MAGNITUDES OF NEW ZEALAND EARTHQUAKES, 1901-1993

D.J. Dowrick[1, 2] and D.A. Rhoades[1, 3]

SUMMARY

Determinations of surface-wave magnitude (M_S) are made on a consistent basis for 202 selected New Zealand earthquakes over the period 1901-1993, including most post-1942 events with local magnitude not less than 6.0 and centroid depth less than 45 km. These determinations have led to a reassessment of magnitudes and locations of some earlier events in the New Zealand Seismological Observatory Catalogue of local magnitudes (M_L), in some cases with substantial revisions. The surface-wave magnitudes are compared with local magnitudes and moment magnitudes (M_W), where available, and the relations between these three variables and centroid depth are examined through regression models. The absence of surface-wave observations for some earthquakes allows an upper limit to be placed on their likely moment magnitudes. The analysis shows that estimates of M_W derived from M_S will have a standard error of about 0.15 and M_W derived from M_L a standard error of about 0.3.

1.0 INTRODUCTION

This paper describes the estimation of the magnitudes of larger New Zealand earthquakes for the period 1901 to 1993. The surface-wave, local and moment magnitudes, M_S, M_L and M_W, their inter-relationships, and the influence of depth are considered.

The above subjects were first addressed about six years ago [1,2] in an attempt to provide magnitudes estimated on a consistent basis for a set of 70 New Zealand earthquakes, based largely on surface-wave magnitudes. The need to extend the study to include more earthquakes, to include more M_W data, and to improve the inter-relationship modelling, has rapidly become pressing. This is partly due to the inadequacy of the New Zealand implementation of the M_L scale, but more fundamentally there is a need to model seismic hazard in the moment magnitude scale, because it has a clearer physical basis (as distinct from other magnitude scales) and is the scale most commonly used internationally in hazard modelling. The moment magnitude database for the present study is much greater than that assembled for the previous study [1], being enlarged by the subsequent five years of earthquakes, and by two special local studies of larger events which have since been carried out [3,4] in addition to the ongoing Harvard moment determinations [5].

In all, 260 earthquakes have been considered in this study. A major part of the present study was the determination of the surface-wave magnitudes of 133 earthquakes, additional to the 69 M_S values in the previous study. A further 67 events, for which no surface wave data were found (in addition to one such event in the previous study), were also examined, and the implications of this are discussed.

Earthquakes with magnitudes down to about M_L 5 and depths down to 300 km have been considered. While no attempt has been made at considering all earthquakes with some nominal minimum magnitude, a majority of most post-1940 events with depth $h_C < 45$ km and magnitude $M_L \geq 5.5$ located in or near the New Zealand land mass have been included in this study.

2.0 THE ASSESSMENT OF SURFACE-WAVE MAGNITUDES

Except for a few observations made on Milne instruments (discussed later), the surface-wave magnitude M_S was determined for each observation using the so-called 'Prague formula' of Vanek *et al.* [6] as follows

$$M_S = \log_{10} (A/T)_{\max} + 1.66 \log10 (D) + 3.3 + C \qquad (1)$$

in which $(A/T)_{\max}$ is the maximum ratio of the ground displacement amplitude, A, of the surface waves in micrometres to the associated period, T, in seconds. D is the epicentral distance in degrees, and C is the station correction (discussed later). For horizontal motions the amplitude and period were taken as

$$A = (A_N^2 + A_E^2)^{1/2}, \qquad T = 0.5\,(T_N + T_E) \qquad (2)$$

where N and E refer to the orthogonal components (generally north-south and east-west). If only one horizontal component was available, an increment of 0.1 was added to that magnitude to allow for the likely contribution of the missing component.

All of the events studied had epicentres within or near the New Zealand land mass, as mapped in Figure 1. Eighty percent (206) of the events have centroid depths less than 50 km.

The data search yielded 1384 values of (A/T) max, of which 1359 came from station bulletins published by the International Seismological Centre (ISC) [7], and 125 values

---

[1] *Institute of Geological & Nuclear Sciences, Lower Hutt*
[2] *Fellow*
[3] *Member*

were measured from seismograms by the first author. Where stations reported both vertical and horizonal component data, the M_S values obtained from both components were used as if they were from different stations, with separate station corrections being applied to each component. The above-mentioned seismograms were recorded at Riverview, in Sydney, and at New Zealand offshore stations, i.e. Scott Base and Hallett (Antarctica), Afiamalu, Rarotonga, and Suva.

