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Reassessment of earthquakes, 1900–1999, in the Eastern Mediterranean and the Middle East

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SUMMARY

We have reappraised locations and surface wave magnitudes of earthquakes this century in the Eastern Mediterranean and the Middle East, between 10° and 44°N and 18° and 70°E. The results are presented in an improved parametric catalogue of shallow earthquakes ($h \leq 40$ km), large enough ($M_S \geq 6.0$) to be of interest in seismotectonics and earthquake engineering. A considerable number of early events of $6 \leq M_S < 7.2$, not included in other catalogues, have been identified and their magnitudes assessed. We find that ISS/ISC locations are systematically shifted by 10–30 km to the north or north-east of their macroseismic epicentres. Also we derived a regional average relationship between log M_0 and M_S. We show that the correlation of magnitude with epicentral intensity is very weak, as is expected, and a source of error in frequency relations.

Keywords: earthquakes, eastern Mediterranean, magnitude, Middle East.

INTRODUCTION

It should be explained at the outset why it became necessary to reassess the sizes and locations of earthquakes in this region. Regional and global earthquake catalogues are not complete or homogeneously compiled in terms of earthquake location and magnitude for the period before the mid-1970s, particularly for the area we have chosen to study. Seismotectonic studies in which earthquake locations must be associated with active faults and seismicity or seismic hazard maps require knowledge of the unambiguous location and size of past earthquakes. The importance of knowing the quality and completeness of a parametric catalogue of the last 100 years is obvious. Regional log(M_0)–M_S and frequency–magnitude relationships in studies of tectonics, and the derivation of regional predictive attenuation laws for engineering purposes, are sensitive to errors in M_S and to completeness of information, particularly for larger earthquakes (e.g. Abercrombie 1994; Ambraseys & Sarma 1999). However, few of these regional or national catalogues fulfil the conditions of uniformity and transparency in the procedures used to assign locations and magnitudes.

Initial epicentral locations come from international agencies such as the ISS, ISC and USGS, and those for the pre-ISC period (before 1967), leave much to be desired. For some regions, earthquakes in that period have been relocated routinely, with different procedures by: Makropoulos *et al.* (1989) for the south part of the Balkans and Asia Minor, Alsan *et al.* (1975) for Turkey and the Aegean area, Nowroozi (1971) for the Persian plateau, eastern Turkey, Caucasus and Hindu-Kush regions, Quittmeyer & Jacob (1979) for Pakistan, Afghanistan, northern India and southeastern Iran, Kondorskaya & Shebalin (1977) for Armenia, Georgia, Azerbaijan, Turkmenistan and Tajikistan, and Gutenberg & Richter (1965), Rothe (1969) and Engdahl *et al.* (1998) for the whole region. However, the procedures used to recalculate the positions of events in that period cannot overcome uncertainties of location arising from poor input data and azimuthal distribution of stations, occasionally resulting in gross mislocation. There are events which have been better relocated recently, but these are few and are mostly in the northwestern part of our area.

The bulk of the locations of events of interest before the mid-1970s come from national catalogues. However, these locations are of little use for our purpose because these have been taken, with few exceptions, without revision from assessments made by one of the international agencies. There are more that 50 regional and national catalogues for the region, the more recent of which are Shebalin *et al.* (1974) for the Balkans and Asia Minor, Sulstarova & Koçiaj (1975) for Albania, Jordanovski *et al.* (1998) for Macedonia, Comninakis & Papazachos (1986) for Greece, Karnik (1968) for Europe and Asia Minor, Ayhan *et al.* (1983) for Turkey, Plassard & Kogoj (1981) for Lebanon, Maamoun & Ibrahim (1984) for Egypt, Moinfar *et al.* (1994) for Iran, Heuckroth & Karim (1970) for Afghanistan, Ambraseys (2000) for northern Pakistan and Bapat *et al.* (1983) for India and Pakistan.

For events after the mid-1970s a relatively small number of events of $M_S \geq 6.0$ have been relocated, but for the sake of uniformity we adopt macroseismic or teleseismic locations.

Of this multitude of catalogues, few contain clearly improved locations of events of $M_S > 5.7$ before the mid-1970s, and although these catalogues have been published recently, they are no more reliable than the older sources from which they have been derived. For instance, locations and magnitudes given in the most recent data file of the Global Seismic Hazard Assessment Program (GSHAP 2000), are nothing more than a recompilation of earlier determinations of locations and magnitudes, without refinement or recalculation.

The importance of knowing the quality and completeness of epicentres and magnitudes in parametric catalogues of the last 100 years is obvious. Complete magnitude estimates are important for the derivation of reliable regional $\log(M_0)$–M_S, relationships which are needed to estimate seismic moments before the mid-1970s. They are equally important for the derivation of long-term frequency–magnitude relationships, which are needed to estimate the total moment release and tectonic motion in continental regions, the rate of which is known from GPS measurements, and for the assessment of aseismic creep. Also the development of predictive relationships of ground motions for engineering purposes requires reliable epicentres and magnitudes. These relationships are sensitive to errors in M_S and degree of incompleteness of the record, particularly for larger earthquakes.

We reassessed locations and surface wave magnitudes of earthquakes from 1900 to 1999 in an area which extends between 10° and 44°N and 18° and 70°E, shown in Fig. 1. The full data set, which is homogeneous but not complete, consists of about 5000 earthquakes of $M_S \geq 4.0$.

We have chosen to present here a parametric catalogue of 369 re-evaluated epicentres and surface wave magnitudes of shallow earthquakes ($h \leq 40$ km), large enough ($M_S \geq 6.0$) to be of interest in seismotectonics and earthquake engineering. Also we make some observations regarding the refinement and compilation of earthquake catalogues in terms of location, depth, magnitude and epicentral intensity, arising from the reappraisal of the full data set.

Data

The full data set consists of two parts. The first part includes reappraised locations and surface wave magnitudes of all earthquakes of $M_S \geq 5.7$ after re-evaluation, as well as of events with reliable estimates of seismic moment M_0, regardless of magnitude. We included also all events whose magnitude was calculated by Gutenberg & Richter (1965) and we reassessed (i) smaller earthquakes ($M_s < 5.7$) if they are associated with surface faulting, (ii) earthquakes whose surface wave magnitudes given by other workers or agencies are much larger than our estimates, (iii) events which triggered strong-motion instruments, and (iv) small events which have caused exceptionally high damage for their magnitude, being of special interest to the engineer; a total 1519 earthquakes.

The second part of the full data set includes a much larger number of earthquakes of magnitude less than 5.0 whose locations and magnitudes are not well defined, bringing up the total for the full data set to just under 5000 events.

Thus the analyses are based on a catalogue of 1519 earthquakes that fulfil conditions (i) to (iv), of which a subset of 360 events, complete for $M_S \geq 6.0$, is present here. Also, 3500 additional minor events were collected but not fully analysed.

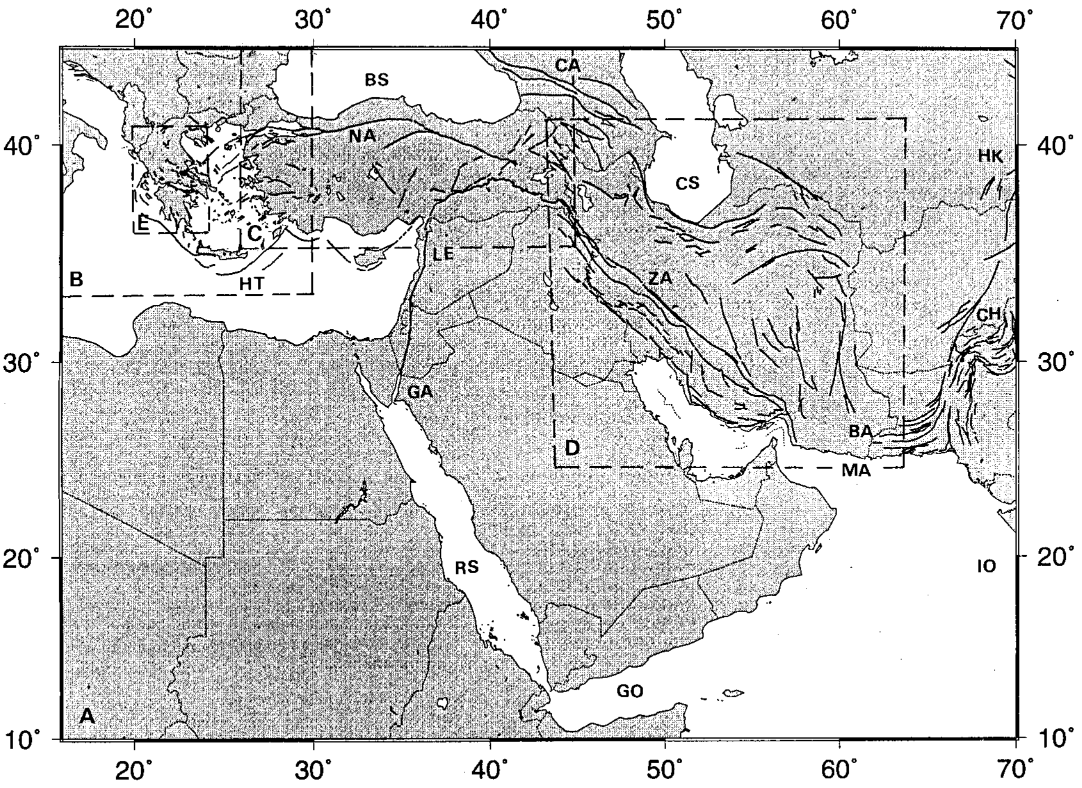


Figure 1. Map of the study area showing active faults associated with earthquakes this century. Notation: BA: Baluchistan, BS: Black Sea, CA: Caucasus, CH: Chaman, CS: Caspian Sea, NA: North Anatolian fault zone, GA: Gulf of Aden, GQ: Gulf of Aqaba, HK: Hindu Kush, HT: Hellenic Trench, IO: Indian Ocean, LE: Levant system, MC: Makran, NA: North Anatolian fault zone, RE: Red Sea, ZA: Zagros. Basic sources for main active faults shown: Ambraseys & Jackson (1998), Armijo *et al.* (1986, 1989), Baramowski *et al.* (1984), Barka & Kadinsky-Cade (1988), Lyberis (1984), Yeats *et al.* (1997).

The first part of the full data set permits not only the investigation of regional scaling of seismic moment down to small magnitudes, but also the extension of the time period over which, via M_S, seismic moments M_0 can be assigned to events back to 1900, and the study of regional attenuation of ground motions. This part of the full data set is too long to be appended to a journal paper and it is presented elsewhere (Ambraseys *et al.* in preparation). Here we give in Table 1 a parametric catalogue of only 369 earthquakes of $M_S \geq 6.0$, which is useful in the assessment of the total strain measured geodetically for comparison with that accounted for by earthquakes and with estimates of fault slip rates measured at the surface, provided the contribution from smaller events is taken into consideration (e.g. Ambraseys & Sarma 1999). The distribution of earthquakes in the first part of the full data set is shown in Fig. 2.

Epicentres

Epicentres in Table 1 are either macroseismic or instrumental and these were reappraised. Instrumental positions are chosen for earthquakes offshore or with epicentres on land in areas from where there is insufficient macroseismic information to assign a position. Routine teleseismic locations are usually in error due to inadequate station coverage, systematic and random reading errors and bias due to differences between the real Earth and the earth model used in the location. For some parts of the world the accuracy of location of recent earthquakes, after the early 1970s, is better known, with an error, barring exceptions, of not less than about 10 km; routine locations can be refined, using reliable input data and improved procedures. However, as one goes back in time, reappraisal and refinement of epicentral positions becomes impracticable, chiefly because of the lack of reliable input data for which there is no foreseeable solution.

Engdahl *et al.* (1998) relocated the position of a large part of the ISC catalogue between 1964 and 1995, using an improved velocity model and also including the arrival times of additional phases, particularly teleseismic depth phases to supplement the direct *P* arrival times in the relocation procedure. Their positions should be better than the ISC locations.

