–	0.0	0.0	–
1964/10/06	143123	40.10	27.93	0	6.3	3	6.9	0.0	–	0.0	0.0	–
1965/03/09	175754	39.16	23.89	0	6.0	3	6.1	0.0	–	0.0	0.0	–
1965/03/31	094731	38.60	22.40	78	6.8	5	6.8	0.0	–	0.0	0.0	–
1965/04/05	031255	37.40	22.10	0	6.1	2	6.1	0.0	–	0.0	0.0	–
1965/04/09	235702	35.13	24.31	39	6.1	6	6.1	0.0	–	0.0	0.0	–
1965/04/27	140906	35.60	23.50	37	5.4	7	5.7	0.0	–	0.0	0.0	–
1965/06/13	200151	37.80	29.30	2	5.9	8	5.6	0.0	–	0.0	0.0	–
1965/07/06	031842	38.27	22.30	10	6.1	4	6.3	0.0	–	0.0	0.0	–
1965/11/28	052605	36.10	27.40	73	5.9	2	6.0	5.3	a	0.0	0.0	–
1965/12/20	000816	40.20	24.80	33	5.8	2	5.6	0.0	–	0.0	0.0	–
1966/02/05	020145	39.05	21.75	9	6.2	4	6.2	6.0	a	0.0	0.0	–
1966/05/09	004253	34.40	26.40	16	5.5	6	5.8	5.4	a	0.0	0.0	–
1966/10/29	023925	38.78	21.11	17	5.5	4	6.0	5.6	a	0.0	0.0	–
1967/03/04	175809	39.20	24.60	10	6.2	3	6.6	0.0	–	0.0	0.0	–
1967/05/01	070902	39.47	21.25	12	5.9	4	6.4	0.0	–	0.0	0.0	–
1967/11/30	072350	41.39	20.46	7	6.2	4	6.3	6.1	a	0.0	0.0	–
1968/02/19	224542	39.50	25.00	8	6.8	9	7.1	6.7	a	0.0	0.0	–
1968/05/30	174026	35.40	27.90	27	6.0	2	5.9	5.6	a	0.0	5.5	N
1968/12/05	075211	36.60	26.90	0	6.1	2	6.0	0.0	–	0.0	0.0	–
1969/01/14	231206	36.10	29.20	0	6.4	2	6.2	6.0	a	0.0	6.0	N
1969/03/03	005910	40.10	27.50	6	5.7	3	5.9	4.7	a	0.0	5.3	N
1969/03/23	210842	39.13	28.44	17	5.9	10	6.1	5.8	a	0.0	5.6	N
1969/03/25	132134	39.20	28.40	8	6.1	10	6.0	5.7	a	0.0	5.5	N
1969/03/28	014829	38.29	28.57	13	6.4	10	6.6	6.2	a	0.0	6.4	N
1969/06/12	151331	34.40	25.00	19	6.0	6	6.1	5.6	a	0.0	5.8	N
1969/07/08	080913	37.50	20.30	10	5.8	4	5.9	5.7	a	0.0	5.4	N
1970/03/28	210223	39.16	29.42	11	6.8	11	7.1	7.0	a	0.0	7.1	N
1970/04/08	135028	38.36	22.53	8	5.9	12	6.2	5.4	a	0.0	5.9	N
1970/04/16	104223	38.97	29.92	8	5.6	10	5.7	5.3	a	0.0	0.0	–
1970/04/19	132937	39.00	29.73	9	6.1	10	6.0	5.6	a	0.0	5.6	N
1970/04/23	090127	39.08	28.60	30	5.7	2	5.6	5.4	a	0.0	5.3	N
1971/05/12	062515	37.60	30.00	12	5.8	13	6.2	5.8	a	0.0	5.9	N
1971/05/12	125722	37.48	29.58	12	5.5	13	5.7	5.6	a	0.0	5.2	N
1971/05/25	054327	39.07	29.67	6	5.9	10	6.1	5.7	a	0.0	5.5	N
1972/05/04	213957	35.10	23.60	40	6.2	14	6.5	6.1	a	0.0	6.3	N
1972/09/13	041320	38.00	22.40	91	6.1	1	6.3	5.4	a	0.0	0.0	–
1973/11/04	155213	38.90	20.50	7	5.8	4	5.8	5.4	a	0.0	5.5	N
1973/11/29	105744	35.18	23.75	3	5.9	6	6.0	5.5	a	0.0	5.6	N
1975/01/08	193233	38.16	22.79	9	5.6	15	5.5	4.7	a	0.0	5.0	N
1975/03/27	051508	40.40	26.10	13	6.1	3	6.6	5.7	a	0.0	6.7	N
1975/04/30	042856	36.18	30.77	21	5.4	8	0.0	5.3	a	0.0	0.0	–
1975/09/12	131017	36.21	21.74	6	4.9	16	5.4	5.0	a	0.0	4.5	N