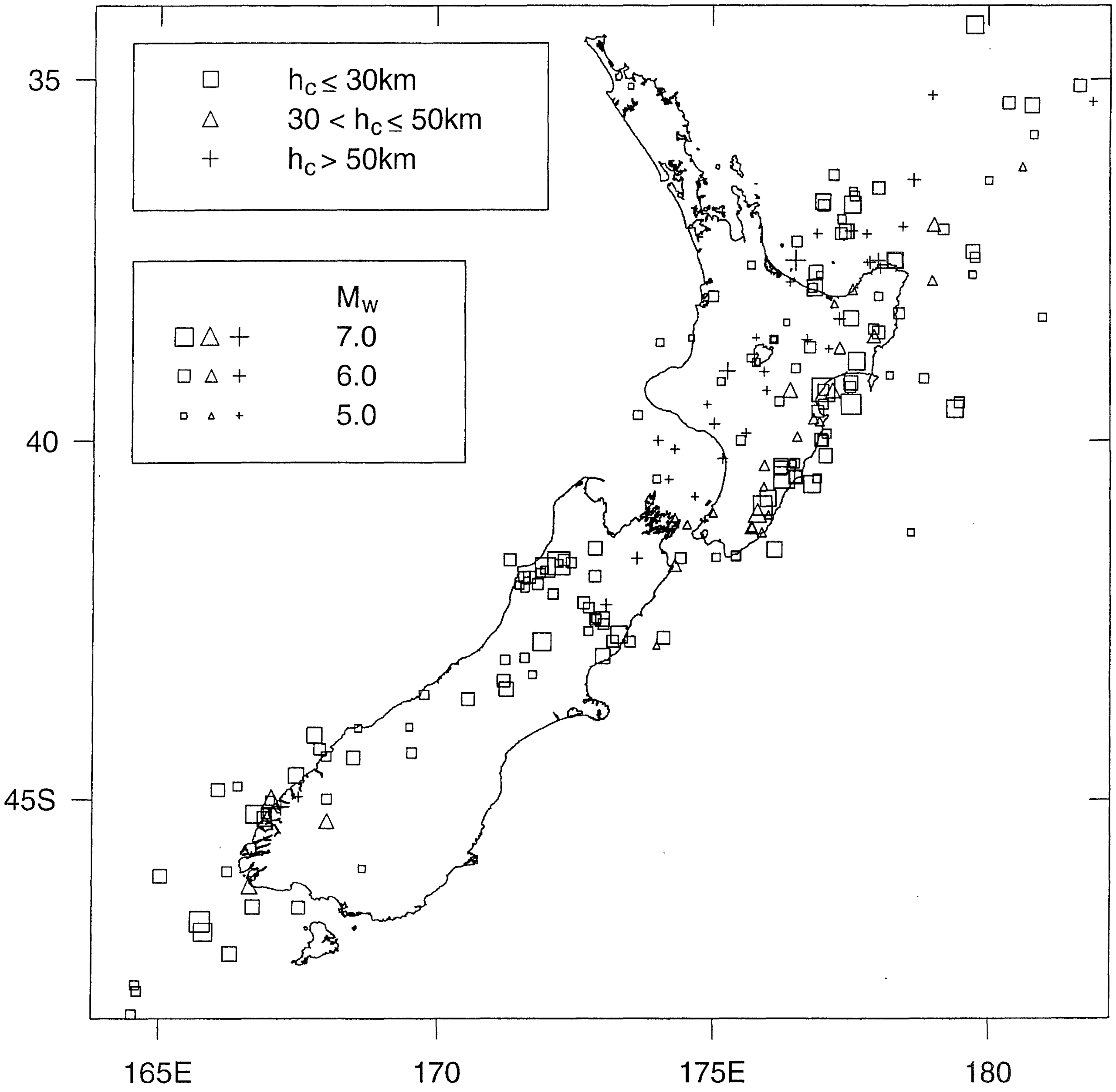

Figure 1: ***Map of locations of earthquakes listed in Table 1 showing, for each event, the actual or inferred moment magnitude M_W and approximate centroid depth h_C. The inferred moment magnitudes were determined from the surface wave magnitude M_S and h_C (see text).***

M_s determined from undamped Milne seismograph data

In a correlation of Milne data against that from other seismographs, Ambraseys and Melville [8] found that M_S should be determined from Milne data using the expression

$$M_S = \log_{10}(2A_t) + 1.25\log_{10}(D) + q + C \qquad (3)$$

in which $(2A_t)$ is the double trace amplitude (peak-to-peak) in millimetres on Milne seismograms, D is the epicentral distance in degrees, C is the station correction and q is a constant with a value of 4.06 for his data set (where $15° \leq D \leq 80°$, N. N. Ambraseys, personal communication).

Of the new data considered in this study, only six Milne station observations were found (from Adelaide, Sydney and Suva), for events in the years 1912, 1929, 1931 and 1943. As in the previous study [1,2], the M_S values from these observations lie within the scatter of the rest of the data.

3.0 EARTHQUAKE SOURCE LOCATIONS

The source locations of the earthquakes studied here are given in Table 1 and Figures 1 and 2, and are of varying reliability depending on the date and location of any given event.

Firstly, consider the geographical co-ordinates. Traditionally these have been thought of as the epicentre, and an epicentre is preferred for the co-ordinates given. However, instrumentally determined epicentres were not very accurate until at least the early 1960's. The plan locations for most pre-1940 events are macroseismic determinations made from the best intensity maps available. The pre-1940 instrumental determinations [9] are inherently not very accurate, expecially those for the aftershocks of the 1929 Buller earthquake. The epicentres listed were adopted, in approximate order of preference (depending on availability), from:

(i) Special local studies of focal mechanisms (notably from References 3, 4, 9),
(ii) Special determinations by W. D. Smith and T. H. Webb for this paper,
(iii) Some of the special determinations by W. D. Smith for the Atlas of Isoseismal Maps [10],
(iv) Latest determinations by the New Zealand Seismological Observatory, as in the computer catalogue (at 20 August 1996). Early graphical solutions (1940-1942) denoted in Table 1.
(v) Macroseismic determinations from intensities, etc, denoted in # Table 1.

The geographic distribution of epicentres is shown in Figure 1.