Some results of a few routine relocations made for the Eastern Mediterranean and the Middle East earthquakes by Nowroozi (1971), Alsan *et al.* (1975), Makropoulos (1978) and Ambraseys *et al.* (1994) were good, but many were not so good, since the difficulties of poor timing and azimuthal station coverage were too great. The problem with the instrumental location of early events is not so much internal with respect to the method used for their calculation, but in regard to their actual locations. The internal accuracy of a location may be enhanced by improving the consistency of the solution even beyond the actual limit of accuracy of the input data. This, however, does not necessarily imply more precision in placing an epicentre. The concentration of many of the stations that were reporting before the early 1950s in the northwest quadrant, in Europe, with little control from stations in other quadrants, causes systematic location errors (see below).

Macroseismic epicentres are an approximate indication of the location of an earthquake and for shallow earthquakes on land they may be defined as the centre of the area mostly affected by the shock. Excluding epicentres in sparsely populated areas and offshore, they can be assessed with an error of 5–15 km depending on the available information and their magnitude. Good quality macroseismic epicentres for shallow depth earthquakes of $M_S < 6.5$ before the early 1960s are less variable and more reliable than instrumental epicentres.

For larger events ($M_S > 6.5$) the location uncertainty of macroseismic epicentres increases, with increasing magnitude, to a few tens of kilometres. This is understandable considering that shallow events of $M_S > 6.5$ will have ruptured faults tens of kilometres or more in length, in which case the macroseismic epicentre loses its meaning as a reference point.

Focal depth

Focal depth has always been a particular problem outside dense local networks of seismic stations. The reason for this is that the location methods routinely employed by the ISS/ISC and the USGS, based on the arrival times of teleseismic *P* waves alone, suffer from a trade-off between origin time and depth, which can cause errors in focal depth of several tens of kilometres. By the early 1980s synthetic seismogram techniques for modelling *P* and *SH* (*P*/*SH*) body waveforms allowed depths to be estimated typically to ± 4 km for earthquakes larger than about M_S 5.5 and to show that most continental seismicity was restricted to the upper 10–20 km of the crust. With these uncertainties in mind, depths in Table 1 are taken from *P*/*SH* body wave modelling, whenever such estimates are available; if not available, depths are taken from Engdahl *et al.* (1998), from relocations made by others, from ISC solutions or from macroseismic estimates, in that order, marked in Table 1 with the appropriate flag.

Magnitude

Surface wave magnitudes M_S were calculated uniformly for the first part of the full data set from 23 105 station magnitudes which were calculated in turn from data culled from about 300 station bulletins using the Prague formula. Station magnitudes were estimated from amplitudes and periods of long waves taken from horizontal and vertical components separately and corrected for station and distance. For the period before 1935 a considerable number of events with $6 < M_S < 7.2$, not included in other catalogues, have been identified and their magnitudes assessed (Ambraseys & Douglas 1999, 2000).

Seismic moment and moment magnitude

There is some confusion in the literature about the definition, notation and use of seismic energy magnitude and moment magnitude, originally denoted by M_W, and **M**, respectively, and surface wave magnitude M_S. Kanamori (1977) defined the seismic energy magnitude M_W as a linear transformation of the logarithm of the seismic moment M_0 given by:

$$M_S \sim M_W \Leftarrow (2/3)\log(M_0) - 10.73 \tag{1}$$

in which M_0 in dyn cm units (10^{-7} N m). Kanamori derived eq. (1) from the observation that in most large, $M_S \geq 7.5$, shallow earthquakes the stress drop is about 30 bar, which is combined with the energy (E) and magnitude (M_S) relation for earthquakes in California, i.e. $\log E = 11.8 + 1.5\ M_S$, which in reverse form is eq. (1). Moment magnitude, M, for shallow earthquakes in California, in the range $5.0 \leq M_S \leq 7.5$, was then defined by Hanks & Kanamori (1979) as being equal to M_W from eq. (1).

Table 1. OT is the origin time, epicentres followed by 1 are macroseismic locations. Epicentres relocated in this study, using ISC procedures, or for early events using a combination of instrumental and macroseismic data to fix origin time and location, are followed by 2. Our next choice was epicentres relocated by Engdahl *et al.* (1998) which were preferred and they are followed by 3. Epicentres, excluding adopted, routinely computed by ISS or ISC are followed by 4. Positions, chiefly in the Aegean, relocated by Makropoulos (1978) are shown by 5. Epicentres relocated by Nowroozi (1971) are followed by 6. For a few events in northern Iran and Turkey we adopted determinations published by the Russian networks, labelled 7. For very recent events, not in ISC, we adopted NEIC locations, shown by 8. Finally, 9 indicates positions adopted from a combination of poor instrumental and macroseismic data, without calculation. Focal depths for the early period are lacking. Where depth estimates are shown these have been taken in the following order of preference: from *P* and *SH* body waveform modelling, Engdahl *et al.* (1998), special papers, and ISC determinations. Seismic moments are taken from different sources: CMT Harvard estimates are followed by 1; moment estimates from body wave P/SH modelling are followed by 2; those from long wave modelling are followed by 3. Moments calculated from eq. (5) are followed by 4. Moment estimates 2, as well as corresponding depths, are preferred. The last column indicates the epicentral or maximum intensity *I* of the event in the MSK scale.

Date			OT	N°	E°	Rf	*h*	M_S	log(M_0)	Rf	*I*
1900	03	06	1758	29.00	33.00	1	0	6.22	25.40	4	0
1900	10	10	0302	16.00	60.00	2	0	6.44	25.73	4	0
1901	03	31	0710	43.30	28.60	1	0	6.27	25.48	4	8
1901	08	06	1835	25.00	58.00	2	0	6.17	25.33	4	0
1901	11	08	1017	39.98	41.35	1	0	6.05	25.15	4	8
1901	12	18	0351	39.40	26.70	9	0	6.29	25.51	4	0
1902	02	13	0939	40.70	48.58	1	0	6.52	25.85	4	9
1902	07	05	1456	40.79	23.05	1	0	6.31	25.54	4	9
1902	07	09	0338	27.00	56.40	9	0	6.30	25.52	4	0
1902	09	20	0636	38.50	67.00	9	0	6.01	25.09	4	0
1903	03	22	1435	33.15	59.70	1	0	6.19	25.36	4	0
1903	03	25	2234	35.00	22.00	2	0	6.14	25.28	4	0
1903	04	28	2339	39.10	42.60	1	0	7.02	26.60	4	9
1903	06	24	1656	37.60	49.60	9	0	6.06	25.16	4	0
1904	04	04	1003	41.90	22.90	1	0	6.90	26.42	4	0
1904	04	04	1026	41.85	23.05	1	0	7.18	26.84	4	9
1904	04	10	0852	41.85	22.65	1	0	6.18	25.34	4	7
1904	08	11	0608	37.60	26.70	9	0	6.15	25.30	4	0
1904	08	18	2005	37.65	26.70	9	0	6.00	25.07	4	0
1904	10	03	0307	12.00	58.00	2	0	7.18	26.84	4	0
1904	10	10	1740	37.60	26.70	9	0	6.00	25.07	4	0
1904	11	09	0328	37.10	59.65	1	0	6.37	25.63	4	0
1905	01	09	0617	37.90	47.80	1	0	6.02	25.10	4	0
1905	01	20	0232	39.60	23.00	9	0	6.49	25.81	4	0
1905	04	30	1602	38.77	28.51	1	0	6.07	25.18	4	8
1905	06	01	0442	42.00	19.50	1	0	6.40	25.67	4	9
1905	08	04	0509	41.80	19.30	1	0	6.13	25.27	4	0
1905	10	08	0727	41.80	23.00	9	0	6.35	25.60	4	0
1905	10	21	1101	42.20	40.50	2	0	6.36	25.61	4	0
1905	11	08	2207	40.00	24.50	2	0	7.24	26.93	4	0
1905	12	04	0704	38.30	38.60	1	0	6.76	26.21	4	9
1906	10	24	1441	37.00	68.00	9	0	7.25	26.95	4	0
1907	10	21	0423	38.50	67.90	1	0	7.62	27.50	4	9
1907	10	21	0444	36.50	67.75	1	0	7.53	27.37	4	0
1907	10	23	2026	37.60	65.40	9	0	6.05	25.15	4	0
1907	10	27	0516	38.35	67.75	1	0	6.45	25.75	4	0
1908	09	28	0627	38.35	39.15	1	0	6.02	25.10	4	0
1908	12	18	1536	13.50	54.00	2	0	6.87	26.38	4	0
1909	01	23	0248	33.41	49.13	1	0	7.42	27.20	4	9
1909	02	09	1124	40.17	37.76	1	0	6.26	25.46	4	8
1909	05	30	0614	38.44	22.16	1	0	6.26	25.46	4	8
1909	10	20	2341	28.90	68.30	1	0	7.06	26.66	4	8
1910	06	25	1920	40.88	34.56	1	0	6.06	25.16	4	0
1911	01	01	1017	37.50	65.70	9	0	6.94	26.48	4	0
1911	01	01	1459	37.50	66.00	9	0	6.47	25.78	4	0
1911	02	18	2136	40.82	20.68	1	0	6.68	26.09	4	9
1911	04	18	1814	31.25	57.05	1	0	6.40	25.67	4	9
1911	06	07	2358	39.20	50.60	2	0	6.18	25.34	4	0
1912	01	24	1622	37.90	20.80	1	0	6.47	25.78	4	0
1912	02	13	0803	40.82	20.68	1	0	6.06	25.16	4	8
1912	08	09	0128	40.75	27.20	1	0	7.31	27.04	4	9
1912	08	10	0923	40.80	27.50	1	0	6.22	25.40	4	8
1912	09	13	2331	40.70	27.00	1	0	6.84	26.33	4	8
1913	06	14	0933	43.12	25.68	1	0	6.94	26.48	4	9
1914	10	03	2206	37.82	30.27	1	0	7.05	26.65	4	9
1914	10	17	0622	38.34	23.46	1	0	6.21	25.39	4	8
1914	11	27	1439	38.75	20.50	1	0	6.36	25.61	4	0
1915	01	27	0109	38.50	20.60	1	0	6.51	25.84	4	0
1915	06	04	1722	39.13	21.47	1	0	6.02	25.10	4	8
1915	08	07	1504	38.50	20.50	2	0	6.60	25.97	4	0
1915	08	10	0202	38.50	20.50	2	0	6.50	25.82	4	0
1915	08	11	0910	38.50	20.50	2	0	6.01	25.09	4	0
1915	08	19	0642	39.00	20.40	2	0	6.12	25.25	4	0
1916	01	24	0655	39.80	37.10	2	0	7.12	26.75	4	0
1918	03	24	2315	35.00	60.70	1	0	6.04	25.13	4	0
1918	09	29	1207	35.10	34.80	2	0	6.26	25.46	4	0
1918	11	29	1042	32.70	67.70	1	0	6.02	25.10	4	8
1919	02	24	0155	36.70	21.00	2	0	6.14	25.28	4	0
1919	10	25	1710	36.60	25.90	2	0	6.08	25.19	4	0
1919	11	18	2154	39.35	27.44	1	0	6.88	26.39	4	8
1919	12	22	2341	40.13	20.71	1	0	6.01	25.09	4	8
1920	02	20	1144	41.95	44.15	1	0	6.30	25.52	4	8
1920	11	26	0851	40.27	19.97	1	0	6.07	25.18	4	9
1921	08	14	1315	15.60	39.60	2	0	6.04	25.13	4	0
1922	08	11	0819	34.80	27.00	2	40	6.35	25.60	4	0
1922	08	13	0010	35.30	27.80	2	40	6.85	26.35	4	0
1923	03	15	0549	43.37	17.32	1	0	6.28	25.49	4	7
1923	09	17	0709	37.63	57.21	1	0	6.41	25.69	4	8
1923	09	22	2047	29.51	56.63	1	0	6.76	26.21	4	8
1923	12	05	2056	39.85	23.60	2	20	6.33	25.57	4	0
1923	12	28	2224	39.90	69.00	1	0	6.38	25.64	4	8
1924	02	18	1703	34.80	34.30	2	0	6.01	25.09	4	0
1924	04	20	1426	14.00	52.50	2	0	6.12	25.25	4	0
1924	09	13	1434	40.10	42.20	1	0	6.85	26.35	4	9
1924	11	20	2028	38.60	29.60	1	0	6.00	25.07	4	7
1926	03	18	1406	36.00	29.41	2	40	6.82	26.30	4	0
1926	12	17	0631	41.38	19.49	1	0	6.00	25.07	4	8
1927	02	14	0343	43.00	18.31	1	0	6.06	25.16	4	8
1927	05	15	0247	44.02	20.50	1	0	6.00	25.07	4	8
1927	07	01	0819	36.70	22.55	2	40	6.46	25.76	4	8
1927	07	11	1303	31.80	35.70	1	0	6.05	25.15	4	8
1927	07	22	0355	34.00	54.00	1	0	6.35	25.60	4	0
1928	03	31	0029	38.09	27.35	1	0	6.53	25.87	4	9
1928	04	14	0859	42.15	25.40	1	0	6.91	26.44	4	9
1928	04	18	1922	42.25	25.00	1	0	7.02	26.60	4	9
1928	04	22	2013	38.03	22.83	1	0	6.32	25.55	4	8
1928	05	02	2153	39.41	29.45	1	0	6.24	25.43	4	8
1928	09	01	0609	28.80	69.60	2	10	6.43	25.72	4	0
1928	09	18	1952	14.20	52.70	2	0	6.01	25.09	4	0
1928	10	15	1419	28.41	67.20	2	20	6.73	26.17	4	0
1929	05	01	1537	37.70	57.80	1	0	7.30	27.02	4	10
1929	05	18	0637	40.23	38.31	1	0	6.20	25.37	4	8
1929	06	03	2029	44.30	67.20	2	0	6.34	25.58	4	7
1929	07	13	0736	37.20	58.20	1	0	6.07	25.18	4	8
1929	07	15	0744	32.08	49.48	1	0	6.00	25.07	4	8
1930	03	31	1233	39.50	23.20	1	0	6.00	25.07	4	0
1930	05	06	2234	38.24	44.60	1	0	7.23	26.02	4	10
1930	05	08	1535	38.40	44.50	1	0	6.18	25.34	4	8
1930	08	23	1053	27.88	55.10	2	30	6.10	25.22	4	0
1931	03	07	0016	41.33	22.43	1	0	6.14	25.28	4	8