Table 1. Continued

Date	Time	Lat N	Lon E	h(km)	M_w	Ref M_o	M	M_{LGR}	Ref	M_{LSM}	M_S	r
1975/09/22	004500	35.38	26.35	0	5.6	6	5.5	5.1	a	0.0	0.0	–
1976/05/11	165945	37.40	20.40	29	6.4	17	6.5	0.0	–	0.0	6.4	N
1977/08/18	092743	35.32	23.43	0	5.7	6	5.6	5.2	a	0.0	5.3	N
1977/09/11	231919	34.90	23.00	4	5.8	17	6.3	5.9	a	0.0	6.0	N
1977/11/03	022257	42.09	24.00	10	5.5	17	5.4	5.6	a	0.0	5.1	N
1977/11/28	025910	35.96	27.79	81	5.4	17	5.8	5.2	a	0.0	0.0	–
1978/03/07	223346	34.33	25.11	27	5.5	17	5.7	5.1	a	0.0	5.0	I
1978/05/23	233412	40.68	23.34	6	5.8	17	5.8	5.4	a	0.0	5.8	I
1978/06/19	103108	40.73	23.28	30	5.3	17	5.3	4.1	a	0.0	5.1	I
1978/06/20	200321	40.71	23.27	6	6.2	17	6.5	6.0	a	6.4	6.4	I
1979/04/09	021021	41.91	19.01	0	5.4	17	5.4	5.0	a	0.0	5.2	I
1979/04/15	061941	41.97	19.00	1	6.9	17	7.1	6.8	a	0.0	6.9	I
1979/04/15	144307	42.21	18.68	10	5.8	17	5.8	0.0	–	0.0	5.8	I
1979/05/15	065923	34.54	24.50	27	6.1	17	5.7	5.4	a	0.0	5.4	I
1979/05/24	172320	42.12	18.71	2	6.2	17	6.3	0.0	–	0.0	6.4	I
1979/06/14	114445	38.74	26.50	11	5.8	17	5.9	5.5	a	0.0	5.7	I
1979/06/15	113416	34.85	24.04	17	5.4	17	5.6	5.1	a	0.0	4.9	I
1979/06/16	184159	38.69	26.54	10	5.3	17	5.1	4.8	a	0.0	5.0	I
1979/07/18	131203	39.61	28.61	4	5.3	17	5.4	5.2	a	0.0	4.9	I
1979/07/23	114154	35.43	26.33	14	5.6	17	5.5	5.1	a	0.0	5.2	I
1979/08/22	201248	35.90	27.39	89	5.3	17	5.4	4.9	a	0.0	4.2	I
1980/05/02	053109	36.35	29.39	0	5.8	17	5.3	0.0	–	0.0	5.3	I
1980/05/18	200306	43.43	21.37	10	5.9	17	0.0	0.0	–	0.0	5.9	I
1980/07/09	021157	39.27	23.83	16	6.6	17	6.5	6.0	a	0.0	6.3	I
1980/07/10	193902	39.27	22.98	6	5.6	17	5.4	5.0	a	0.0	5.5	I
1980/08/11	091559	39.30	22.82	3	5.2	17	5.3	4.7	a	5.7	4.8	I
1981/02/24	205337	38.22	22.92	5	6.6	17	6.7	6.3	a	6.7	6.6	I
1981/02/25	023551	38.14	23.09	2	6.3	17	6.4	5.9	a	0.0	6.3	I
1981/03/04	215805	38.20	23.25	6	6.2	17	6.4	5.8	a	0.0	6.4	I
1981/03/05	065907	38.22	23.15	9	5.4	17	5.5	4.6	a	0.0	5.3	I
1981/03/07	113443	38.20	23.27	4	5.4	17	5.5	5.1	a	0.0	4.7	I
1981/03/10	151618	39.31	20.74	1	5.4	17	5.6	5.3	a	0.0	4.7	I
1981/06/24	184127	37.87	20.10	4	5.2	17	5.3	5.2	a	0.0	4.6	I
1981/06/28	172023	37.81	20.06	15	5.4	17	5.6	5.2	t	0.0	5.2	I
1981/09/13	232525	34.76	25.07	1	5.5	17	5.2	4.9	a	0.0	5.1	I
1981/12/19	141051	39.00	25.26	14	6.8	17	7.2	6.3	a	0.0	7.2	I
1981/12/27	173914	38.81	24.94	19	6.3	17	6.5	6.0	a	0.0	6.5	I
1981/12/29	080045	38.71	24.84	5	5.4	17	5.4	5.4	a	0.0	5.4	I
1982/01/18	192725	39.78	24.50	11	6.6	17	7.0	6.4	a	0.0	6.9	I
1982/06/22	030430	37.04	21.20	42	5.4	17	5.7	5.0	t	0.0	5.4	I
1982/08/17	222225	33.74	22.82	30	6.3	17	6.4	5.7	a	0.0	6.6	I
1982/11/16	234121	40.77	19.56	9	5.6	17	5.7	5.3	a	0.0	5.7	I
1983/01/03	001225	34.53	24.31	70	5.1	17	5.5	4.8	a	0.0	0.0	–
1983/01/17	124131	38.10	20.20	7	6.8	17	7.0	6.2	a	6.7	7.0	I
1983/01/19	000213	38.15	20.22	0	5.8	17	5.7	5.5	a	5.6	5.6	I
1983/01/31	152701	38.18	20.39	4	5.4	17	5.3	5.3	a	5.4	5.0	I
1983/02/21	001308	37.86	20.13	15	5.3	17	5.4	5.1	a	0.0	4.9	I
1983/03/19	214139	34.68	25.33	63	5.6	17	5.7	5.2	a	0.0	5.0	I
1983/03/23	235106	38.20	20.30	1	6.2	17	6.2	5.7	a	6.0	6.2	I

Table 1. Continued

Date	Time	Lat N	Lon E	h(km)	M_w	Ref M_o	M	M_{LGR}	Ref	M_{LSM}	M_S	r
1983/03/24	041731	38.10	20.29	7	5.4	17	5.5	5.1	a	5.6	5.1	I
1983/05/14	231347	38.44	20.33	5	5.4	17	5.4	5.0	a	0.0	5.4	I
1983/07/05	120127	40.30	27.20	10	6.1	17	6.1	5.9	a	0.0	5.8	I
1983/07/14	025419	35.67	21.81	27	5.3	17	5.3	5.2	a	0.0	5.1	I
1983/08/06	154352	40.00	24.70	8	6.6	17	6.8	5.9	t	6.4	6.9	I
1983/08/26	125210	40.46	23.96	9	5.1	17	4.9	5.1	t	5.7	4.8	I
1983/09/27	235939	36.72	26.93	159	5.4	17	5.6	5.2	a	0.0	0.0	–
1983/10/10	101700	40.23	25.32	21	5.4	17	5.5	5.4	a	0.0	5.1	I
1983/10/21	203449	40.10	29.33	3	5.4	17	5.1	0.0	–	0.0	4.9	I
1984/02/11	080249	38.37	22.09	0	5.6	17	5.6	5.1	a	0.0	5.5	I
1984/05/06	091202	38.77	25.64	3	5.4	17	5.4	4.9	a	0.0	5.2	I
1984/05/13	124600	42.97	17.58	10	5.4	17	0.0	0.0	–	0.0	5.1	I
1984/05/22	135706	35.87	22.45	45	5.1	17	5.3	4.7	a	0.0	3.9	I
1984/06/17	074802	38.79	25.73	11	5.1	17	5.6	4.8	t	0.0	4.5	I
1984/06/21	104343	35.40	23.30	0	6.2	17	6.2	5.9	a	0.0	5.9	I
1984/07/09	185711	40.65	21.89	5	5.2	17	5.3	4.9	a	5.4	5.1	I
1985/01/16	233559	40.67	19.22	9	5.2	18	5.4	5.0	a	0.0	5.0	I
1985/04/21	084941	35.63	22.02	40	5.3	17	5.4	5.1	a	0.0	5.3	I
1985/04/30	181412	39.26	22.89	6	5.6	17	5.8	5.3	a	0.0	5.5	I
1985/05/23	160221	36.52	22.15	6	5.2	17	5.3	4.7	a	0.0	5.0	I
1985/07/22	213237	34.69	28.30	42	5.2	17	5.7	4.9	t	0.0	4.0	I
1985/09/07	102049	37.37	21.23	5	5.4	17	5.6	4.9	t	0.0	5.3	I
1985/09/27	163956	35.01	26.57	21	5.6	17	5.5	5.0	a	0.0	5.2	I
1985/09/28	145016	41.51	22.32	0	5.2	17	5.2	4.6	t	0.0	0.0	–
1985/11/09	233043	41.22	24.02	8	5.2	17	5.5	4.8	t	5.8	5.3	I
1985/11/21	215714	41.68	19.37	1	5.5	17	5.7	4.9	t	0.0	5.3	I
1986/02/21	053956	42.92	25.97	21	5.4	17	0.0	4.9	t	0.0	5.5	I
1986/03/03	012405	41.95	20.33	2	4.9	17	0.0	4.7	a	0.0	5.0	I
1986/03/25	014135	38.34	25.19	3	5.5	17	0.0	5.0	t	0.0	5.5	I
1986/03/29	183638	38.37	25.17	1	5.3	18	0.0	5.2	t	0.0	5.4	I
1986/05/22	195218	34.25	26.55	36	5.5	17	0.0	4.7	t	0.0	5.2	I
1986/06/08	045502	36.02	21.47	94	5.1	17	0.0	4.8	t	0.0	4.9	I
1986/09/13	172434	37.05	22.11	9	5.9	17	0.0	5.7	t	6.2	5.8	I
1986/10/02	101243	34.62	28.53	122	5.2	17	0.0	4.9	a	0.0	4.4	I
1986/10/11	090012	37.91	28.53	0	5.6	17	0.0	5.5	t	0.0	5.4	I
1986/12/07	141711	43.01	26.01	15	5.6	17	0.0	0.0	–	0.0	5.7	I
1987/02/27	233453	38.42	20.36	1	5.7	17	0.0	5.2	t	0.0	5.6	I
1987/04/12	024719	35.36	23.32	99	5.1	17	0.0	4.9	t	0.0	0.0	–
1987/05/29	184031	37.45	21.53	50	5.2	17	0.0	5.0	t	0.0	4.6	I
1987/06/10	145011	37.17	21.39	15	5.3	17	0.0	4.9	t	0.0	5.0	I
1987/06/19	184542	36.80	28.18	85	5.3	17	0.0	4.6	t	0.0	0.0	–
1988/01/09	010247	41.16	19.68	8	5.9	17	0.0	5.1	t	0.0	5.7	I
1988/04/24	204934	40.83	28.24	12	5.3	17	0.0	5.2	t	0.0	5.1	I
1988/05/18	051742	38.36	20.42	5	5.3	17	0.0	5.1	t	0.0	4.9	I
1988/09/05	200327	34.27	26.59	97	5.2	17	0.0	4.7	a	0.0	5.2	I
1988/10/16	123404	37.91	21.06	9	5.8	17	0.0	5.5	t	6.1	5.8	I
1988/11/20	210109	35.35	28.92	87	5.4	17	0.0	5.0	a	0.0	4.8	I
1989/02/19	142846	37.04	27.98	1	5.4	17	0.0	4.2	t	0.0	4.7	I
1989/02/24	004034	37.73	29.26	0	5.3	17	0.0	4.8	t	0.0	4.7	I