Secondly, consider the earthquake depths. Two depths for each event are listed in Table 1, i.e. (i) focal depth, h, and (ii) centroid depth, h_C. The focal depths listed were adopted, in approximate order of preference, from:

(a) As for (ii) above,
(b) As for (iii) above,
(c) As for (iv) above,
(d) Macroseismic estimates.

Where reliable instrumentally determined centroid depths were not available, a range of other information had to be considered, notably the focal depth. The focal depth was usually assumed to be an acceptable approximation to the centroid depth, especially for small deep events, except where it conflicted with models of the seismogenic slab. The centroid depths listed were adopted, in order of preference, from:

(1) Centroid depths from (i) above,
(2) Derived from focal depths from (ii) above,
(3) Derived from focal depths from (iii) above,
(4) Derived from focal depths from (iv) above,
(5) Macroseismic estimates,
(6) Depths from (2) to (5) were all checked for validity against the seismogenic crust or slab depth range below the "epicentre" (using the seismicity hypocentre models of Ansell and Bannister [11] and Anderson and Webb [12]), and adjusted if necessary by Dowrick.

A scatterplot of events in terms of magnitude versus centroid depth is shown in Figure 2. The deepest event (h_C = 300 km) at M_W 7.3 is the third largest in the data set, while the two largest events have depths of 10 and 17 km respectively. Our data is much more complete compared to the New Zealand catalogue for shallow earthquakes (h_C < 45 km) than for deeper earthquakes, as indicated in Table 2. This comes about mainly because, for deeper events, M_L tends to overestimate M_W and fewer M_S estimates are possible.

Earthquakes with Substantial Relocations

Revisions of estimates of magnitudes and source locations of past earthquakes is an ongoing process, as modelling techniques are refined. Such revisions mostly involve quite small changes, but a substantial number of the earthquakes involved in this study have recently been the subject of changes to their estimated locations which are large enough to warrant specific mention. As seen from Table 3, these events all date from earlier decades of this century when determination of source parameters was much less reliable than it is now.

The locations of a substantial number of the earthquakes under consideration were reviewed for either or both of two reasons. First, the discrepancy between M_S and M_L demanded a much greater depth. Second, the locations of these earthquakes, as listed in the New Zealand Seismological Observatory catalogue, did not accord with the felt intensity data. In some cases they were not felt at all, although they would have been if located as listed in the catalogue. In other cases the intensity patterns were very different from those of intensity models.

In view of the above findings, 23 of the events in Table 3 were relocated by W.D. Smith using computer analysis of NZSO seismograph network data. These revisions are restricted to post-1942 earthquakes, because earlier local data are generally unsuitable.

The M_S 6.2 1927 February 25 earthquake was relocated by D. J. Dowrick by modelling the attenuation of the intensities. The M_S 7.6 Pahiatua earthquake of 1934 March 5 was relocated during a special study [13] involving instrumental data and intensities. The 1939 Feb 10 earthquake previously listed as a crustal magnitude M^* 7 event, (M^* denotes a macroseismic magnitude) was not reported overseas and was not felt widely or strongly in New Zealand, and appears to have been much smaller and has now been assigned magnitude M^* 5.5. A further earthquake from the pre-1943 era needing relocation was the M_L 5.8 1941 April 6 event. This event was clearly deep rather than of "normal" depth, as in the catologue, but its source location could not be determined from instrumental data. Hence it has been subjectively assigned h_C = 150 km, which places it in the dipping slab of the Pacific plate below the Nelson region.

A recent study [9] of focal mechanisms of larger historic South Island earthquakes from the period 1918-1962 has also provided preferred locations for a number of earthquakes. These studies have also produced estimates of M_W, but because these estimates are less reliable than M_W obtained for more recent earthquakes, the relationships involving M_W developed in Section 5.0 below are based on data from post-1963 earthquakes only. A parallel study [14] of North Island earthquakes from the period 1917-1961, although not completed in time for the present study, provided some of the centroid depths adopted in Table 1.

While the accuracy of the source locations is important in general, for the purposes of this paper only the depth is used (as described in Section 5 below). For regional seismicity studies, however, the epicentral locations are also important. In this respect some of the relocations in Table 3 are of significance, i.e. those of the events of 1943/2/20, 1948/10/3, 1948/12/10 and 1949/6/7. Previously these four events were taken as shallow, with locations near Waiheke Island and Coromandel Peninsula. In addition they were collectively the largest, and hence statistically dominant, events in the historical catalogue for this region of low seismicity. The fact that they were actually very deep events in a different region (offshore Bay of Plenty) greatly reduces the apparent historical seismicity of the Auckland/Coromandel region.