Table 1. (*Continued.*)

Date			OT	N°	E°	Rf	h	M_S	$\log(M_0)$	Rf	I
1931	03	08	0150	41.32	22.51	1	0	6.70	26.12	4	9
1931	04	27	1650	39.43	46.00	1	0	6.37	25.63	4	9
1931	08	24	2135	30.00	67.70	1	0	6.79	26.26	4	8
1931	08	27	1527	29.20	67.60	1	0	7.31	27.04	4	8
1932	09	26	1920	40.50	23.80	1	0	6.82	26.30	4	9
1932	09	29	0357	40.77	23.48	1	0	6.32	25.55	4	8
1933	04	23	0557	36.75	27.20	2	40	6.46	25.76	4	0
1933	05	11	1909	40.70	23.67	1	0	6.28	25.49	4	7
1933	10	05	1329	34.52	57.07	1	0	6.15	25.30	4	0
1933	11	28	1109	32.01	55.94	1	0	6.23	25.42	4	8
1934	02	04	1327	30.30	51.50	2	0	6.29	25.51	4	0
1935	01	04	1441	40.50	27.60	9	0	6.41	25.69	4	0
1935	01	04	1620	40.55	27.75	9	0	6.31	25.54	4	0
1935	04	11	2314	36.35	53.30	1	0	6.25	25.45	4	9
1935	05	01	1024	40.40	43.35	1	0	6.02	25.10	4	8
1935	05	15	0201	28.40	67.50	9	0	6.00	25.07	4	0
1935	05	30	2132	29.80	66.70	1	0	7.75	27.70	4	10
1935	06	02	0916	29.50	66.60	1	0	6.03	25.12	4	8
1935	07	05	1753	38.00	67.00	9	0	6.18	25.34	4	7
1936	06	30	1926	33.70	60.00	1	0	6.00	25.07	4	7
1938	02	14	0254	40.40	53.70	1	0	6.10	25.22	4	7
1938	04	19	1059	39.47	33.98	1	0	6.66	26.06	4	9
1938	07	20	0023	38.30	23.79	1	0	6.04	25.13	4	8
1938	09	27	0231	10.80	40.60	2	0	6.09	25.21	4	0
1939	09	22	0037	39.05	26.93	1	0	6.57	25.93	4	8
1939	12	26	2357	39.70	39.70	1	0	7.73	27.67	4	10
1940	01	29	1607	34.70	25.50	2	40	6.00	25.07	4	0
1940	05	04	2101	35.75	58.50	1	0	6.46	25.76	4	7
1940	07	30	0012	39.75	35.35	9	0	6.06	25.16	4	8
1941	02	16	1639	33.40	58.90	1	0	6.21	25.39	4	8
1941	03	01	0352	39.70	22.53	1	0	6.15	25.30	4	8
1941	05	23	1952	37.23	28.27	1	0	6.00	25.07	4	8
1942	07	03	0250	26.10	66.80	2	0	6.22	25.40	4	0
1942	08	27	0614	41.61	20.40	1	0	6.06	25.16	4	8
1942	10	28	0222	39.25	27.93	1	0	6.03	25.12	4	0
1942	11	15	1701	39.32	28.03	1	0	6.19	25.36	4	8
1942	12	20	1403	40.70	36.40	1	0	7.12	26.75	4	10
1942	12	29	0342	43.38	17.27	1	0	6.05	25.15	4	8
1943	01	11	1950	38.62	69.30	1	0	6.30	25.52	4	8
1943	06	20	1532	40.68	30.48	1	0	6.41	25.69	4	8
1943	11	26	2220	41.00	33.50	2	15	7.32	27.05	4	9
1944	02	01	0323	41.05	32.20	2	12	7.42	27.20	4	9
1944	06	25	0416	39.03	29.37	1	0	6.09	25.21	4	8
1944	07	17	1053	36.20	42.40	1	0	6.00	25.07	4	0
1944	10	06	0234	39.70	26.50	1	0	6.83	26.32	4	8
1945	10	26	1356	40.90	33.50	1	0	6.10	25.22	4	7
1945	11	27	2156	25.00	63.50	2	0	8.07	28.18	4	0
1946	07	16	0526	34.20	25.65	5	17	6.00	25.07	4	0
1946	11	04	2147	39.79	54.61	1	0	7.00	26.57	4	8
1947	06	04	0029	39.80	24.20	2	40	6.03	25.12	4	0
1947	08	05	1424	25.10	63.50	2	40	7.01	26.59	4	0
1947	08	30	2221	35.50	23.37	5	34	6.21	25.39	4	0
1947	09	23	1228	33.70	58.70	1	0	6.89	26.41	4	9
1947	09	26	0304	33.80	58.60	1	0	6.03	25.12	4	0
1947	10	06	1955	36.80	22.05	2	25	6.93	26.47	4	0
1948	01	28	1551	36.33	67.28	1	0	6.51	25.84	4	8
1948	01	30	0843	25.14	63.69	2	30	6.52	25.85	4	0
1948	02	09	1258	35.32	27.15	5	30	7.17	26.83	4	0
1948	04	22	1042	38.60	20.50	2	15	6.69	26.11	4	0
1948	06	30	1221	38.96	20.53	5	36	6.52	25.85	4	0
1948	07	05	1353	29.90	57.70	1	0	6.08	25.19	4	7
1948	07	24	0603	34.40	24.50	2	40	6.50	25.82	4	0
1948	10	05	2012	37.88	58.50	1	0	7.24	26.93	4	9
1949	04	24	0422	27.20	56.50	2	40	6.31	25.54	4	0
1949	07	23	1503	38.65	26.30	1	15	6.68	26.09	4	0
1949	08	17	1844	39.40	40.65	1	0	6.87	26.38	4	9
1951	08	13	1833	40.70	33.30	1	0	6.92	26.45	4	9
1952	10	10	1847	30.50	69.50	1	0	6.17	25.33	4	8
1952	12	17	2303	34.47	24.22	5	17	6.41	25.69	4	0
1952	12	25	2222	29.20	70.00	2	0	6.00	25.07	4	0
1953	02	12	0815	35.39	54.88	1	0	6.50	25.82	4	9
1953	03	18	1906	39.90	27.40	1	0	7.06	26.66	4	9
1953	08	09	0741	38.24	20.80	5	21	6.27	25.48	4	0
1953	08	11	0332	38.35	20.74	5	11	6.66	26.06	4	0
1953	08	12	0923	38.13	20.74	5	11	6.85	26.35	4	0
1953	08	12	1205	37.88	20.76	5	18	6.12	25.25	4	0
1953	09	07	0359	41.20	33.00	1	0	6.00	25.07	4	7
1953	09	10	0406	34.72	32.24	2	10	6.23	25.42	4	8
1953	09	10	0406	34.80	32.78	2	10	6.10	25.22	4	0
1953	10	21	1839	38.30	20.59	5	0	6.22	25.40	4	0
1954	03	31	1825	12.40	57.90	4	0	7.02	26.60	4	0
1954	04	30	1302	39.20	22.20	1	0	6.77	26.23	4	9
1955	04	19	1647	39.30	23.03	2	15	6.13	25.27	4	8
1955	07	16	0707	37.55	27.20	2	10	6.76	26.21	4	0
1955	09	12	0609	32.30	29.70	2	0	6.29	25.51	4	0
1956	02	20	2031	39.84	30.41	1	0	6.17	25.33	4	8
1956	06	09	2313	35.10	67.40	2	20	7.50	27.32	4	10
1956	07	09	0311	36.72	25.80	2	15	7.18	26.84	4	0
1956	07	09	0324	36.65	25.70	2	30	6.00	25.07	4	0
1956	07	21	1532	23.30	70.00	1	0	6.11	25.24	4	8
1956	09	16	0837	33.80	69.60	1	0	6.46	25.76	4	8
1956	10	31	1403	27.25	54.65	1	0	6.25	25.45	4	9
1957	03	08	1214	39.33	22.75	1	0	6.47	25.78	4	0
1957	03	08	1221	39.30	22.55	1	0	6.66	26.06	4	8
1957	03	08	2335	39.40	22.80	2	20	6.00	25.07	4	0
1957	04	24	1910	36.39	28.62	2	40	6.60	25.97	4	0
1957	04	25	0225	36.45	28.55	2	20	6.79	26.26	4	0
1957	05	26	0633	40.60	31.00	1	0	7.17	26.83	4	9
1957	07	02	0042	36.05	52.45	1	0	6.82	26.30	4	8
1957	12	13	0145	34.55	47.80	1	0	6.68	26.09	4	8
1958	08	16	1913	34.30	48.17	1	0	6.63	26.02	4	8
1958	08	27	1516	37.45	20.67	5	9	6.31	25.54	4	0
1959	05	14	0636	35.05	24.70	2	0	6.00	25.07	4	0
1959	09	01	1137	40.87	19.74	1	0	6.00	25.07	4	8
1959	11	15	1708	37.78	20.55	2	13	6.69	26.21	2	0
1959	12	21	1119	13.96	51.67	4	0	6.53	25.87	4	0
1960	05	26	0510	40.58	20.62	1	0	6.12	25.25	4	9
1961	06	01	2329	10.60	39.80	1	0	6.21	25.39	4	8
1961	06	02	0451	10.40	39.90	2	0	6.08	25.19	4	0
1961	06	11	0510	27.75	54.50	1	0	6.49	25.81	4	8
1962	01	07	1003	43.16	17.07	2	20	6.00	25.07	4	0
1962	01	11	0505	43.16	17.00	2	15	6.00	25.07	4	0
1962	03	18	1530	40.65	19.58	1	15	6.16	25.31	4	8
1962	04	10	2137	37.76	20.09	5	5	6.08	25.19	4	0
1962	06	11	0715	43.55	18.45	1	8	6.00	25.07	4	8
1962	09	01	1920	35.70	49.80	1	10	7.16	26.57	2	9
1963	07	16	1827	43.18	41.62	1	10	6.39	25.72	3	8
1963	07	26	0417	41.99	21.43	1	10	6.23	25.04	3	9
1963	09	18	1658	40.70	28.95	2	15	6.37	24.98	2	0
1964	10	06	1431	40.10	28.20	1	14	6.80	25.61	2	9
1965	03	09	1757	39.24	23.79	3	7	6.53	25.16	2	0
1965	04	09	2357	35.02	24.30	3	39	6.13	25.18	2	0
1965	07	06	0318	38.33	22.40	3	10	6.44	25.22	2	8
1966	02	05	0201	39.07	21.72	1	11	6.18	25.38	2	8
1966	02	07	0426	29.75	69.45	1	9	6.67	26.09	2	8
1966	02	07	2306	29.75	69.45	1	5	6.45	25.76	2	0
1966	08	01	1909	30.15	68.80	1	6	6.16	25.35	0	0
1966	08	01	2102	30.15	68.80	1	9	6.91	26.44	4	8
1966	08	19	1222	39.20	41.40	1	16	6.85	26.23	3	9
1966	08	20	1159	39.30	41.16	1	11	6.30	25.23	3	0