Table 1. Continued

Date	Time	Lat N	Lon E	h(km)	M_w	Ref M_o	M	M_{LGR}	Ref	M_{LSM}	M_S	r
1989/03/17	054254	34.55	25.44	56	5.7	17	0.0	5.1	t	0.0	5.0	I
1989/03/19	053659	39.23	23.57	5	5.4	17	0.0	5.3	a	0.0	5.4	I
1989/03/28	132910	33.91	24.55	94	5.5	17	0.0	4.9	a	0.0	5.2	I
1989/04/27	230652	37.06	28.03	2	5.5	17	0.0	5.0	t	0.0	5.0	I
1989/04/28	133019	37.06	28.01	3	5.5	17	0.0	4.9	t	0.0	5.1	I
1989/06/07	194553	38.00	21.63	5	5.2	17	0.0	4.5	t	0.0	4.9	I
1989/06/14	180637	33.96	26.03	99	5.5	17	0.0	4.8	a	0.0	5.0	I
1989/08/20	183230	37.26	21.14	2	5.8	17	0.0	5.3	t	0.0	5.7	I
1989/08/24	021314	37.94	20.14	3	5.2	17	0.0	5.2	t	0.0	4.8	I
1989/08/27	012114	34.59	26.30	104	5.6	17	0.0	4.9	t	0.0	4.8	I
1989/09/05	065231	40.15	25.09	10	5.4	17	0.0	4.9	t	0.0	4.9	I
1990/06/16	021620	39.30	20.60	0	5.5	17	0.0	5.5	a	0.0	5.3	I
1990/07/09	112216	34.80	26.72	17	5.4	17	0.0	5.0	t	0.0	5.0	I
1990/07/18	112925	37.04	29.51	0	5.5	17	0.0	5.0	d	0.0	4.9	I
1990/12/21	065743	40.92	22.36	8	6.1	17	0.0	5.4	t	6.3	6.0	I
1991/03/19	120923	34.67	26.36	4	5.5	17	0.0	5.2	t	0.0	4.5	I
1991/06/26	114333	38.34	21.04	4	5.3	17	0.0	4.7	t	0.0	5.2	I
1991/10/18	140455	35.71	28.56	20	5.0	17	0.0	4.8	t	0.0	4.3	I
1992/01/23	042418	38.40	20.57	2	5.6	17	0.0	4.9	t	0.0	5.2	I
1992/03/20	053725	36.65	24.51	15	5.2	17	0.0	5.0	t	0.0	5.0	I
1992/04/30	114440	35.10	26.60	19	5.7	17	0.0	5.6	t	0.0	5.6	I
1992/07/23	201244	39.81	24.40	15	5.4	17	0.0	5.0	t	0.0	5.1	I
1992/11/06	190810	38.19	27.05	15	6.0	17	0.0	5.4	t	0.0	6.0	I
1992/11/18	211042	38.34	22.44	5	5.9	17	0.0	5.4	t	0.0	5.7	I
1992/11/21	050719	35.65	22.39	65	5.9	17	0.0	5.3	t	0.0	0.0	–
1993/03/05	065506	37.05	21.50	3	5.2	17	0.0	4.8	t	0.0	5.1	I
1993/03/18	154700	38.28	22.14	73	5.8	17	0.0	5.0	t	0.0	5.2	I
1993/03/26	115818	37.66	21.30	14	5.4	17	0.0	4.8	t	6.0	5.1	I
1993/06/13	232640	39.28	20.49	3	5.3	17	0.0	4.8	t	0.0	5.1	I
1993/07/14	123149	38.17	21.77	2	5.6	17	0.0	4.8	t	5.6	5.4	I
1993/11/04	051837	38.37	22.05	3	5.3	17	0.0	4.9	t	0.0	5.2	I
1994/01/11	072251	35.83	21.83	33	5.5	17	0.0	5.0	t	0.0	5.4	I
1994/01/28	154525	38.67	27.47	3	5.4	17	0.0	4.9	t	0.0	5.1	I
1994/02/25	023049	38.76	20.56	0	5.4	17	0.0	5.1	t	0.0	5.1	I
1994/04/16	230934	37.36	20.63	10	5.5	17	0.0	5.2	t	0.0	5.3	I
1994/05/23	064612	35.00	24.90	80	6.0	17	0.0	5.3	t	0.0	0.0	–
1994/05/24	020539	38.83	26.49	22	5.5	17	0.0	5.0	t	0.0	5.2	I
1994/11/13	065602	36.92	28.99	12	5.3	17	0.0	4.9	t	0.0	4.9	I
1994/11/29	143030	38.87	20.48	9	5.1	17	0.0	4.7	t	0.0	4.9	I
1995/01/02	123608	38.32	22.31	1	4.5	19	0.0	3.8	t	0.0	0.0	–
1995/01/03	225148	35.14	23.25	17	4.9	20	0.0	4.2	t	0.0	3.9	I
1995/01/07	203049	37.90	19.93	5	4.9	20	0.0	4.6	t	0.0	4.6	I
1995/01/23	173500	38.26	22.08	0	4.2	19	0.0	3.6	t	0.0	0.0	–
1995/02/03	222909	34.06	24.95	41	4.8	20	0.0	4.6	t	0.0	3.9	I
1995/02/16	130218	34.32	26.56	15	5.0	20	0.0	4.7	t	0.0	4.0	I
1995/03/30	181716	34.33	24.56	2	4.8	20	0.0	4.6	a	0.0	4.2	I
1995/04/04	171010	40.54	23.62	8	4.5	19	0.0	4.1	t	4.8	0.0	–
1995/05/03	141641	40.55	23.66	8	4.2	19	0.0	3.9	t	4.3	0.0	–
1995/05/03	153956	40.54	23.64	7	4.5	19	0.0	4.2	t	4.5	0.0	–