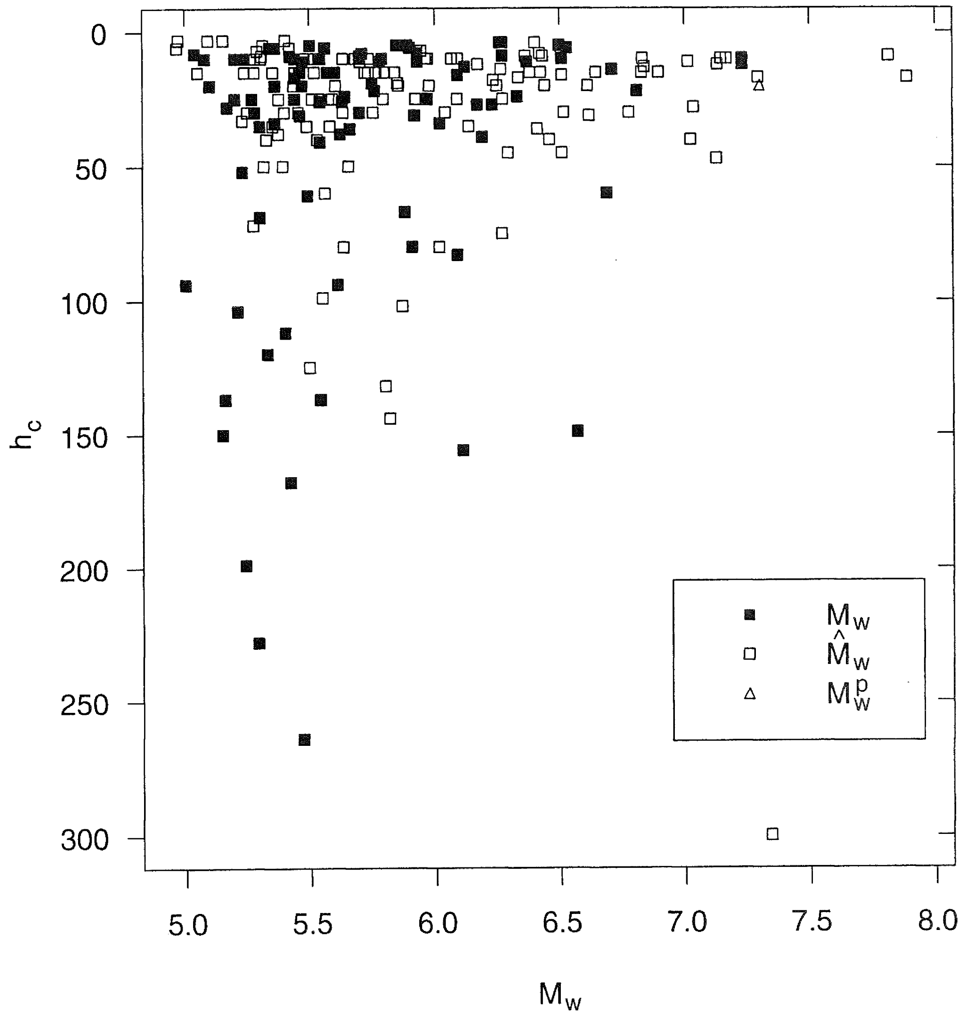

Figure 2: ***Scatter plot of centroid depth h_c against actual moment (solid square) or inferred moment magnitude M_W for earthquakes listed in Table 1.***

TABLE 1: Location and Magnitude Estimates of New Zealand Earthquakes

yr	mth	dy	hr	°S	°E[1]	h[2]	h_c	M_L[3]	M_W[4]	M_o[5]	M_s	s.e.[6]	n[7]	N[8]
1901	Nov	15	2015	42.70	173.30#	12	10	7.0*	6.78^		6.87	0.18	6	11
1903	Aug	1	1620	39.60	177.00#	cru	20	6.0*					0	0
1904	Aug	8	2251	40.60	176.80#	25?	30	7.5*	6.73^		6.75	0.14	9	14
1911	Oct	5	0736	39.50	177.00#	<45?	25	6.5*	5.56^		5.32	0.15	2	2
1912	May	26	0635	38.00	175.00#	cru	10	6.2*	5.65^		5.52	0.16	2	3
1913	Feb	22	0106	42.00	171.50#	cru	15	6.0*	5.32^		5.00	0.20	1	1
1913	Apr	12	0742	41.00	175.70#	cru	15	5.7*					0	0
1914	Feb	8	0001	41.00	175.00#	<45?	35	6.2*	5.32^		4.90	0.15	2	2
1914	Oct	6	1916	37.50	178.30#	<20?	15	7.5*	6.60^		6.66	0.08	8	28
1914	Oct	28	0016	37.50	178.30#	<20?	15	6.5*	6.38^		6.42	0.09	7	7
1914	Nov	22	0814	37.50	176.50#	300	300	7.0*	7.29^		6.46	0.09	7	29
1917	Aug	5	1551	40.80	176.00#	<45?	20	6.5*	6.57^		6.61	0.08	9	43
1918	Nov	3	1114	47.13	166.27	50	8	6.7*	6.38^		6.44	0.10	5	41
									[6.73]	[0.14E20]				
1921	Jun	28	1358	39.30	176.40#	80	80?	7.0*	6.58^		6.41	0.09	6	43
1921	Sep	6	0426	38.00	178.00#	cru	30	6.0*	5.37^		5.00	0.20	1	1
1922	Jun	9	2047	38.60	176.10#	v.sh	3	?					0	0
1922	Jun	18	1730	38.60	176.10#	v.sh	3	6.0*					0	0
1922	Jul	4	0515	38.60	176.10#	v.sh	3	?	4.93^		4.39	0.20	1	1
1922	Jul	14	0356	38.60	176.10#	v.sh	3	5.7*	5.12^		4.73	0.20	1	2
1922	Jul	14	1952	38.60	176.10#	v.sh	3	5.7*					0	0
1922	Jul	17	0419	38.60	176.10#	v.sh	3	?					0	0
1922	Jul	26	0416	38.60	176.10#	v.sh	3	?					0	0
1922	Sep	5	0233	38.60	176.10#	v.sh	3	5.2*	5.37^		5.14	0.20	1	1
1922	Dec	25	0333	43.00	173.00#	cru	20	6-7.5*	6.40^		6.42	0.08	8	37
									[6.37]	[0.4E19]				
1925	Apr	30	1005	42.80	173.50#	cru	15	6.0*	5.70^		5.57	0.20	1	1
1926	Nov	11	2251	37.70	175.50#	sha	5	5.2*					0	0
1927	Feb	25	1541	37.00	179.00#	60	45	6.7*	6.25^		6.16	0.08	11	35
1928	Mar	6	1920	39.00	174.10#	cru	10	6.0*					0	0
1928	Mar	24	2135	44.00	169.50#	cru	10	6.0*	5.21^		4.84	0.15	2	2

---

[1] Epicentres marked with hash (#) are macroseismic estimates, those marked G are graphical, the remainder are instrumental computational.