Table 1. (*Continued.*)

Date			OT	N°	E°	Rf	h	M_S	$\log(M_0)$	Rf	I
1966	08	20	1201	39.30	41.16	1	27	6.31	25.54	4	0
1967	03	04	1758	39.09	24.61	3	10	6.77	25.39	2	0
1967	05	01	0709	39.48	21.20	1	10	6.19	25.00	2	8
1967	07	22	1657	40.70	30.70	1	12	7.21	26.88	2	9
1967	07	26	1853	39.50	40.30	1	21	6.10	25.40	3	8
1967	11	23	0835	14.47	51.97	3	15	6.61	25.99	4	0
1967	11	30	0723	41.36	20.39	1	9	6.45	25.34	2	8
1968	02	19	2245	39.39	24.93	3	15	7.06	26.54	2	0
1968	05	30	1740	35.45	27.88	4	27	6.00	25.08	3	0
1968	08	31	1047	34.02	58.96	1	9	7.21	26.75	2	10
1968	09	01	0727	34.05	58.25	1	9	6.45	25.47	2	0
1968	09	03	0819	41.80	32.50	1	4	6.38	25.59	2	8
1968	09	11	1917	34.00	59.40	1	6	6.03	24.44	2	8
1968	09	14	1348	28.35	53.25	1	7	6.05	25.46	3	8
1968	11	15	0625	38.03	58.02	1	18	6.00	24.11	2	7
1969	01	14	2312	36.10	29.30	1	0	6.34	25.72	3	7
1969	03	23	2108	39.10	28.50	1	12	6.06	24.83	2	8
1969	03	25	1321	39.14	28.45	1	10	6.07	24.95	2	0
1969	03	28	0148	38.45	28.50	1	3	6.58	26.10	2	8
1969	03	29	0915	11.95	41.35	1	9	6.21	25.35	2	9
1969	03	31	0715	27.53	33.91	3	6	6.44	26.03	2	0
1969	04	05	0218	12.00	41.33	1	5	6.14	25.35	2	8
1969	06	12	1513	34.39	25.02	3	22	6.09	25.04	2	0
1970	03	28	2102	39.10	29.40	1	8	7.12	26.70	2	9
1970	04	08	1350	38.35	22.65	2	9	6.19	24.98	2	0
1970	05	14	1812	42.95	46.90	1	15	6.66	26.15	3	8
1970	07	30	0052	37.67	55.89	1	11	6.53	25.62	2	8
1970	07	30	0458	14.24	51.83	3	25	6.58	25.94	4	0
1971	05	12	0625	37.65	30.00	1	12	6.17	25.14	2	8
1971	05	22	1644	38.90	40.64	1	9	6.80	25.97	2	9
1971	11	08	0306	26.98	54.47	3	7	6.00	25.07	4	0
1972	04	10	0206	28.30	52.98	1	9	6.91	26.09	2	9
1972	05	04	2140	35.17	23.54	3	14	6.20	25.41	2	0
1972	06	24	1529	36.25	69.30	1	42	6.36	25.28	2	8
1972	09	17	1407	38.24	20.30	3	8	6.36	25.43	2	0
1975	03	07	0704	27.36	56.45	1	20	6.05	25.15	4	8
1975	03	27	0515	40.45	26.12	4	15	6.54	25.30	2	0
1975	09	06	0920	38.55	40.75	1	5	6.50	26.00	2	9
1975	10	03	0514	30.27	66.31	3	3	6.70	26.12	4	0
1975	10	03	1731	30.41	66.41	3	3	6.43	25.72	4	0
1976	04	08	0240	40.33	63.67	7	15	6.96	26.31	2	8
1976	04	08	0259	40.14	63.74	7	20	6.00	25.07	4	0
1976	05	11	1659	37.38	20.43	3	13	6.41	25.75	2	0
1976	05	17	0258	40.28	63.38	7	15	7.05	26.38	2	9
1976	07	28	2017	43.18	45.60	7	12	6.26	25.30	2	0
1976	11	07	0400	33.82	59.19	1	8	6.34	25.14	2	8
1976	11	24	1222	39.10	44.00	1	10	7.26	26.90	2	9
1977	03	21	2118	27.60	56.45	1	12	6.84	26.15	1	9
1977	03	21	2242	27.59	56.47	3	26	6.02	25.26	1	0
1977	04	01	1336	27.52	56.28	3	12	6.00	25.00	1	0
1977	09	11	2319	34.92	23.04	3	30	6.07	24.92	2	0
1977	12	28	0245	16.54	40.29	3	10	6.46	26.00	1	0
1978	06	20	2003	40.73	23.25	1	7	6.41	25.43	1	8
1978	09	16	1535	33.40	57.10	1	7	7.41	27.12	1	9
1978	11	04	1522	37.80	48.85	1	21	6.04	25.58	1	8
1978	11	07	1705	11.53	42.60	4	14	6.00	24.91	1	0
1978	12	14	0705	32.10	49.64	3	17	6.24	25.28	1	0
1979	01	10	0126	26.59	60.97	3	6	6.04	25.04	1	0
1979	01	10	1505	26.50	61.02	3	5	6.24	25.23	1	0
1979	01	16	0950	33.80	59.50	1	11	6.78	25.83	1	0
1979	04	15	0619	41.98	18.98	2	12	7.03	26.49	1	0
1979	05	24	1723	42.24	18.75	4	6	6.31	25.34	1	0
1979	11	14	0221	33.91	59.81	1	10	6.73	25.91	1	8
1979	11	27	1710	34.05	59.63	1	8	7.26	26.66	1	8
1979	12	07	0923	34.15	59.80	1	10	6.12	25.18	1	8

Date			OT	N°	E°	Rf	h	M_S	$\log(M_0)$	Rf	I
1980	01	12	1531	33.58	57.26	3	13	6.00	25.11	1	0
1980	04	20	0237	11.78	57.75	3	14	6.22	25.75	1	0
1980	05	04	1835	38.06	49.20	3	15	6.13	25.89	1	0
1980	07	09	0211	39.23	22.76	1	8	6.35	25.94	1	8
1980	07	09	0235	39.24	22.57	3	38	6.10	25.22	4	0
1981	02	24	2053	38.10	22.84	2	12	6.68	25.95	1	0
1981	02	25	0235	38.13	23.05	2	8	6.37	25.58	1	0
1981	03	04	2158	38.18	23.17	2	7	6.32	25.45	1	0
1981	06	11	0724	29.90	57.70	1	20	6.63	26.00	1	9
1981	07	28	1722	30.00	57.70	1	14	7.00	26.83	1	9
1981	12	19	1410	39.19	25.26	3	20	7.13	26.38	1	0
1981	12	27	1739	38.86	24.91	3	6	6.51	25.52	1	0
1982	01	18	1927	39.91	24.37	3	7	6.90	25.97	1	0
1982	08	17	2222	33.77	22.93	3	35	6.48	25.60	1	0
1982	12	16	0040	36.12	68.95	3	22	6.70	25.79	1	8
1983	01	17	1241	38.01	20.23	3	11	6.98	26.38	1	0
1983	03	23	2351	38.22	20.28	3	7	6.10	25.34	1	0
1983	04	08	0228	11.40	57.53	3	14	6.24	25.79	1	0
1983	07	05	1201	40.28	27.26	1	7	6.12	25.26	1	8
1983	08	06	1543	40.14	24.74	2	7	7.06	26.08	1	0
1983	10	30	0412	40.28	42.18	1	15	6.74	25.94	1	8
1984	03	19	2028	40.40	63.30	1	15	7.02	26.49	1	9
1985	10	29	1313	36.76	54.80	3	13	6.00	25.20	1	0
1986	03	06	0005	40.20	51.57	7	31	6.32	25.81	1	0
1986	07	07	1626	10.35	56.83	3	16	6.17	25.60	1	0
1988	12	07	0741	40.85	44.13	1	6	6.76	26.20	1	10
1989	08	20	1116	11.71	41.96	3	5	6.15	25.79	1	8
1989	08	20	1827	11.79	41.68	3	27	6.73	26.17	4	0
1989	08	21	0109	11.83	41.84	3	6	6.10	25.71	1	0
1989	09	16	0205	40.35	51.55	2	31	6.52	25.65	1	0
1989	09	17	0053	40.22	51.79	4	35	6.16	25.34	1	0
1990	03	04	1946	28.95	66.35	1	21	6.14	25.15	1	8
1990	06	17	0451	27.10	65.60	1	15	6.24	25.26	1	8
1990	06	20	2100	36.96	49.33	3	12	7.46	27.15	1	9
1990	11	06	1845	28.23	55.52	1	11	6.66	25.92	1	8
1990	12	21	0657	40.86	22.35	1	15	6.12	25.23	1	7
1991	04	29	0912	42.41	43.67	4	5	6.97	26.52	1	8
1991	04	29	1830	42.51	43.89	4	8	6.06	25.20	1	0
1991	06	15	0059	42.44	44.02	4	8	6.24	25.46	1	8
1992	03	05	0855	11.53	42.82	3	9	6.27	25.41	1	0
1992	03	13	1718	39.71	39.60	1	9	6.89	26.08	1	9
1992	04	24	0707	27.42	66.20	1	29	6.15	25.11	1	0
1992	10	23	2319	42.57	45.12	4	16	6.41	25.69	1	0
1992	11	06	1908	38.00	26.90	1	11	6.00	25.15	1	7
1994	02	23	0802	30.90	60.60	1	7	6.06	25.23	1	7
1994	02	24	0011	30.82	60.53	3	9	6.09	25.52	1	0
1994	03	01	0349	29.11	52.63	3	9	6.07	25.15	1	0
1994	05	01	1200	36.93	67.17	3	20	6.26	25.29	1	0
1995	05	13	0847	40.10	21.65	1	11	6.51	25.88	1	8
1995	06	15	0015	38.37	22.25	3	7	6.34	25.78	1	0
1995	10	01	1557	38.12	30.11	1	4	6.04	25.67	1	8
1995	11	22	0415	28.79	34.76	3	15	7.06	26.86	1	0
1996	07	20	0000	36.18	27.05	4	27	6.11	25.34	1	0
1996	09	05	2044	42.75	17.90	4	10	6.05	25.08	1	0
1996	10	09	1310	34.53	32.10	4	19	6.73	26.32	1	0
1997	02	04	1037	37.68	57.42	1	6	6.68	25.83	1	8
1997	02	27	2108	29.96	68.20	4	32	6.95	26.72	1	0
1997	05	10	0757	33.85	59.85	1	13	7.2	26.86	1	0
1997	10	13	1339	36.38	22.07	8	37	6.4	25.74	1	0
1997	11	18	1307	37.57	20.66	8	0	6.4	24.08	1	0
1998	03	14	1940	30.15	57.61	8	9	6.6	25.98	1	8
1998	05	30	0622	37.21	69.93	8	35	6.5	25.91	1	0
1998	06	27	1355	36.88	35.31	8	16	6.2	25.49	1	7
1999	03	04	0536	28.34	57.19	8	0	6.5	25.96	1	0
1999	08	17	0001	40.64	29.83	8	15	7.4	27.15	1	9