Table 1. Continued

Date	Time	Lat N	Lon E	h(km)	M_w	Ref M_o	M	M_{LGR}	Ref	M_{LSM}	M_S	r
1995/05/03	213654	40.54	23.64	8	4.6	20	0.0	4.5	t	5.0	4.7	I
1995/05/03	214327	40.55	23.66	11	4.7	20	0.0	4.6	t	5.2	4.7	I
1995/05/04	003410	40.54	23.63	9	5.3	17	0.0	5.0	a	5.6	5.1	I
1995/05/04	004341	40.54	23.59	5	4.4	19	0.0	3.6	t	4.1	0.0	–
1995/05/08	051107	38.33	22.18	7	4.6	20	0.0	4.0	t	0.0	0.0	–
1995/05/09	011438	40.75	20.81	11	4.9	20	0.0	4.7	t	0.0	4.2	I
1995/05/13	084715	40.16	21.67	14	6.5	17	0.0	6.1	t	6.3	6.6	I
1995/05/13	105834	40.08	21.56	8	5.0	20	0.0	4.5	t	0.0	0.0	–
1995/05/13	114330	40.13	21.63	12	5.2	20	0.0	4.4	t	0.0	4.7	I
1995/05/13	180600	40.13	21.62	13	4.6	20	0.0	4.3	t	0.0	4.4	I
1995/05/13	190049	40.12	21.79	7	4.7	20	0.0	4.1	t	0.0	4.2	I
1995/05/13	235626	40.00	21.57	6	4.8	20	0.0	4.3	t	0.0	4.2	I
1995/05/14	024700	40.06	21.56	6	4.9	17	0.0	4.2	t	0.0	4.6	I
1995/05/14	030937	40.09	21.61	6	4.6	20	0.0	4.1	t	0.0	4.5	I
1995/05/14	055915	40.06	21.49	4	4.6	20	0.0	4.2	t	0.0	4.3	I
1995/05/14	083510	40.11	21.47	5	4.4	20	0.0	3.8	t	0.0	4.7	I
1995/05/14	094541	40.14	21.65	14	4.0	19	0.0	3.9	t	0.0	0.0	–
1995/05/14	213111	40.04	21.60	5	4.0	19	0.0	3.7	t	0.0	0.0	–
1995/05/15	041355	40.06	21.62	9	5.2	17	0.0	4.6	t	5.1	4.9	I
1995/05/15	081700	40.11	21.52	3	4.5	20	0.0	4.0	t	4.7	0.0	–
1995/05/15	090151	40.06	21.54	6	4.5	20	0.0	3.6	t	0.0	0.0	–
1995/05/15	091944	40.12	21.45	20	4.4	20	0.0	3.9	t	0.0	0.0	–
1995/05/16	043727	39.99	21.51	5	4.8	20	0.0	4.0	t	0.0	0.0	–
1995/05/16	230041	40.00	21.55	6	4.7	19	0.0	4.2	t	4.9	0.0	–
1995/05/16	235727	40.06	21.57	12	5.1	19	0.0	4.4	t	5.0	0.0	–
1995/05/17	041424	40.05	21.58	9	5.2	19	0.0	4.8	t	5.3	5.0	I
1995/05/19	064849	40.01	21.58	7	5.1	17	0.0	4.6	t	5.2	4.9	I
1995/05/20	200930	39.94	21.52	7	4.5	20	0.0	3.8	t	0.0	0.0	–
1995/05/21	040421	39.99	21.46	13	4.3	20	0.0	3.9	t	0.0	0.0	–
1995/05/23	043739	40.08	21.54	8	4.3	20	0.0	3.7	t	0.0	0.0	–
1995/05/24	062408	39.96	21.50	8	4.5	20	0.0	3.9	t	0.0	0.0	–
1995/05/24	161854	40.08	21.59	5	3.5	21	0.0	3.2	t	0.0	0.0	–
1995/05/24	173426	40.08	21.59	4	4.0	21	0.0	3.6	t	0.0	0.0	–
1995/05/24	192905	40.08	21.59	6	3.5	21	0.0	3.1	t	0.0	0.0	–
1995/05/24	212243	40.08	21.54	6	3.5	21	0.0	3.2	t	0.0	0.0	–
1995/05/25	014027	40.05	21.60	6	3.3	21	0.0	3.2	t	0.0	0.0	–
1995/05/25	040544	39.99	21.52	6	3.6	21	0.0	3.5	t	0.0	0.0	–
1995/05/25	043507	40.08	21.58	7	3.5	21	0.0	3.3	t	0.0	0.0	–
1995/05/25	084853	40.07	21.68	8	3.5	21	0.0	3.1	t	0.0	0.0	–
1995/05/25	213719	40.03	21.61	7	3.5	21	0.0	3.0	t	0.0	0.0	–
1995/05/25	231216	40.14	21.78	12	3.7	21	0.0	3.1	t	0.0	0.0	–
1995/05/27	055255	40.01	21.53	14	3.6	21	0.0	3.2	t	0.0	0.0	–
1995/05/28	195640	38.39	22.00	6	4.7	20	0.0	4.3	t	0.0	4.2	I
1995/05/30	062106	40.08	21.47	13	3.6	21	0.0	3.4	t	0.0	0.0	–
1995/05/30	064600	40.10	21.49	9	3.6	21	0.0	3.4	t	0.0	0.0	–
1995/05/30	120642	40.05	21.64	6	4.0	21	0.0	3.9	t	0.0	0.0	–
1995/05/30	143001	39.97	21.56	6	4.0	21	0.0	3.9	t	0.0	0.0	–
1995/06/01	101727	39.98	21.50	9	3.6	21	0.0	3.2	t	0.0	0.0	–
1995/06/02	074714	40.02	21.53	6	3.7	21	0.0	3.5	t	0.0	0.0	–
1995/06/03	102014	40.12	21.58	6	3.6	21	0.0	3.4	t	0.0	0.0	–