[2] cru: crustal, sha: shallow, v.sh: very shallow, nor: normal, R: restricted depth solution.

[3] M values marked with an asterisk (*) are macroseismic estimates of magnitude, the remainder are M_L.

[4] M_o and M_w in square brackets are Doser & Webb [9] values (see text). M_o expressed in Nm.
Values marked with a circumflex (^) are inferred moment magnitudes.
P indicates prelim. M_W based on M_S, prelim. body-wave M_W and isoseismal map.

[5] M_o [3, 4] (Harvard), if available, is given in round brackets under M_o.

[6] Standard error of M_S estimate.

[7] Number of observations used in estimating M_S.

[8] Number of non-New Zealand stations recording earthquake. Note: a station may yield more than one observation.

TABLE 1 cont.

yr	mth	dy	hr	°S	°E	h	h_C	M_L	M_W	M_0	M_S	s.e.	n	N
1929	Mar	9	1050	42.80	171.90	<15	11	6.9*	6.95^		7.05	0.06	23	98
									[6.97]	[0.3E20]				
1929	May	7	1614	40.00	175.50$^{\#}$	cru	10	6.0*	5.45^		5.22	0.15	2	3
1929	Jun	16	2247	41.70	172.20$^{\#}$	20	9	7.6*	7.72^		7.79	0.06	23	125
1929	Jun	18	1431	41.70	172.20$^{\#}$	cru	10	6.0*					0	0
1929	Jun	18	2158	41.70	172.20$^{\#}$	cru	10	6.0*					0	0
1929	Jun	19	0325	41.70	172.20$^{\#}$	<15	10	?	5.27^		4.95	0.20	1	17
1929	Jun	19	0917	41.69	172.43	12R	11	?	5.67^		5.54	0.15	2	16
									[6.29]	[0.3E19]				
1929	Jun	20	1447	41.70	172.20$^{\#}$	cru	10	6.3*					0	0
1929	Jun	22	1530	41.49	172.86	20	14	6.5*	6.23^		6.24	0.09	7	64
									[6.49]	[0.6E19]				
1929	Jun	22	1839	41.88	172.85	cru	7	6.3*	5.90^		5.86	0.11	4	38
									[6.37]	[0.4E19]				
1929	Jul	15	0857	41.65	172.29	cru	19	5.8*	5.82^		5.71	0.12	3	23
									[6.29]	[0.3E19]				
1930	Feb	12	0622	40.50	176.50$^{\#}$	<45?	25	7.0*	6.23^		6.21	0.07	15	51
1930	Nov	9	0602	41.00	173.00$^{\#}$	cru	15	5.5*					0	0
1931	Feb	2	2246	39.30	177.00$^{\#}$	30	17	7.8*	7.79^		7.83	0.05	28	158
1931	Feb	3	0841	39.30	177.00$^{\#}$	cru	15	?	5.77^		5.66	0.12	3	14
1931	Feb	8	0143	39.20	177.50$^{\#}$	<45?	17	6.5*	6.29^		6.31	0.07	13	46
1931	Feb	13	0127	39.50	177.50$^{\#}$	30	17	7.1*	7.22^		7.30	0.05	29	136
1931	May	5	1458	38.50	178.00$^{\#}$	cru	25	6.2*	6.05^		5.99	0.07	14	25
1931	Sep	15	2222	45.00	168.00$^{\#}$	<60?	30	4.5-6*	5.60^		5.36	0.21	1	18
1931	Sep	21	1334	37.50	178.00$^{\#}$	80	75	6.7*	6.23^		6.02	0.13	3	69
1932	Mar	5	0140	36.50	178.00$^{\#}$	30	25	4.5-6*	6.05^		5.99	0.12	3	14
1932	May	5	0823	39.60	176.90$^{\#}$	<30	20	6-7.5*	5.95^		5.87	0.08	9	29
1932	Jul	20	0452	40.00	174.00$^{\#}$	cru	60	6.2*	5.53^		5.11	0.20	1	19
1932	Sep	15	1355	38.90	177.60$^{\#}$	30	13	7.0*	6.79^		6.87	0.05	26	111
1934	Mar	5	1146	40.51	176.29	12	20	7.5*	7.30p		7.56	0.05	30	159
1934	Mar	10	0758	40.50	176.50$^{\#}$	cru	25	6.0*	5.89^		5.78	0.11	4	8
1934	Mar	15	1046	39.31	177.17$^{\#}$	10	40	6.2*	6.42^		6.37	0.07	14	48
1938	Dec	15	0912	40.00	177.00$^{\#}$	<45?	25	6.6*	5.76^		5.61	0.11	4	21
1938	Dec	16	1721	45.00	167.00	60	47	7.0*	7.06^		7.05	0.06	24	128
									[6.90]	[0.25E20]				
1939	Feb	10	1535	45.00	168.00$^{\#}$	cru	80?	5.5*					0	0
1939	Apr	20	2206	46.50	167.50$^{\#}$	cru	10	6.0*	6.06^		6.05	0.12	3	42
1940	Feb	26	0616	39.50	176.50^{G}	cru	20	6.0*					0	0
1940	Mar	19	1453	39.00	176.50^{G}	sha	15	5.0	5.43^		5.17	0.15	2	2
1940	Aug	2	0507	39.10	178.20^{G}	40	25	5.0	5.17^		4.69	0.20	1	2
1940	Oct	7	0126	38.60	176.70^{G}	160	80	5.7	5.60^		5.13	0.20	1	8
1940	Oct	11	1548	39.80	179.60^{G}	nor	15	5.0					0	0