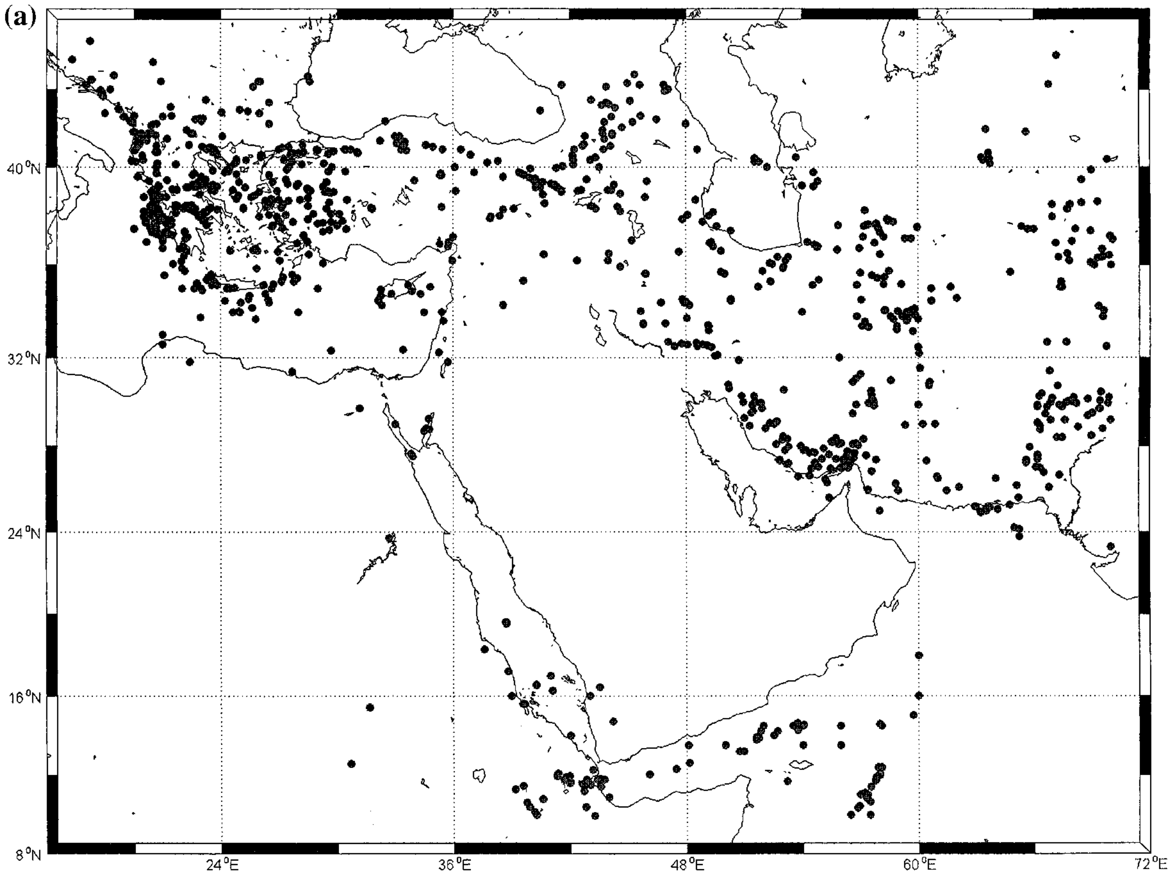


Figure 2. (a) Distribution of shallow earthquakes ($h \leq 40$ km) of $M_S \geq 5.0$ ($N = 1045$). (b) Distribution of shallow earthquakes ($h \leq 40$ km) of $M_S \geq 6.0$ ($N = 338$). (c) Distribution of intermediate-depth earthquakes ($h \leq 40$ km) of $M_S \geq 7.0$ ($N = 49$). (d) Distribution of shallow earthquakes ($h \geq 50$ km) of $M_S \geq 5.0$ ($N = 87$).

However, the equality $M = M_W = M_S$, as defined above, holds only for events that rupture the entire thickness of the seismogenic zone and its validity, therefore is regionally dependant (Ekström & Dziewonski 1988). M is nothing more than a definition, or a transformation of M_0 through eq. (1) and for the region of our interest $M \neq M_S$ for $M_S < 6.0$. For the sake of clarity we use M_W for M and M_S in this work.

Ekström & Dziewonski (1988) derived global average relationships between M_S and log M_0, in which the independent variable is log M_0. They used 2341 reported M_S values from the preliminary determination of epicentres (PDE), and corresponding scalar moments from the Harvard CMT catalogue. Only events up to 1987, for which both the NEIC and the CMT depths are <50 km, in the log(M_0) range 23.5–28.6 were considered. A relationship was then determined in the form

$$M_S = -19.24 + \log M_0 \qquad \text{for} \log M < 24.5\,, \tag{2a}$$

$$M_S = -19.24 + \log M_0 - 0.088(\log M_0 - 24.5)^2$$
$$\text{for } 24.5 \leq \log M_0 \leq 26.4\,, \tag{2b}$$

$$M_S = -10.76 + (2/3)\log M_0 \qquad \text{for} \log M_0 > 26.4\,. \tag{2c}$$

Note that eq. (2a) was derived on the assumption that the slope of the regression is one for log $M_0 < 24.5$, and eq. (2c) on the assumption that the slope is 2/3 for log $M_0 > 26.4$.

These authors then rewrite eq. (2) to obtain global average relationships in the form

$$\log M_0 = 19.24 + M_S \qquad \text{for } M_S < 5.3\,, \tag{3a}$$

$$\log M_0 = 30.20 - (92.45 - 11.40 M_S)^{0.5} \qquad \text{for } 5.3 \leq M_S \leq 6.8\,, \tag{3b}$$

$$\log M_0 = 16.14 + 1.5 M_S \qquad \text{for } M_S > 6.8\,. \tag{3c}$$

However, since eqs (3) are eqs (2) rewritten, formally, they are not the correct relationships for estimating log M_0 from M_S

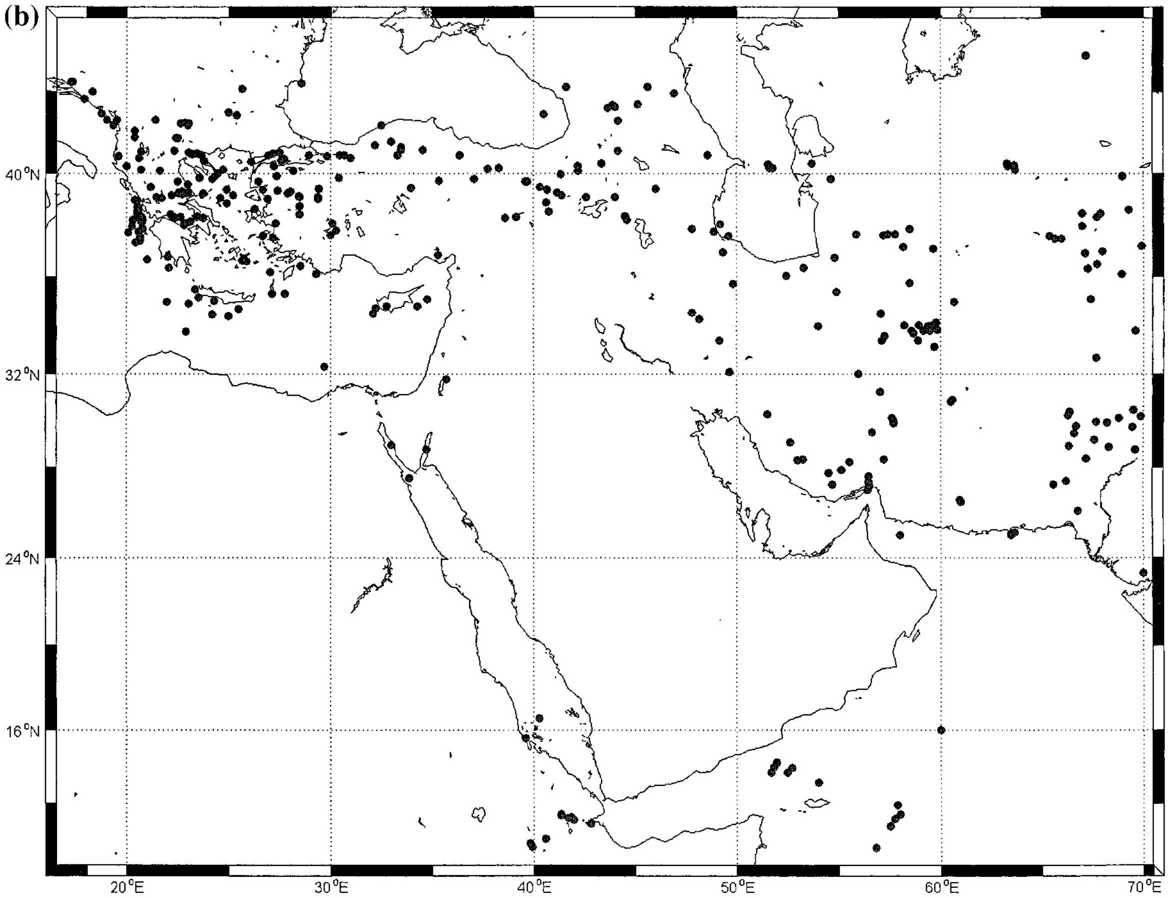
Also, there is regional bias in M_0 and global average relationships, such that eqs (2) and (3) may be inappropriate for the estimation of tectonic motion in continental regions. Ekström (1987) found that for continental events

$$\log M_0 = 19.24 + M_S \qquad \text{for } M_s < 7.16\,, \tag{4a}$$

$$\log M_0 = 15.66 + 1.5 M_S \qquad \text{for } M_S \geq 7.16\,. \tag{4b}$$

Eq. (4a) is identical to eq. (3a), but for $M_S > 6$, eq. (4) underestimates M_0 from eq. (3) (Fig. 3).