Table 1. Continued

Date	Time	Lat N	Lon E	h(km)	M_w	Ref M_o	M	M_{LGR}	Ref	M_{LSM}	M_S	r
1995/06/05	052019	39.45	20.26	15	4.3	20	0.0	4.2	t	0.0	3.7	I
1995/06/06	004651	40.16	21.60	11	3.6	21	0.0	3.2	t	0.0	0.0	–
1995/06/06	043558	40.13	21.58	10	4.2	21	0.0	4.3	t	4.8	0.0	–
1995/06/09	152048	40.12	21.61	4	3.8	21	0.0	3.8	t	0.0	0.0	–
1995/06/11	172010	40.13	21.61	14	3.7	21	0.0	3.5	t	0.0	0.0	–
1995/06/11	185146	39.95	21.53	9	4.8	20	0.0	4.3	t	4.9	0.0	–
1995/06/11	203821	39.95	21.55	9	3.7	21	0.0	3.5	t	0.0	0.0	–
1995/06/12	031950	39.95	21.51	11	3.6	21	0.0	3.0	t	0.0	0.0	–
1995/06/15	001549	38.37	22.15	11	6.5	17	0.0	5.8	t	0.0	6.4	I
1995/06/15	011620	38.34	22.19	10	3.5	19	0.0	3.2	t	0.0	0.0	–
1995/06/15	045118	38.27	22.22	10	4.6	20	0.0	4.1	t	0.0	4.3	N
1995/06/15	070101	38.42	22.25	2	4.5	20	0.0	3.8	t	0.0	0.0	–
1995/06/15	104149	38.32	22.18	9	3.8	19	0.0	3.5	t	0.0	0.0	–
1995/06/17	142028	38.35	22.27	13	4.0	19	0.0	3.6	t	0.0	0.0	–
1995/06/18	011405	38.36	22.13	8	3.9	19	0.0	3.4	t	0.0	0.0	–
1995/06/18	042824	38.38	22.23	0	4.3	19	0.0	3.6	t	0.0	0.0	–
1995/06/19	035358	39.99	21.82	7	4.7	19	0.0	3.9	t	0.0	3.9	I
1995/06/19	150020	39.98	21.80	8	4.1	20	0.0	3.7	t	0.0	0.0	–
1995/06/20	143832	38.36	22.10	11	3.5	19	0.0	3.1	t	0.0	0.0	–
1995/07/01	215804	38.31	22.17	6	4.2	19	0.0	3.8	t	0.0	0.0	–
1995/07/03	222959	38.28	22.32	0	4.6	19	0.0	4.1	t	0.0	0.0	–
1995/07/05	182437	38.38	22.11	8	4.6	19	0.0	4.1	t	0.0	4.9	I
1995/07/10	181238	38.44	22.10	11	4.1	19	0.0	3.8	t	0.0	0.0	–
1995/07/15	093700	38.49	22.26	3	3.8	19	0.0	3.5	t	0.0	0.0	–
1995/07/17	231814	40.08	21.52	14	5.2	17	0.0	5.0	t	5.1	4.8	I
1995/07/18	074253	40.10	21.58	10	4.5	19	0.0	4.2	t	4.7	0.0	–
1995/07/19	182314	40.09	21.62	9	4.8	19	0.0	4.0	t	0.0	0.0	–
1995/09/28	234443	42.62	18.15	0	5.2	17	0.0	5.0	t	0.0	5.0	I
1995/10/01	155712	38.06	30.15	5	6.4	17	0.0	5.6	t	0.0	6.1	I
1995/12/07	180053	34.73	23.94	9	5.6	17	0.0	4.8	t	0.0	4.8	I
1995/12/10	032749	34.76	23.99	17	5.2	17	0.0	4.9	t	0.0	4.7	I
1996/02/01	175759	37.77	20.05	15	5.3	17	0.0	4.9	t	0.0	4.9	I
1996/04/02	075926	37.84	26.87	17	5.4	17	0.0	4.5	t	0.0	5.0	I
1996/04/12	153911	36.59	27.04	162	5.2	17	0.0	4.7	t	0.0	0.0	–
1996/04/26	070128	36.34	27.96	72	5.4	17	0.0	5.3	a	0.0	0.0	–
1996/07/20	000039	36.07	27.46	10	6.2	17	0.0	5.5	t	0.0	6.0	I
1996/07/22	014439	36.21	27.32	43	5.0	17	0.0	4.0	t	0.0	4.4	I
1996/07/26	185550	40.08	20.64	1	5.3	17	0.0	4.5	t	0.0	5.0	I
1996/09/05	204413	42.48	17.95	10	6.0	17	0.0	5.0	t	0.0	5.9	I
1996/09/09	155709	42.70	17.75	42	5.3	17	0.0	4.4	t	0.0	4.9	I
1996/09/17	134524	42.90	17.65	30	5.4	17	0.0	4.9	t	0.0	5.1	I
1997/01/21	204751	38.14	28.89	31	5.2	17	0.0	4.9	t	0.0	4.5	I
1997/05/16	070051	40.91	20.42	8	5.3	17	0.0	4.8	t	0.0	5.3	I
1997/07/27	100752	35.51	21.18	14	5.5	17	0.0	5.1	t	0.0	4.8	I
1997/10/13	133939	36.45	22.16	13	6.4	17	0.0	5.8	t	6.3	6.5	I
1997/11/05	122253	34.51	23.93	20	5.4	17	0.0	4.8	t	0.0	4.7	I
1997/11/05	211028	38.40	22.45	0	5.6	17	0.0	4.9	t	0.0	5.4	I
1997/11/14	213851	38.73	25.91	20	5.8	17	0.0	5.1	t	0.0	5.8	I
1997/11/18	130741	37.58	20.57	10	6.6	17	0.0	6.1	t	6.7	6.5	I

Table 1. Continued

Date	Time	Lat N	Lon E	h(km)	M_w	Ref M_o	M	M_{LGR}	Ref	M_{LSM}	M_S	r
1997/12/02	192246	36.68	19.40	15	5.2	17	0.0	4.6	t	0.0	4.4	I
1998/01/10	192157	37.29	20.86	10	5.4	17	0.0	5.0	t	0.0	5.1	I
1998/03/09	112122	36.02	28.53	50	5.1	17	0.0	4.8	t	0.0	4.2	I
1998/04/04	161652	38.10	30.16	15	5.2	17	0.0	0.0	–	0.0	4.6	I
1998/04/29	033037	35.96	21.88	10	5.5	17	0.0	5.1	t	0.0	5.2	I
1998/05/01	040014	37.62	20.75	10	5.3	17	0.0	4.7	t	0.0	4.9	I
1998/09/30	234258	41.83	20.65	10	5.3	17	0.0	4.6	t	0.0	5.0	I
1998/10/06	122741	37.13	20.98	0	5.4	17	0.0	4.8	t	0.0	5.3	I
1998/10/07	184740	33.80	25.58	38	5.1	17	0.0	4.4	t	0.0	4.7	I
1999/04/17	081758	36.03	21.59	20	5.3	17	0.0	4.8	t	0.0	5.0	I
1999/04/30	033046	43.75	20.20	15	5.4	17	0.0	4.9	t	0.0	4.8	N
1999/06/11	075016	37.70	21.27	21	5.2	17	0.0	4.7	t	0.0	0.0	–
1999/07/01	074103	43.58	21.01	15	5.2	17	0.0	0.0	–	0.0	4.8	N
1999/07/25	065656	38.96	28.19	15	5.2	17	0.0	4.7	t	0.0	4.9	N
1999/08/17	000150	41.01	29.97	17	7.6	17	0.0	7.1	t	0.0	7.8	N
1999/08/19	151747	40.68	29.10	15	5.1	17	0.0	4.6	t	0.0	4.7	N
1999/08/31	081051	40.43	30.25	15	5.1	17	0.0	0.0	–	0.0	4.9	N
1999/09/07	115651	38.06	23.54	16	6.0	17	0.0	5.4	t	5.9	5.8	N
1999/09/13	115532	40.42	30.24	15	5.8	17	0.0	0.0	–	0.0	5.8	N
1999/09/29	001310	40.55	29.69	15	5.2	17	0.0	5.1	t	0.0	4.5	N
1999/10/05	005328	36.85	28.24	6	5.2	17	0.0	4.8	t	0.0	4.6	N
1999/11/11	144130	40.95	30.10	15	5.6	17	0.0	5.2	t	0.0	5.5	N
1999/12/22	090615	41.81	20.78	1	5.1	17	0.0	4.2	t	0.0	4.7	N
2000/02/22	115532	34.95	25.38	7	5.3	17	0.0	4.9	t	0.0	4.9	N
2000/03/10	220148	34.13	25.98	15	5.2	17	0.0	0.0	–	0.0	5.1	N
2000/04/05	043658	34.08	25.83	15	5.5	17	0.0	5.1	t	0.0	5.4	N
2000/04/21	122310	37.78	29.39	15	5.4	17	0.0	4.6	t	0.0	4.8	N
2000/05/24	054038	35.92	21.87	20	5.7	17	0.0	5.2	t	0.0	5.6	N
2000/05/24	100145	35.92	21.79	15	5.2	17	0.0	4.4	t	0.0	0.0	–
2000/05/26	012822	38.92	20.64	0	5.5	17	0.0	4.8	t	0.0	5.4	N
2000/06/13	014318	35.17	27.17	10	5.4	17	0.0	4.9	t	0.0	5.0	N
2000/06/15	213036	34.81	20.22	0	5.1	17	0.0	4.8	t	0.0	4.1	N
2001/05/01	060056	35.65	27.61	29	4.9	22	0.0	4.7	t	0.0	0.0	–
2001/05/29	044400	35.56	27.83	0	5.2	22	0.0	4.5	t	0.0	0.0	–