TABLE 1 cont.

yr	mth	dy	hr	°S	°E	h	h_C	M_L	M_W	M_O	M_S	s.e.	n	N
1941	Jan	9	0239	38.10	177.20^{G}	sha	50	5.2	5.28^		4.76	0.20	1	2
1941	Apr	6	1806	41.60	173.10^{G}	nor	150	5.8					0	1
1942	Jun	24	1116	40.90	175.90^{G}	15	12	7.0*	7.07^		7.16	0.06	15	95
1942	Aug	1	0447	41.00	175.80^{G}	nor	35	5.6	5.55^		5.26	0.15	2	20
1942	Aug	1	1234	41.00	175.80^{G}	43	40	7.1*	6.96^		6.97	0.06	14	100
1942	Dec	2	0015	41.20	175.70^{G}	nor	35	6.0	6.10^		6.01	0.11	4	18
1943	Feb	17	0215	45.30	168.00	123	36	6.5	6.37^		6.33	0.10	5	36
									[6.17]	[0.2E19]				
1943	Feb	17	1353	45.96	168.64	12R	15	5.6	5.20^		4.81	0.20	1	1
1943	Feb	20	1611	37.39	177.03	291	291	5.2					0	0
1943	Feb	21	0143	34.51	177.88	12R	10	5.6					0	0
1943	Mar	1	0744	40.53	173.97	33R	30	5.7	5.22^		4.75	0.15	2	1
1943	Mar	14	0845	45.19	166.92	12R	15	5.9	5.70^		5.57	0.20	1	1
1943	May	8	0533	44.35	169.54	12R	10	5.9	5.60^		5.45	0.15	2	2
1943	Aug	2	0046	46.20	166.61	12R	31	6.2	6.57^		6.58	0.06	14	94
									[6.64]	[0.1E20]				
1943	Aug	23	0706	43.02	171.59	12R	10	5.7	5.49^		5.29	0.13	3	14
1943	Sep	22	2318	35.36	180.77	33R	9	6.1	6.39^		6.45	0.09	6	84
1943	Oct	20	1251	44.82	166.40	12R	30	5.6	5.42^		5.09	0.21	1	1
1944	Aug	13	1053	37.04	177.38	251	251	5.9					0	0
1945	Jan	2	0456	39.91	177.06	12R	25	5.6	5.48^		5.20	0.15	2	3
1945	Sep	1	2244	46.83	165.80	12R	28	6.5	6.98^		7.02	0.07	14	103
									[7.42]	[0.15E21]				
1946	Feb	4	2148	36.32	177.19	12R	10	5.7	5.70^		5.59	0.15	2	3
1946	Feb	12	0616	39.77	175.02	132	132	6.0	5.77^		5.14	0.15	2	5
1946	Feb	26	0530	38.55	176.98	103	103	5.6					0	4
1946	Jun	26	1234	43.46	171.26	12R	9	6.2	6.32		6.37	0.08	8	54
									[6.49]	[0.6E19]				
1946	Jun	28	0712	43.34	171.21	12R	10	5.8	6.03^		6.02	0.11	4	14
1946	Sep	29	0835	35.16	178.84	200R	200	5.3					0	0
1947	Mar	25	2032	38.92	178.24	12R	10	6.0			7.20	0.06	16	96
1947	May	5	0205	39.28	175.51	82	82	5.8					0	0
1947	May	17	0706	38.28	178.67	12R	10	5.6			7.18	0.07	13	107
1947	Aug	27	1337	39.56	179.38	12R	15	6.2	6.77^		6.85	0.06	17	117
1947	Oct	13	0731	44.42	168.48	12R	18	6.2	6.20^		6.19	0.08	8	15
									[6.17]	[0.2E19]				
1947	Nov	8	2241	39.47	179.46	12R	15	5.9	5.69^		5.55	0.12	3	11
1948	May	22	1857	42.47	172.88	12R	15	5.9	5.49^		5.26	0.15	2	4
1948	May	22	1921	42.48	172.99	12R	4	6.4	6.36^		6.43	0.07	12	68
									[6.44]	[0.5E19]				
1948	May	22	2001	42.55	173.01	12R	15	5.7	5.81^		5.71	0.15	2	13
1948	May	22	2121	42.49	172.86	12R	15	5.8	5.73^		5.61	0.15	2	5

TABLE 1 cont.