We derived a regional log $M_0 - M_S$ relation by fitting a set of bilinear relationships to the full data set, with M_S as the independent variable, using CMT or *P*/*SH* moments and the corresponding uniformly reassessed M_S values of 577 shallow



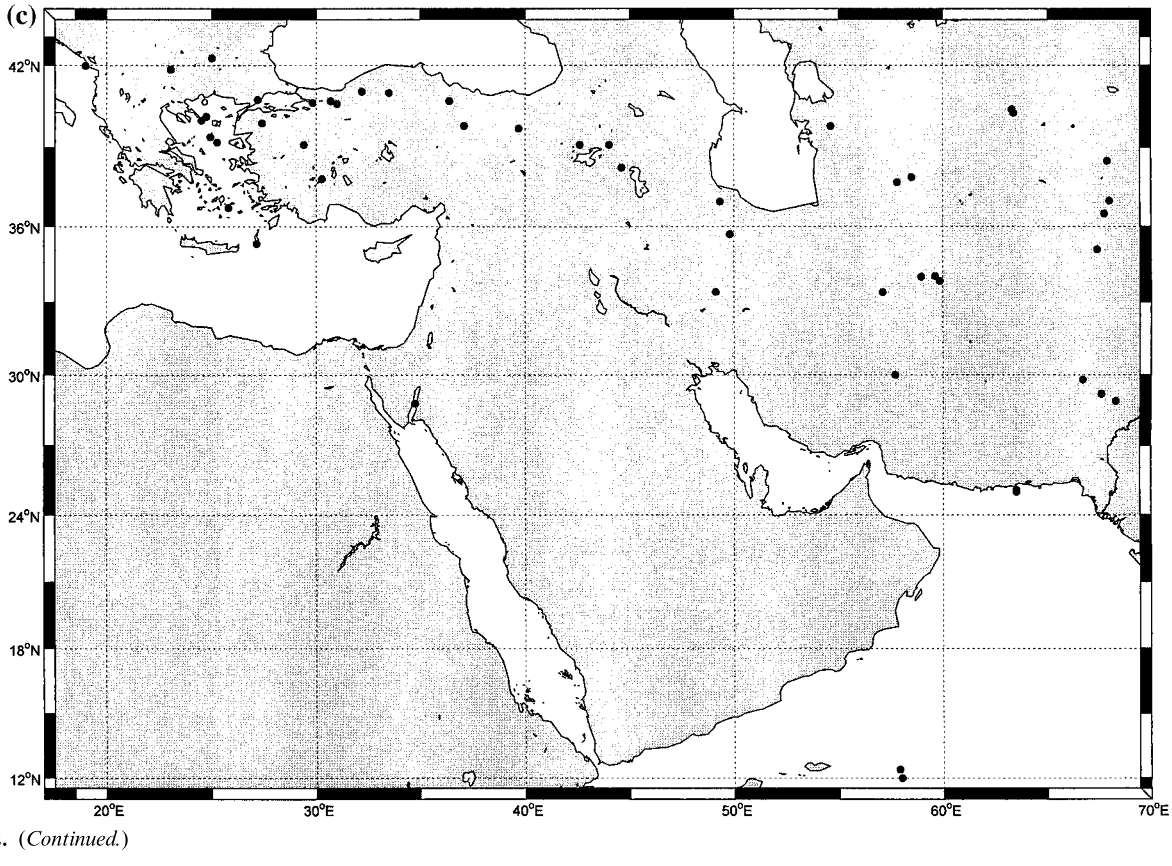


Figure 2. (*Continued.*)

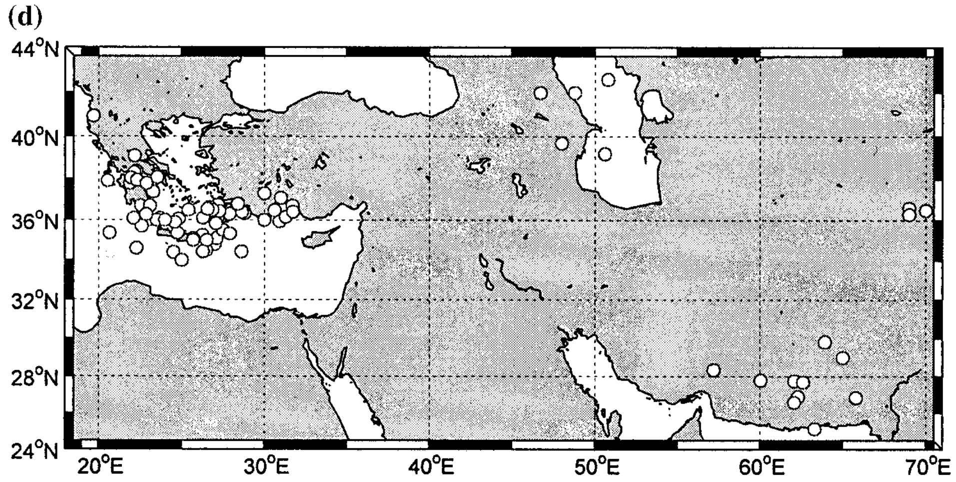


Figure 2. (*Continued.*)

earthquakes, in the log M_0 range 22.4–27.3. Allowing for the theoretical and observed variation in slope in the log $M_0 - M_S$ relationship, from one for small events to 3/2 for large earthquakes (Kanamori & Anderson 1975), we find that

$$\log M_0 = 19.08 + M_S \qquad \text{for } M_S \leq 6.0\,, \tag{5a}$$

$$\log M_0 = 16.07 + 1.5 M_S \qquad \text{for } M_S > 6.0\,. \tag{5b}$$

The constants in eq.(5) were determined from a reduced data set in which M_S and log M_0 were averaged in narrow bins of 0.2 units, which is less than the error with which these values are known. The magnitude at which the slope of the log $M_0 - M_S$ relationship changes is 6.0 (Figs 3c and 4).

REGIONAL FREQUENCY–MAGNITUDE DISTRIBUTION

The annual cumulative rate, $\acute{n}$, of occurrence of earthquakes of magnitude equal to or greater than M_S for a homogeneous region or a single fault zone is usually expressed by

$$\log(\acute{n}) = a + bM_S\,, \tag{6}$$

in which a is a measure of the level of seismic activity and b is the rate at which events occur within a given magnitude range.

For non-homogeneous regions containing many active faults eq. (6) becomes log bilinear, with a change in slope which may be compared with the break in slope of the $\log(M_0) - M_S$ relationship, an indication of a change of self-similarity.

Using the first part of the full data set for $M_S \geq 5.5$, we examined the 100 year frequency distribution for (a) the whole region (10° – 43°N and 18° – 70°E), (b) the Balkans (33° – 43°N and 18° – 30°E), (c) Turkey (35° – 43°N and 26° – 45°E), (d) Iran (24° – 41°N and 44° – 64°E) and (e) central Greece (36° – 41°N and 20° – 24°E). Eq. (6) was fitted to the data for the whole region and also for the subregions separately, and the fitting was optimized by a log bilinear relation rather than by a polynomial. The corresponding frequency plots, with M_S averaged in magnitude steps of $\Delta M = 0.2$, are shown in Fig. 5, from which we notice that the slopes b_1 and b_2 of the frequency distributions of the four regions are very similar. On average b_1 is $-0.75(\pm 0.06)$, close to the value of $-2/3$, and $b_2 = -1.91(\pm 0.17)$. Considering that 100 years may not be long enough for all faults to demonstrate their activity and for the data to satisfy completeness for large events, the value of b_2 could be somewhat smaller.

The change of slope occurs between M_S 6.4, for the smallest

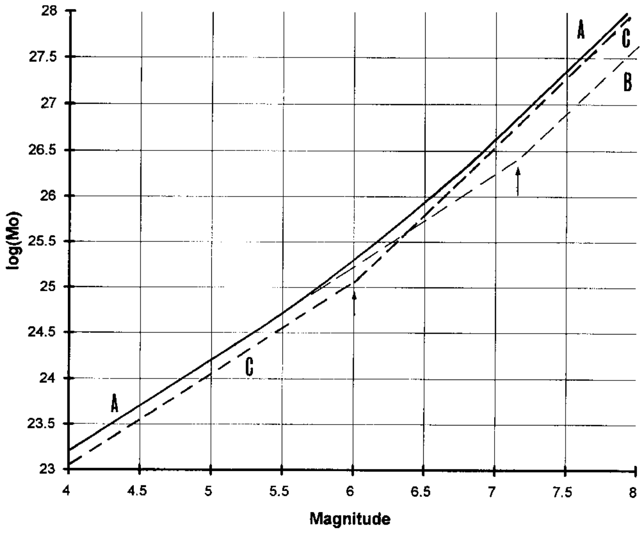


Figure 3. Log M_0–M_S relationships: A = global (eq. 3), B = continental (eq. 4) and C = regional (eq. 5).

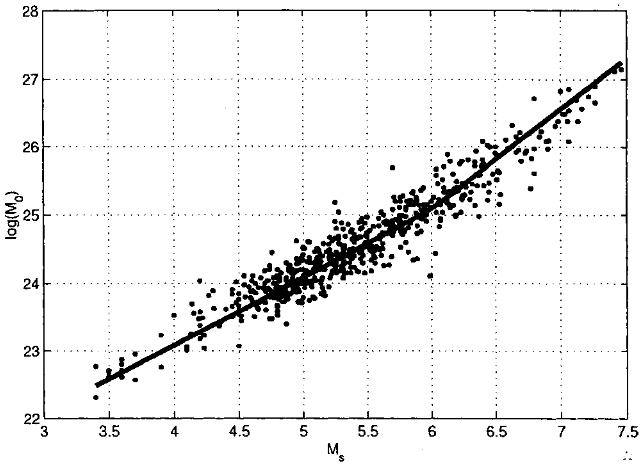


Figure 4. Log M_0–M_S plot of data points for 577 shallow earthquakes in the log M_0 range 22.4–27.3 used to fit regional eq. (5).

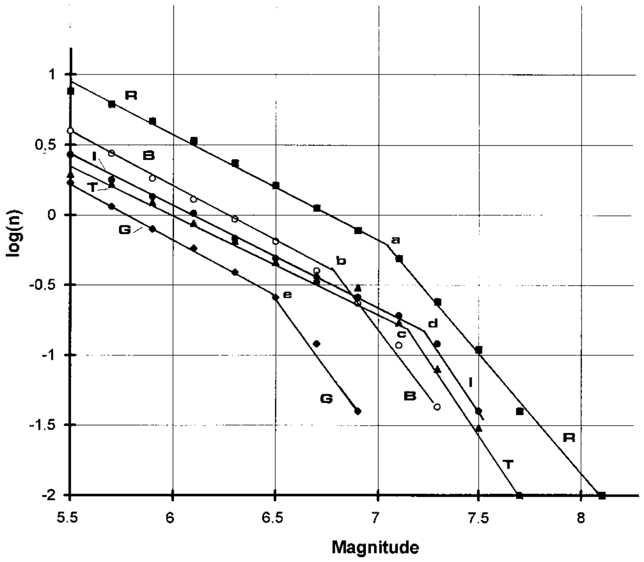


Figure 5. Cumulative frequency–magnitude distribution of test areas. See Table 2 for details.

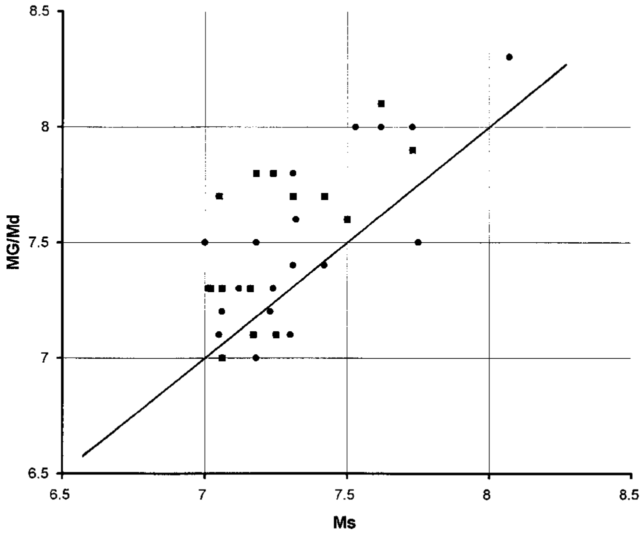


Figure 6. Comparison of surface wave magnitudes estimated by Gutenberg & Richter (1965) (M_g solid circles) and Duda (1965) (M_d solid squares), with recalculated M_S from the Prague formula.

and more homogeneous region of central Greece, and 7.3 for the largest and more heterogeneous region of Iran which is also characterized by a thicker seismogenic zone. This change in slope is similar to that of the log M_0–M_S relationship and it is consistent with the magnitude–moment scaling law changing, being different for small events for which log M_0 and M_S have a 1:1 relation, while for earthquakes of intermediate size that rupture the whole depth of the seismogenic layer the ratio decreases to 1:1.5, perhaps reaching smaller values for very large earthquakes. This bilinear distribution is also compatible with the frequency of occurrence of events in regions containing many active faults of different lengths and mobilities. It is different from the distribution for a single fault or for a relatively small area where the larger earthquakes will be regarded as likely to occur more frequently than expected from the extrapolation of the small event size. Such an extrapolation will underestimate seismic hazard (e.g. Scholz 1982, 1997).