Ref M_o: 1. Papadimitriou (1993), 2. North (1977), 3. Taymaz et al. (1991), 4. Baker et al. (1997), 5. Bezzeghoud (1987), 6. Taymaz et al. (1990), 7. Lyon-Caen et al. (1988), 8. Yilmazturk and Burton (1999), 9. Kiratzi et al. (1991), 10. Eyidogan and Jackson (1985), 11. Braunmiller and Nabelek (1996), 12. Liotier (1989), 13. Taymaz and Price (1992), 14. Kiratzi and Langston (1989), 15. Ioannidou (1989), 16. Prochazkova (1979), 17. CMT Solutions, 18. Louvari (2000), 19. Chouliaras and Stavrakakis (1997), 20. Arvidsson and Ekström (1998), 21. Roumelioti et al. (2002), 22. GFZ Potsdam.

moment, M_o. In the seventh column the appropriate M_o reference is given. For the sake of homogeneity, the Harvard CMT catalogue was used as the basic source of information. In the case where such information was not available, M_o values were taken from other sources. The magnitudes, M, calculated by relations (1) and (2) using the records of the Wiechert or Mainka seismographs, are given in the eighth column. The values of these magnitudes were taken from the catalogue of Comninakis and Papazachos (1986). Magnitudes, M_{LGR}, ranging from 3.0 to 7.1, are listed in the ninth column. The basic source for these magnitudes was the bulletins of the Geophysical Laboratory of the University of Thessaloniki. If no such values were available, the M_{LGR} magnitudes were taken from the bulletins of the Geodynamic Institute of the National Observatory of Athens. Codes t, a and d, given in the tenth column, denote M_{LGR} mag-

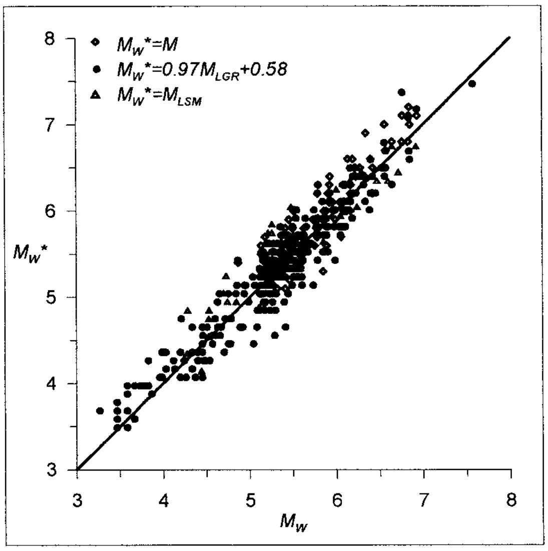

Figure 2. Moment magnitudes, M_W*, calculated by relations (3, 4 and 6 using the values M, M_{LGR}, M_{LSM}) versus the corresponding moment magnitude, M_W. The straight line is for M_W* = M_W.

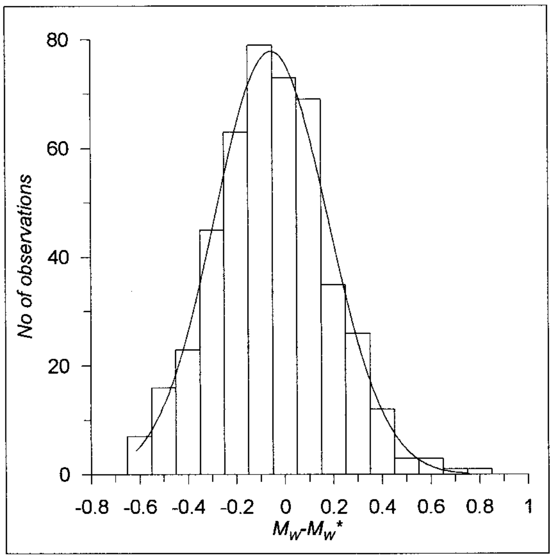

Figure 3. Histogram of the frequency distribution of the differences M_W-M_W*.

nitudes calculated from the short-period seismographs of the Geophysical Laboratory of the University of Thessaloniki, from the amplitudes recorded at the Wood Anderson seismograph of the National Observatory of Athens (NOA), and from the signal durations recorded at short period instruments of NOA, respectively. Magnitudes, M_{LSM} calculated from strong motion records are listed in the eleventh column and range from 4.1 to 6.7. These magnitudes have been calculated by Margaris and Papazachos (1999). In the last two columns of Table 1, M_s magnitudes taken from the bulletins of ISC, USCGS and NEIC are shown together with a code denoting the source from which the magnitude has been taken (I for ISC and N for USCGS or NEIC). The reported M_s magnitudes range from 3.7 to 7.8.

Comparison of moment magnitude values calculated by different Institutes for the same earthquake shows a zero average bias with an average standard error of $\sigma_W = 0.10$ for the earthquakes listed on Table 1. The corresponding value for M_{LGR} comparison as it is calculated by Athens (National Observatory) and Thessaloniki (Geophysical Laboratory) is σ_{MLGR} = 0.24. These standard errors give a preliminary idea about the robustness and the relative estimation errors of the magnitude scales later discussed.

Results

Figure 2 shows a plot of magnitudes M_w* calculated by relations (3), (4) and (6), using the values M, M_{LGR}, M_{LSM}, versus the corresponding moment magnitude, M_w, listed in Table 1. The M_w = M_w* line is also shown. Figure 3 shows the frequency histogram of the M_w-M_w* differences, fitted by a normal distribution which has an almost zero mean (= 0.05) and a standard deviation of 0.23. Therefore, for all practical purposes, we can consider that:

$$M_w^* = M_w, \quad \sigma = 0.23 \quad 3.3 \leq M_w \leq 7.6 \qquad (7)$$

The corresponding standard deviations for M_w* calculated by the use of relations (3), (4), (6) are 0.20, 0.24, 0.25, respectively. These values indicate that magnitudes M_w* calculated by the use of records of Wiechert or Mainka seismographs (relation 3), or Wood-Anderson/other short period seismographs (relation 4) or by strong motion accelerograms (relation 6) are equivalent to moment magnitude within reasonable uncertainties.

Figure 4 shows a plot of the surface wave magnitudes, M_s, given by ISC or NEIC as listed in Table 1, versus the moment magnitude, M_w. The solid line corresponds to M_s = M_w. It is observed that for $M_w \geq 6.0$ the surface wave magnitude is equal to M_w. The mean of the difference M_w-M_s is 0.0 with a standard deviation of 0.28, that is:

$$M_s^* = M_w, \quad \sigma = 0.28 \quad M_w \geqslant 6.0 \qquad (8)$$

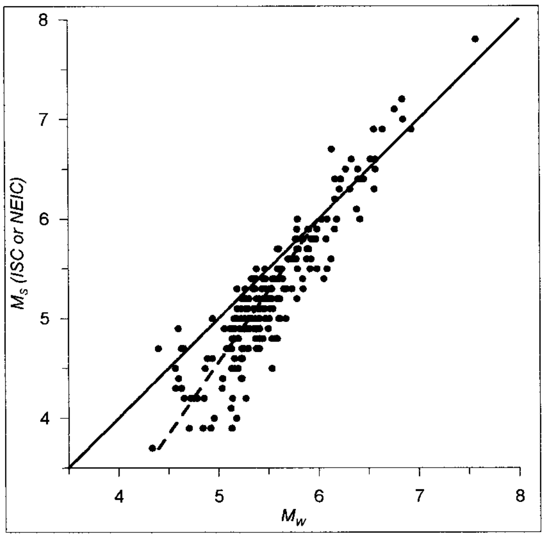

Figure 4. Surface-wave magnitude, M_S given by ISC or NEIC versus the corresponding moment magnitude, M_W. The full line is for surface wave magnitude equal to moment magnitude.