yr	mth	dy	hr	°S	°E	h	h_c	M_L	M_W	M_0	M_S	s.e.	n	N
1948	Jun	19	0618	43.37	169.02	12R	12	5.7					0	5
1948	Jun	19	0705	43.67	169.59	12R	12	5.7					0	7
1948	Oct	3	2158	36.63	176.03	215	215	5.0					0	0
1948	Dec	7	0819	39.50	179.52	12R	10	5.7					0	0
1948	Dec	10	2016	37.32	177.00	250R	250	4.8					0	0
1949	Feb	13	1824	34.25	179.74	33R	15	6.7	6.84^		6.92	0.06	17	138
1949	May	27	0854	45.46	167.43	92	92	6.4					0	9
1949	Jun	7	1828	36.74	175.99	164	164	4.5					0	0
1949	Jun	20	0435	35.11	177.18	179	179	5.3					0	0
1949	Dec	18	0935	39.43	176.17	130	130	5.9					0	0
1950	Jan	7	1421	41.11	174.56	40R	40	5.4					0	0
1950	Jan	12	2048	41.16	174.52	38	38	5.5	5.34^		4.92	0.21	1	1
1950	Feb	28	1858	38.80	177.05	100R	100	5.8					0	10
1950	Mar	13	0938	40.54	174.00	70	70	5.6					0	0
1950	Sep	5	0204	39.66	179.52	33R	20	5.8					0	0
1950	Oct	10	1842	45.02	166.98	33R	20	5.8	5.41^		5.11	0.15	2	15
1951	Jan	10	1915	42.79	173.18	12R	10	5.5	5.93^		5.89	0.12	3	23
1951	Feb	10	0327	40.21	177.04	33R	20	6.1	6.21^		6.20	0.09	7	55
1951	Apr	23	0650	37.53	177.84	80R	80	6.2	5.99^		5.68	0.15	2	95
1951	Jun	24	0441	39.46	176.20	33R	25	6.3	5.51^		5.25	0.12	3	31
1951	Jul	7	1015	44.89	167.25	33R	30	5.7					0	6
1951	Oct	3	1738	40.99	172.69	12R	12	5.5					0	2
1952	Aug	28	1040	39.99	176.96	12R	30	5.8	6.01^		5.91	0.10	5	11
1953	Jul	4	0207	38.86	175.68	12R	5	5.5	5.28^		4.99	0.20	1	1
1953	Oct	18	0338	38.64	174.03	12R	15	5.3	5.25^		4.88	0.20	1	1
1954	May	4	0241	44.80	167.75	50R	50	5.1					0	1
1955	Mar	3	1602	35.48	179.10	232	232	5.6					0	0
1955	Dec	4	0201	35.67	177.89	150R	150	5.5					0	38
1956	Jan	30	0843	37.10	177.42	12R	15	5.9	6.34^		6.37	0.07	10	80
1956	Feb	24	0918	35.33	180.36	12R	10	5.6	5.94^		5.90	0.10	5	59
1956	Mar	2	2243	38.90	175.80	12R	3	5.4					0	0
1956	Dec	28	1424	38.30	177.50	33R	30	6.3	6.47^		6.47	0.07	12	101
1957	Feb	22	0030	39.19	175.14	5R	15	5.6	5.25^		4.88	0.15	2	2
1957	Aug	11	0512	39.05	175.92	99	99	5.6	5.52^		4.90	0.12	3	55
1957	Aug	21	0548	41.03	176.00	33R	50	5.6	5.36^		4.89	0.15	2	1
1957	Dec	31	1428	44.87	166.05	12R	12	6.1	6.14^		6.14	0.07	13	145
1958	Jan	31	0632	39.95	176.53	12R	35	6.1	5.46^		5.12	0.11	5	42
1959	May	22	0657	41.07	174.30	33R	40	5.8	5.29^		4.83	0.17	2	51
1960	Feb	3	0221	37.61	178.04	144	144	5.9	5.79^		5.11	0.12	4	90
1960	Feb	21	0046	42.28	173.06	102	102	5.8	5.84^		5.38	0.10	6	77
1960	May	23	0101	38.26	178.67	12R	50	5.0					0	0

TABLE 1 cont.