The absence of a break in slope of a log-linear frequency–magnitude relation implies that either the region is tectonically homogeneous or, in the case of large, non-homogeneous regions, the magnitudes in the upper range of the scale have been overestimated. Such an overestimation often arises when magnitudes, chiefly of pre-1960 medium to large events, have been calculated by different methods and scales. How large overestimation can be is shown in Fig. 6, in which we compare uniformly recalculated magnitudes of shallow, pre-1955 events of $7.0 \leq M_S \leq 7.7$ (Ambraseys 2000) with magnitudes estimated by Gutenberg & Richter (1965) and Duda (1965).

Completeness

We may ask now how complete the data set in Table 1 is. It is indeed unlikely that all small and perhaps a few moderate shocks in the early part of the 20th century in Afghanistan, Africa and offshore would have been recorded. It is very probable, however, that most moderate and all large earthquake have been noted, although not necessarily fully identified. It is reasonable to suppose, therefore, that the available 20th-century data for the whole region are almost complete only for moderate earthquakes or greater, but we can devise no formal methods to test completeness other than by testing their implications. With short-term, 100 year long data sets it is simply not reasonable to ignore the chance that for a particular region much or all of our record of large events may be from a quiescent or active period in the seismic activity. This is one of the possibilities that must be borne in mind in making assumptions with short-term data sets, and this is the principal reason why statistics alone cannot quickly and simply answer the question of completeness for seismic hazard evaluation.

Intensity

For most of the earthquakes for which macroseismic information is available, it is possible to assess the extent of the epicentral area and the associated maximum observed intensity, which may be considered to be the epicentral intensity I_0 if observed at a number of localities. Field studies in the region show that epicentral intensity I_0 in rural areas 'saturates', that is, it appears to be effectively the same at intensity of about VIII MSK, because at this level all rural houses are destroyed and any village or town would thus appear equally but no more damaged at so-called higher intensity. It may be argued that in the MSK scale the destruction of all very weak structures corresponds to intensity IX and not to VIII. However, the scale does not specify what is meant by destruction and what is collapse; for instance, heavily fractured walls and dislodged lintels of an adobe dwelling imply destruction but only damage for an engineered kiln brick house. As a consequence any attempt to assess intensities larger than about VII, particularly in rural areas, becomes judgmental and quite often unduly subjective.

Also, we observed that in the last few decades the rapid change of the type of construction in rural and urban areas, and also the occupation of unsafe sites for development and expansion of cities, has made it difficult to compare the effects of recent with earlier earthquakes, and to assign uniformly maximum intensities. The most recent typical examples of systematic occupation of vulnerable sites in the expansion of

Table 2. Cumulative frequency–magnitude distribution of test areas. See Fig. 5.

Region	Area		Surface 10^6 km^2	Range M_S	N	a_1	b_1	break M_S	a_2	b_2
	N°	E°								
(a) Region	10–43	18–70	18.9	5.7–8.1	766	5.08	−0.75	7.1	11.94	−1.72
(b) Balkans	33–43	18–30	1.2	5.5–7.2	373	5.07	−0.81	6.8	12.16	−1.85
(c) Turkey	35–43	26–45	1.5	5.5–7.7	195	4.03	−0.67	7.1	13.86	−2.06
(d) Iran	24–41	44–64	3.0	5.5–7.6	269	4.39	−0.72	7.3	11.40	−1.70
(e) Greece	36–41	18–24	0.3	5.5–6.9	171	4.67	−0.81	6.4	12.60	−2.05

urban areas and its serious consequences are provided by the recent earthquakes in Athens, Greece (1999 September 7) and Izmit, Turkey (1999 August 17).

Our intensity data are sufficient to allow correlation with magnitude. The final column in Table 1 gives the intensity in the MSK (Medvedev–Sponheuer–Karnik) scale, estimated in this study for 187 earthquakes of $M \geq 6.0$, and Fig. 7 shows the correlation of intensity with magnitude of 461 earthquakes of $I_0 \geq$ VI taken from the full data set.

This figure shows that the correlation of epicentral intensity with magnitude and vice versa, which is still used in hazard analyses, is very weak and not suitable for practical applications. A linear fit of the data for M_S and I_0 taken as the independent variables alternatively gives

$$I_0 = 1.87 + 0.99 M_S \qquad \text{with } \sigma = 0.60\,, \tag{7a}$$

$$M_S = 1.58 + 0.56(I_0) \qquad \text{with } \sigma = 0.45\,, \tag{7b}$$

shown by the lines marked A and B in Fig. 7, respectively.

COMPARISON OF MACROSEISMIC WITH INSTRUMENTAL LOCATIONS

We assessed the relative accuracy of instrumental locations between 1913 and 1997 by comparing them with macroseismic

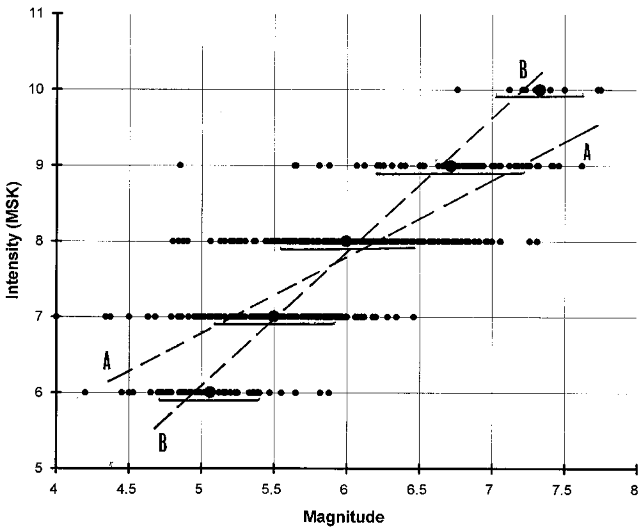


Figure 7. Correlation of epicentral intensity with magnitude for 461 shallow earthquakes. Eqs (7b) and (7a), which correspond to lines B and A, were fitted to individual intensity points with intensity or magnitude as the independent variable, respectively. Large solid circles are the mean values of M_S for a given intensity, and bars indicate standard deviation.

positions. We calculated the shift of the instrumental from the corresponding macroseismic epicentres, and noted the azimuth of the shift measured from the macroseismic position. This method has been used by Ambraseys (1978), Berberian (1979) and Soufleris (1980) to assess the predominant shift of teleseismic locations in Iran and Greece.

Instrumental locations were taken from the bulletins of the British Association for the Advancement of Science (BAAS 1900–1917), the International Seismological Summary (ISS 1919–1970) and the International Seismological Centre (ISC 1971–1998). Macroseismic positions were assessed from field evidence, press reports and technical papers.

For the early period 1899–1912, BAAS published a considerable number of epicentres of the larger shocks (BAAS 1911, 1912, 1913). Macroseismic information was used to determine the approximate position and time of the event, whenever it was possible. When macroseismic information was not available, as is the case with most of the earthquakes in remote parts of the region or at sea, epicentres are likely to be in gross error. These locations are too crude, and were thus not used here. Another set of BAAS epicentre determinations cover the period 1913–1917; these are marginally more reliable and were retained for comparison, chiefly because they are often used in national and global catalogues.

ISS locations, which begin in 1918, vary in accuracy, and early ones, before the 1940s, must be used with great caution. They may be divided into three categories: (a) epicentres properly calculated; (b) positions adopted from old locations, without calculation, on the assumption that they must be of the same origin; and (c) epicentres assessed from macroseismic locations. Of these categories, (b) and (c) are not truly instrumental positions and they are often in gross error, while category (a) may be used with caution and only in the absence of better relocations. ISC locations begin with 1971, and these were used for comparison up to 1998. However, for events between 1963 and 1995, locations by Engdahl *et al.* (1998) supersede IS and ISC estimates, which are shown in Table 1.

The macroseismic data set, for which we have both instrumental and macroseismic locations, excluding aftershocks, consists of 384 shallow earthquakes of good and 423 of moderate quality, in the magnitude range $4.0 \leq M_S \leq 6.5$. The determination of macroseismic locations has been the subject of a detailed study, which is presented in full elsewhere (Ambraseys *et al.* 2001).

Fig. 8 shows the location shift as a function of time. If we take macroseismic locations as reference points, this figure shows how rapidly the shift decreases with time, from more than 100 km in the early BAAS report to a few tens of kilometres or less in the ISS period. Shifts decrease further, in the last decades to values of about 15 km or less, instrumental

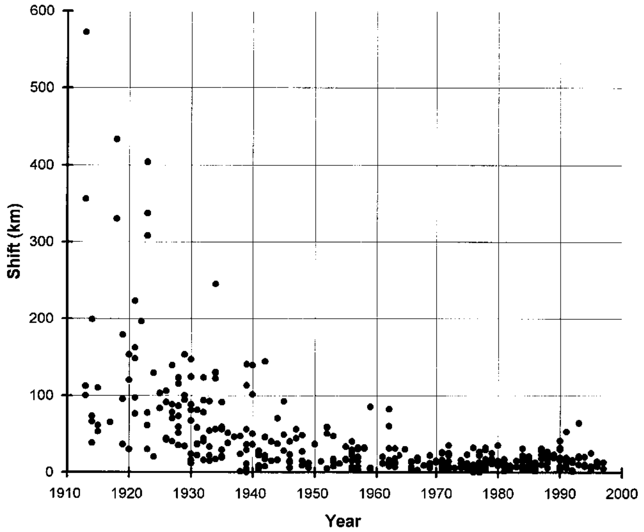


Figure 8. Time distribution of observed shifts of epicentres of 384 shallow earthquakes in the magnitude range 4.0–6.5, calculated by BAAS/ISS/ISC, with respect to their macroseismic position.

locations now falling within the epicentral region, and as a consequence the use of the macroseismic epicentre as a check on location accuracy ceases to be valid.

A more representative estimate of the variation of shift with time can be made by excluding events with adopted locations and of magnitude $M_S > 6.5$. This restriction removes a number of outlying data points but it does not change the rate at which the shift decreases with time, which remains very similar to that shown in Fig. 8.

The remaining locations show that as one passes from the BAAS to the ISS and ISC data sets, the location precision increases with time. This can be seen in Fig. 9, which shows the variation of shift with time, averaged over five-year periods. This figure displays the improvement of ISS locations in the late 1920s, when the average shift was reduced to 60 km, and

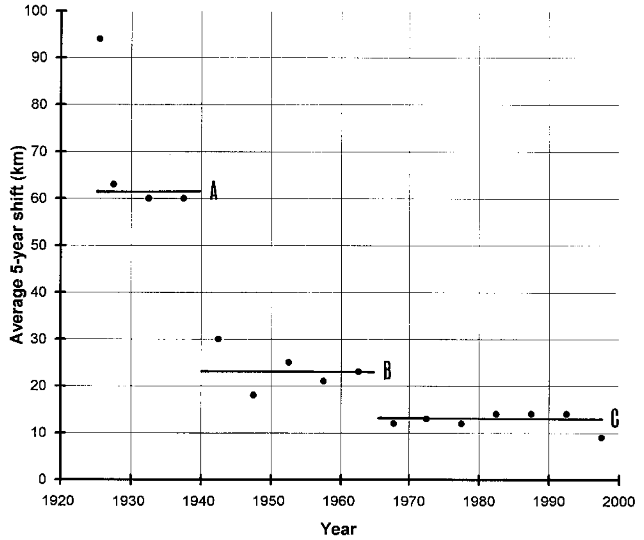


Figure 9. Time distribution of shifts, averaged over 5 year periods, of earthquakes (1918–1997) of $M_S \leq 6.5$, excluding adopted locations and mislocations. Group shifts are A: 61, B: 23 and D: 13 km.

again after the early 1940s when shifts fell to an average of about 25 km, an improvement due to better time keeping and an increase in seismographic stations equipped with better recording instruments. There was a further improvement in the early 1960s, which can be attributed to the installation of the WWSS network, which reduced the average shift to 20 km.