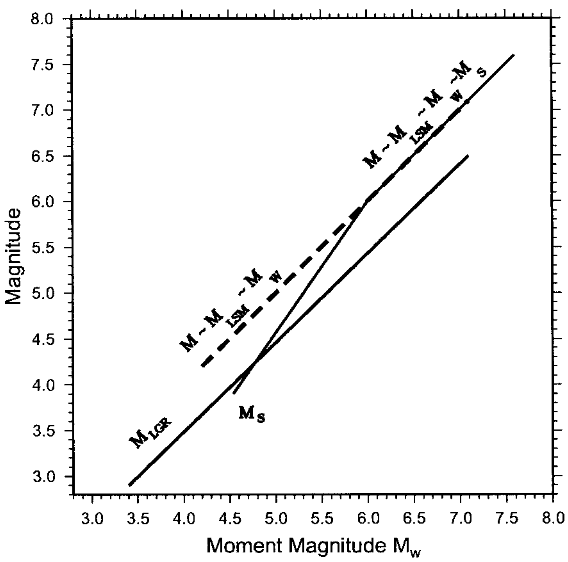

Figure 5. Relation of the magnitudes M, M_{LGR}, M_{LSM} and M_S versus moment magnitude, M_W for earthquakes in the broader Aegean region.

For $M_w < 6.0$ the data approximately follow the relation:

$$M_s^* = 1.44M_w - 2.64, \sigma = 0.30 \; M_w \leq 6.0 \quad (9)$$

which is represented by the dashed line in Figure 4, and is almost identical to relations derived from global datasets (e.g. Heaton, 1986). It should be noted that equation (9) exhibits a larger standard error (σ = 0.30) than the corresponding error (σ = 0.23) found for M_w* using the examined magnitude scales (M, M_{LGR}, M_{LSM}).

Figure 5 shows the variation of M, M_{LGR}, M_{LSM} and M_s versus moment magnitude, M_w, for the magnitude ranges applicable to each scale.

Conclusions and discussion

Instrumental magnitudes included in the two catalogues of the Geophysical Laboratory of the University of Thessaloniki (Comninakis and Papazachos, 1986; Papazachos et al., 2000) are 'equivalent' moment magnitudes, M_w*, derived by the Wiechert or Mainka seismograph records (M_w* = M), or by the Wood-Anderson or other short period seismographs (M_w* = M_{LGR}+0.5). Therefore, according to relation (7), all magnitudes given in these catalogues are equivalent to moment magnitude, within reasonable uncertainties (σ = 0.23). The formulae used to estimate the magnitudes of the historical earthquakes (Papazachos and Papazachou, 1997; Papazachos et al., 2000) included in these catalogues were calibrated on the basis of the instrumentally determined magnitudes. Consequently these catalogues are also homogeneous, since their magnitudes are equivalent moment magnitudes, M_w*.

Ambraseys (2001) calculated M_s magnitudes and compared them with magnitudes (usually denoted with M) published in the catalogue of Comninakis and Papazachos (1986) or in the bulletins of the Geophysical Laboratory of the University of Thessaloniki. The magnitudes of these earthquakes which occurred in Greece and surrounding area between 1901–1993 range between 4.5 and 7.7. From this comparison (see Figure 8a in Ambraseys, 2001) it can be concluded that for $6.0 \leq M \leq 7.7$, the M-M_s difference varies from 0.3 to –0.1, with an average value that is practically zero, within error limits. Therefore, since M_s is equivalent to moment magnitude for this magnitude range (e.g. Heaton et al., 1986) this observation verifies our suggestion that M magnitudes in the Greek catalogues are equivalent to moment magnitudes. Furthermore, in the same Figure a systematic increase of the M-M_s difference is observed with decreasing M for M<6.0. This difference is erroneously interpreted by Ambraseys (2001) as an indicator of a systematic overestimation and problematic behavior of M, since he is misinterpreting these M estimates as being equivalent to M_s. The appropriate interpretation of this behavior is that these M (= M_w*) estimates are equivalent to M_w (not M_s) which is known (e.g. Heaton et al., 1986) to deviate from M_s for $M_w<6.0$, in the same manner as shown in Figure 8a of Ambraseys (2001) and quantitatively described by equation (9). Therefore, Ambraseys' (2001) results fully support our conclusion that M_w* magnitudes included in the Greek catalogues are equivalent to moment magnitudes and contradict his own conclusion that magnitudes included in Greek catalogues of the Geophysical Laboratory of the University of Thessaloniki are systematically overestimated.

The results of the present study suggest that M_w estimations based on conversions from M_s for $M_w<6.0$ are subject to larger estimation errors (σ = 0.30) than the corresponding error (σ = 0.23) when these estimates (M_w*) are based on the locally applied magnitude scales (M, M_{LGR}, M_{LSM}). The poor performance of M_s for $M_w<6.0$ is expected, especially for smaller magnitude events as it can be seen from Figure 4 for $4.3 \leq M_w \leq 5.3$ where the standard error increases up to $\sim$0.35–0.4. This is due to the fact that M_s corresponds roughly to $\sim$20s surface waves which are strongly influenced by the crustal and lithospheric variations between the broader Aegean area and the remote recording stations. On the other hand, local magnitude estimates based on a large number of short- (M_{LGR}, M_{LSM}) or intermediate- (M) period recordings of body-waves at relatively short distances are expected to show a much higher correlation with the M_w values derived from modeling of long-period body-waves which have traveled through the much more homogeneous (on a global scale) mantle. Moreover, this correlation also implies that, the derived M_w* values represent a more reliable measure of earthquake size, compared to M_s, for applications which concern the frequency band of engineering interest. Therefore, the use of M_s in Greece for the estimation of M_w for $M_w<6.0$ (e.g. for seismicity studies), as well as its use for earthquake engineering purposes (e.g. strong motion attenuation studies) should clearly be avoided if an alternative estimate of M_w* based on the magnitude scales M, M_{LGR} and M_{LSM} is available.

Acknowledgements

The authors would like to thank three anonymous reviewers for the valuable and instructive review. This work has been partially financed by EPPO – Greece, (Projects 20237, 20238 and 20246). This is Department of Geophysics contribution 595.

References

Ambraseys, N.N., 2001, Assessment of surface wave magnitudes of earthquakes in Greece, *J. of Seismology* **5**, 103–116.

Ambraseys, N.N. and Jackson, J., 1990, Seismicity and associated strain in central Greece between 1890 and 1998, *Geophys. J. Int.* **101**, 663–708.

Ambraseys, N.N., Simpson, K.A. and Bommer, J.J., 1996, Prediction of horizontal response spectra in Europe, *Earthquake Engin. And Struct. Dyn.* **25**, 371–400.

Arvidsson, R., and G. Ekström, 1998, Global CMT analysis of moderate earthquakes, Mw4.5, using intermediate-period surface waves, *Bull. Seism. Soc. Am.* **88**, 1003–1013.