A similar comparison between macroseismic epicentres and those recomputed by Engdahl *et al.* (1998) for 1964–95 shows that the average shift is very close to that for ISS/ISC locations, but with a smaller, overall standard deviation.

The regional variation of shift and azimuth of ISS locations can be examined by calculating shifts in the N–S and E–W directions in 10° cells for all 807 events for which we have both instrumental and macroseismic locations, and by smoothing their variation with a sliding window. Fig. 10 shows that in the Eastern Mediterranean region ISS epicentres are located to the north of their macroseismic positions by about 20 km on average, whereas in the Middle East shifts are larger and in a more northeasterly direction. Because of the large variations of the precision of ISS locations in time, shifts shown in Fig. 10 are nothing more than the general pattern of regional mislocation during the ISS period.

A separate treatment of ISC epicentres shows an improvement in epicentre estimates and reduced shifts by about one-third. There is still, however, a systematic shift of instrumental positions towards the NNE with an overall standard deviation in azimuth larger than that from the ISS data set, which is difficult to explain. Shifts of the ISC data set are shown in Fig. 10. Note, however, that the difference between instrumental and macroseismic locations is only significant if they are greater than the radius of the epicentral or maximum observed intensity, and also that the standard deviation of the average five-year shift, in all cases, is not better than half of the mean value. This implies that smaller events, having smaller radii, are more suitable for such a comparison than large ones.

DISCUSSION AND CONCLUSIONS

Many of the existing regional and global parametric earthquake catalogues of the last 100 years do not fulfil the condition of transparency. The example shown in Fig. 6, which compares uniformly recalculated magnitudes (Abe 1988, 1994; Abe & Noguchi 1983a,b; Ambraseys & Douglas 1999, 2000) with magnitudes estimated by Gutenberg & Richter (1965) and Duda (1965), demonstrates, for instance, that for $M_S > 7.0$ an overestimation of magnitudes by 0.3–0.5 units is possible and it happens in our case: there is an overestimation sufficiently large to obscure or to eliminate the break in the regional frequency relation, to blur scaling laws and to exaggerate grossly early 20th-century seismicity (Satyabala & Gupta 1996 for northern India).

Instrumental locations before the early 1970s are of low accuracy. As Fig. 10 shows, ISS/ISC locations are systematically shifted by 10–30 km to the N or NE of their macroseismic epicentres, a bias which is unlikely to be due to systematic errors in the macroseismic positions.

We find that good macroseismic evidence is by far the most reliable, particularly for events of $M_S < 6.5$ of the first half of this century when instrumental positions were uncertain, and we give macroseismic locations more weight. Macroseismic epicentres are good enough for the association of earth-

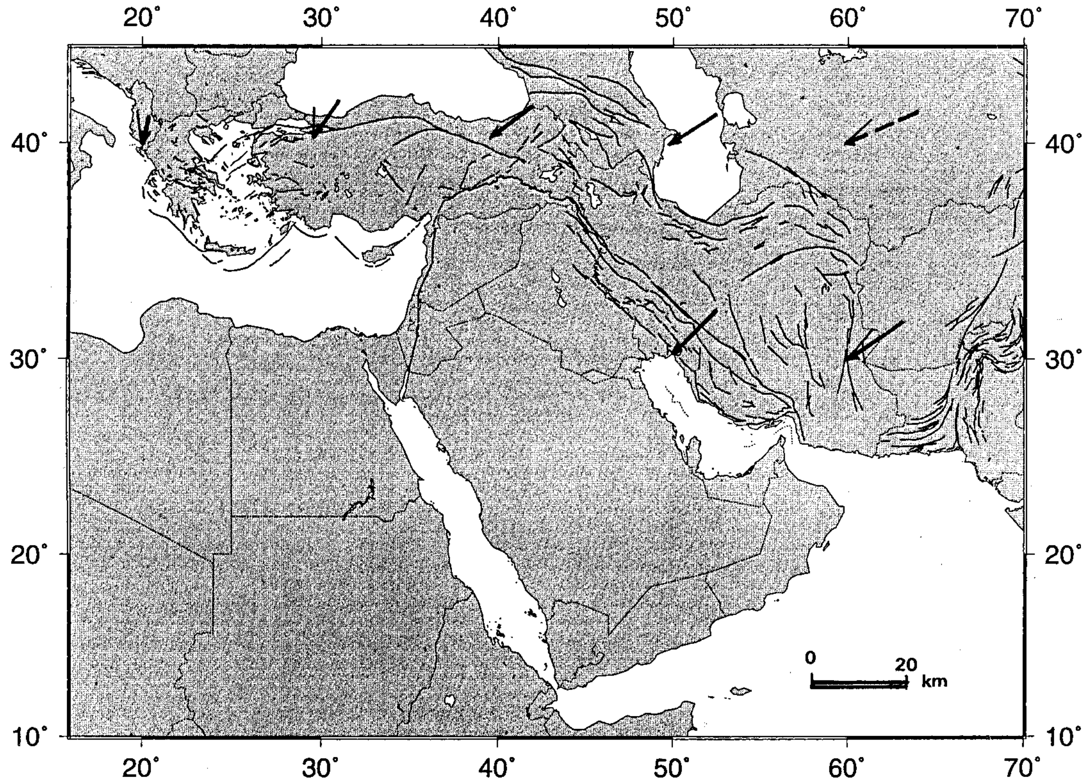


Figure 10. Averaged shift of ISS and ISC locations from macroseismic positions for events of $M_S \leq 6.5$ shown by thick and thin arrows, respectively. Arrows point to the macroseismic epicentre. Data averaged over 10° square cells.

quakes with local tectonics as well as for the calculation of the magnitude of early events; a location error of 50 km would correspond only to a second decimal place error in magnitude. While there can be no objection to calculating epicentres whose accuracy is greater than that actually required, there is a degree of precision beyond which refinement becomes pointless.

The relocations by Engdahl *et al.* (1998) for depth should be better than those routinely calculated by ISC and these authors demonstrate that this is so in several subduction zones, where improved depths clearly show the descending slabs. However, a comparison between the Engdahl depths and those determined for the region by waveform modelling shows that for crustal events the error in the Engdahl *et al.* (1998) depth can still be as large (J Jackson, personal communication, 2000).

The revised data are plotted in Fig. 2. The 1045 shallow earthquakes ($h < 40$ km) of $M_S \geq 5.0$ shown in Fig. 2(a) depict most of the active parts of the region. This figure, together with Fig. 2(b) and (c), which focus on the distribution of events of $M_S \geq 6.0$ and 7.0, clearly shows the narrow zones of seismicity along the rigid plate boundaries of the Red Sea, Gulf of Aden and Indian Ocean in contrast to the dispersed activity in the deforming continental Alpine–Himalayan belt.

The present-day activity in continental zones is not restricted to junctions between zones or along important elements in the geological history of the region; it extends over wide zones which accommodate relative motion between them. This is not clearly seen in the seismicity of this century shown in Fig. 2, which gives only a 100 year long image of the seismic potential of the region, missing out the high, pre-1900 seismic activity of the East Anatolian fault zone and of its continuation into the Levant–Dead Sea Fault system, which extends to the Gulf of Aqaba in the south.

Also, the North Anatolian fault zone, which separates the rigid Black Sea and central Anatolia region, and which has produced many large earthquakes, is clearly defined, as well as the Zagros intracontinental collision fold-and-thrust belt in western Iran. Also shown are the two N–S trending active belts in eastern Iran, and further east along the Afghan–Pakistan border.

From the Baluchistan coast the seismicity trends north in a zone that includes the Ornach-Nal, Ghazaband and Chaman fault zones, which continue to near Kabul, where it joins the Hindu Kush and Pamir. These features are seen more clearly in Fig. 2(b), but not so clearly in Fig. 2(c) which is for large events and for which 100 years is too short to disclose long-term activity.

Fig. 2(d) shows the locations of 87 events of subcrustal and intermediate depth ($h \geq 50$ km) of magnitude $M_S \geq 5.0$, not corrected for depth, or of body wave magnitude $m > 5.5$. Their selection was made from events of depths estimated from *P* and *SH* (*P*/*SH*) body waveform modelling, special studies or from Engdahl *et al.* (1998). These earthquakes are located in the subduction regions of the Hellenic Trench, Makran and possibly the Caspian Sea. The Hellenic Trench can be seen extending from the Ionian Islands in the west to Rhodes in the east with the Eastern Mediterranean oceanic crust being subducted beneath the southern Aegean and possibly east of Rhodes. The Makran coast, with the Arabian Sea floor subducting at a shallow angle to the north, is also depicted by a few well-located events.

With these maps it is possible to identify tentatively the probable regions of future activity occurring in present-day regions of low seismicity, if these are not already known from recent and historical coseismic surface ruptures.

Relations between surface wave magnitude M_S and seismic moment M_0, and vice versa, provide suitable functions for the correlation between one source size indicator and the other. Current relationships for assessing M_0 from the surface wave magnitude of shallow earthquakes have been derived from global or large subglobal data sets for active regions by Ekström & Dziewonski (1988), Rezapour & Pearce (1998) and Perez (1999) and for stable continental regions by Johnston (1996a,b). In these relationships there is regional bias in M_0 and global average log $M_0 - M_S$ relationships, such that eqs (2) and (3) may be inappropriate for the estimation of tectonic motion in continental regions.

Fig. 3 shows that in the log $M_0 - M_S$ relationships (3) and (4) the transition from a slope of unity to a larger value occurs at larger moments for continental events than for global events. Conversely, eq. (5) suggests that in continental regions such as ours, this transition occurs at a magnitude which is smaller than for the global average. This is consistent with our data set, which comes from relatively thin seismogenic zones dominated by widths from 5 to 20 km. Note, however, that the values of log M_0 from eqs (3) and (4) come from equations which were fitted to the data with log M_0 as the independent variable, and as such they are questionable for small and large log M_0 values.

Magnitude estimates in parametric catalogues are quite often derived from empirical relations as a function of the epicentral intensity and magnitude which are then used to calculate frequency–magnitude relations and to predict ground motions.

The large scatter in $M_S - I_0$ relationships shown in Fig. 7 suggests that they need additional variables, such as source depth, local soil conditions and regional differences in vulnerability of the exposed building stock, and that a one-to-one $M_S - I_0$ relationship is very tenuous. Fig. 7 also demonstrates the problem that possibly escapes attention because it is so familiar: that solving eq. (7a) for M_S or eq. (7b) for I, rather than using the appropriate variable for regression, is not correct. In our case, for $M_S = 6 \pm 0.5$, or $I_0 = 8 \pm 1$, solving eq. (7a) or eq. (7b) for the independent variable makes relatively little difference. However, for values of M_S or I_0 larger or smaller than $M_S = 6$ or $I_0 = 8$, solving for the independent variable results in unacceptable large errors. A possible solution would be to use an orthogonal (major-axis) regression, which provides the optimum fit and results in a single, reversible solution regardless of which is the variable (e.g. Troutman & Williams 1987). However, this would not minimize the prediction errors for the dependent variable and in our case an orthogonal fit gives

$$M_S = 0.62 + 0.69(I_0) \qquad \text{with } \sigma = 0.68\,, \tag{7c}$$

which lies between lines A and B of Fig. 7 with a coefficient of determination for the data set of only 0.45 There is no formal answer to the question of which of the two methods, direct or orthogonal, should be used; the direct solution that minimizes the errors in the prediction of the dependent variable is probably preferable. Nevertheless, the large uncertainties in such relationships make their practical use questionable.

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