Baker, C., Hatzfeld, D., Lyon-Caen, H., Papadimitriou, E. and Rigo, A., 1997, Earthquake mechanisms of the Adriatic Sea and western Greece, *Geophys. J. Int.* **131**, 559–594

Bezzeghoud, M., 1987, Inversion et analyse spectrale des ondes, *P. Ph. D. Thesis*, University Paris VII, 232 pp.

Boore, D.M., 1989, The Richter scale: its development and use for determining earthquake source parameters, *Tectonophysics* **166**, 1–14.

Braunmiller, J. and Nabelek, J., 1996, Geometry of continental normal faults: Seismological constraints, *J. Geophys. Res.* **10**, 3045–3052.

Chouliaras, G. and Stavrakakis, G.N., 1997, Seismic source parameters from a new dial-up network in Greece, *Pure Applied Geophysics* **150**, 91–111.

Comninakis, P.E. and Papazachos, B.C., 1986, A catalogue of earthquakes in Greece and surrounding area for the period 1901–1985, *Publ. of the Geophys. Lab., Aristotle University of Thessaloniki* **1**, 172 pp.

Eyidoğǎn, H. and Jackson, J., 1985, A seismological study of normal faulting in the Demirci, Alasehir and Gediz earthquakes of 1969–1970 in western Turkey; implications for the nature and geometry of deformation in the continental crust, *Geophys. J. R. astron. Soc*. **81**, 569–607.

Gutenberg, B., 1945, Amplitudes of surface waves and magnitudes of shallow earthquakes, *Bull. Seism. Soc. Am*. **35**, 3–12.

Hanks, T. and Kanamori, H., 1979, A moment magnitude scale, *J. Geophys. Res*. **84**, 2348–2350.

Heaton, T., Tajima, F. and Mori, A., 1986, Estimating ground motions using recorded accelerograms, *Surv. Geophys*. **8**, 25–83.

Ioannidou, H., 1989, Seismic source parameters by the inversion of body waves: Greece and the surrounding area, *Ph. D. Thesis*, Athens University, 185 pp.

Karnik, V., 1996, Seismicity of Europe and the Mediterranean, *Academy of Sciences of the Czech Republic, Geoph. Inst.*

Kiratzi, A.A., 1984, Magnitude scales for earthquakes in the broader Aegean area, *Ph. D. Thesis,* Aristotle University of Thessaloniki, 189 pp.

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

Kiratzi, A. and Langston, C., 1989, Estimation of earthquake source parameters of the May 4, 1972 event of the Hellenic Arc by the inversion of waveform data, *Phys. Earth Planet. Inter.* **57**, 225–232.

Kiratzi, A., Wagner, G. and Langston, C., 1991, Source parameters of some large earthquakes in the Aegean determined by body waveform inversion, *Pure Applied Geophysics* **105**, 515–527.

Latoussakis, J., 1984, A proposal for a modified relation of frequency-magnitude for earthquakes and a contribution to the study of seismicity in the area of Greece, *Ph. D. Thesis*, University of Athens, 167 pp.

Liotier, Y., 1989, Modelisation des ondes de volume des seismes de l'arc Ageen, *DEA de l'Universite Joseph Fourier, Grenoble, France*.

Louvari, E., 2000, A detailed seismotectonic analysis of the Aegean Sea and the surrounding lands based on the fault plane solutions of small earthquakes, *Ph. D. Thesis,* Aristotle University of Thessaloniki, pp 373.

Lyon Caen, H., Armijo, R., Drakopoulos, J., Baskoutas, J., Delibasis, N., Ganlon, R., Kouskouna, V., Latoussakis, J., Makropoulos, K., Papadimitriou, P., Papanastasiou, D. and Pedotti, G., 1988, The 1986 Kalamata (South Peloponnesus) earthquake: Detailed study of a normal fault, evidence for east-west extension in the Hellenic Arc, *J. Geophys. Res* **93**, 14967–15000.

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

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

North, R., 1977, Seismic moments, source dimensions and stress associated with earthquakes in the Mediterranean and Middle East*, Geophys. J. R. Astr. Soc*. **49**, 137.

Papadimitriou, E.E., 1993, Focal mechanisms along the convex side of the Hellenic Arc, *Bolletino di Geofisica Teorica ed Applicata* **35**, 401–426.

Papanastasiou, D., 1989, Detectability and accuracy of local parameters determination by the seismographic network of the National Observatory of Athens, *Ph.D. Thesis*, Univ. of Athens, 225 pp.

Papazachos, B.C., 1989, Measures of earthquake size in Greece and surrounding area, *Proc. of the 1st Scient. Conf. of Geophysics, Geophys. Soc. of Greece, 19–21 April 1989, Athens*, 438–447.

Papazachos, B.C., and Vasilicou, A., 1966, Studies on the magnitude of earthquakes, *Progress Report in Seismology and Physics of the Earth's Interior*, 1964–1966, 17–18.

Papazachos, B.C. and Comninakis, P.E., 1971, Geophysical and tectonic features of the Aegean arc, *J. Geophys. Res*. **76**, 8517–8533.

Papazachos, B.C., Kiratzi, A.A. and Karakostas, B.G., 1997, Toward a homogeneous moment-magnitude determination for earthquakes in Greece and surrounding area, *Bull. Seism. Soc. Am*. **87**, 474–483.

Papazachos, B.C., Comninakis, P.E., Karakaisis, G.F., Karakostas, V.G., Papaioannou, Ch.A., Papazachos, C.B. and Scordilis, E.M., 2000, A catalogue of earthquakes in Greece and surrounding area for the period 550BC–1999, *Publ. Geophys. Lab. Aristotle Univ. of Thessaloniki* **1**, 338 pp.

Papazachos, B.C. and Papazachou, C.B., 1997, The earthquakes of Greece, *Ziti Editions, Thessaloniki*, 304 pp.

Prochazkova, D., 1979, Determination of source parameters of some European earthquakes on the basis of records of seismic station Kasperske Hory, *Travaux Geophys.* XXVII.

Richter, C., 1935. An instrumental earthquake magnitude scale*, Bull. Seism. Soc. Am*. **25**, 1–32.

Roumelioti, Z., Kiratzi, A., Theodoulidis, N. and Papaioannou, Ch., 2002, S-wave spectral analysis to retrieve the source parameters of the 1995 Kozani-Grevena (NW Greece) aftershock sequence, *J. of Seismology* in press.

Scordilis, E., 1985, A microseismicity study of the Servomacedonian massif and the surrounding area, *Ph. D. Thesis*, University of Thessaloniki, 250 pp.

Taymaz, T., Jackson, J. and Westaway, R., 1990, Earthquake mechanisms in the Hellenic trench near Crete, *Geophys. J. Int*. **102**, 695–731.

Taymaz, T., Jackson, J. and McKenzie, D., 1991, Active tectonics of the north and central Aegean Sea, *Geophys. J. Int.* **106**, 433–490.

Taymaz, T. and Price, S., 1992, The 1971 May 12 Burdur earthquake sequence, SW Turkey: a synthesis of seismological and geological observations, *Geophys. J. Int.* **108**, 589–603.

Trifunac, M.D., 1991, M_{LSM} , *Soil Dynamics and Earthquake Engineering* **10**, 17–25.

Uhrhammer, R. and Collins, E., 1990, Synthesis of Wood Anderson seismograms from broadband digital records, *Bull. Seism. Soc. Am*. **80**, 702–716.

Yilmazturk, A. and Burton, P.W., 1999, Earthquake source parameters as inferred from body waveform modeling, southern Turkey. *J. Geodynamics* **27**, 469–499.