yr	mth	dy	hr	°S	°E	h	h_C	M_L	M_W	M_O	M_S	s.e.	n	N
1960	May	24	1446	44.17	167.73	50R	9	6.5	6.46^		6.53	0.07	15	216
									[6.17]	[0.2E19]				
1961	May	14	0012	40.41	176.23	12R	40	5.2					0	1
1961	Jul	4	0823	44.46	168.12	12R	40	5.1					0	0
1961	Dec	27	2347	41.51	176.11	12R	16	6.2	6.46^		6.51	0.07	14	133
1962	Jan	23	0649	38.58	174.60	12R	15	5.4	5.01^		4.47	0.20	1	1
1962	Apr	17	1743	42.85	173.98	33	33	5.2	5.20^		4.70	0.15	2	1
1962	May	10	0027	41.65	171.32	12R	7	5.6	5.91^		5.88	0.08	8	82
									[5.62]	[0.3E18]				
1962	May	10	0430	41.27	175.88	12R	40	5.7	5.50^		5.16	0.15	2	2
1962	Sep	22	1508	37.03	178.44	125	125	5.5	5.46^		4.67	0.15	2	1
1962	Oct	15	2336	43.54	169.77	12R	20	5.6	5.57^		5.36	0.09	7	84
1963	Apr	12	0841	38.71	176.76	12R	20	5.5	5.82^		5.71	0.09	8	74
1963	Dec	22	1335	35.10	173.50	10R	6	4.9	4.93^		4.36	0.20	1	1
1964	Mar	8	0135	44.30	167.87	12R	5	5.8	5.89	0.76E18	5.80	0.08	12	73
1965	Apr	11	0011	42.74	174.10	12R	16	6.1	6.09	0.15E19	5.75	0.08	11	146
1965	Jun	15	0920	37.90	177.53	33R	50	5.8	5.62^		5.30	0.09	7	91
1965	Dec	8	1805	37.09	177.50	234	156	6.5	6.11	0.16E19			0	148
1966	Mar	4	2358	38.45	177.91	33R	24	6.0	5.64	0.32E18	5.77	0.07	12	115
1966	Apr	23	0649	41.63	174.40	22	19	5.8	5.75	0.46E18	5.62	0.09	7	83
1967	Mar	24	1909	40.70	176.51	12R	25	5.3					0	33
1968	May	23	1724	41.76	171.96	15	10	6.7	7.23	0.78E20	7.41	0.06	26	272
1968	May	24	1740	41.84	171.87	12R	10	5.3	5.51^		5.31	0.11	4	92
1968	May	24	2057	41.99	171.82	12R	11	5.7	5.78	0.53E18	5.64	0.08	10	114
1968	May	25	2349	41.91	171.79	12R	10	5.3					0	42
1968	Jun	14	1903	41.80	171.94	12R	10	5.5	5.25^		4.91	0.12	3	48
1968	Sep	25	0702	46.49	166.68	12R	4	5.9	6.27	0.28E19	6.15	0.07	11	111
1968	Nov	1	0132	41.62	175.05	33R	25	5.4	5.35^		4.99	0.12	4	66
1971	Aug	13	1442	42.13	172.10	12R	9	5.8	5.70	0.40E18	5.55	0.07	10	118
1972	Jan	8	2133	37.57	175.69	12R	7	5.3	5.26^		4.94	0.15	2	31
1973	Jan	5	1354	39.04	175.25	160	149	7.0	6.57	0.80E19	6.27	0.07	11	323
1973	Feb	21	1442	39.72	176.79	12R	25	5.4					0	69
1974	Feb	28	1359	36.69	177.00	12R	5	5.9	6.50	0.62E19	6.37	0.06	27	243
1974	Mar	3	1251	36.74	177.01	12R	5	5.7	5.85	0.65E18	5.64	0.07	15	144
1974	Sep	20	1948	44.40	167.99	12R	25	5.5	5.55^		5.30	0.11	4	123
1974	Nov	5	1038	39.65	173.63	12R	17	6.0	5.44	0.16E18	5.45	0.07	13	98
1975	Jan	4	2037	40.77	174.67	72	72	5.9	5.24^		4.56	0.15	2	65
1975	Jun	10	1011	40.34	175.93	33R	38	5.8	5.62	0.30E18	5.14	0.08	10	189
1976	Jan	30	0300	40.99	175.44	33R	25	5.3					0	31
1976	Mar	20	1759	39.26	177.49	12R	30	5.4	5.72^		5.53	0.09	7	108
1976	May	4	1356	44.67	167.45	12R	10	6.5	6.51	0.65E19	6.38	0.06	21	283
1976	Oct	27	2057	37.83	176.34	12R	5	5.0					0	12

TABLE 1 cont.

yr	mth	dy	hr	°S	°E	h	h_c	M_L	M_W	M_o	M_S	s.e.	n	N
1976	Dec	5	0457	38.11	175.54	12R	5	5.1					0	10
1977	Jan	18	0541	41.73	174.30	33R	34	6.0	6.02	0.12E19	5.93	0.07	13	231
										(0.15E19)				
1977	May	11	0242	43.26	171.73	33R	10	5.3	5.20	0.70E17	5.04	0.15	2	42
1977	May	31	1850	37.88	176.81	9	6	5.4	5.39^		5.15	0.10	5	51
1978	Jan	18	0954	42.65	172.74	33R	15	5.7	5.41^		5.14	0.15	2	42
1978	Sep	22	1042	37.80	176.39	199	199	5.6	5.24	0.81E17			0	42
1979	Feb	27	1920	35.31	181.87	228	228	5.3	5.29	0.96E17			0	96
1979	Mar	24	2106	41.94	171.63	12R	10	5.6	5.08	0.46E17			0	116
1979	Apr	19	1801	37.70	176.93	12R	8	5.1	5.04	0.40E17			0	21
1979	Jun	17	1415	39.50	174.89	137	137	5.7	5.16	0.61E17			0	52
1979	Oct	12	1025	46.69	165.74	12R	12	6.5	7.23	0.78E20	7.24	0.06	21	404
										(0.10E21)				
1979	Oct	28	1841	37.13	177.79	182	120	5.3	5.33	0.11E18			0	93
1979	Oct	29	0856	38.29	180.96	33R	20	5.4	5.36	0.12E18			0	52
1980	Jun	23	1645	39.90	175.60	61R	61	5.5	5.49	0.19E18			0	79
1980	Jul	3	0148	40.52	176.89	33R	25	5.2	5.44	0.16E18	4.96	0.10	5	32
1980	Oct	5	1532	39.70	176.82	36R	36	5.5	5.66	0.34E18	5.57	0.07	11	139
1980	Nov	24	0422	37.70	179.70	12R	25	5.5	5.20	0.69E17	4.67	0.13	3	55
1980	Nov	25	0457	37.78	178.97	41R	41	5.4	5.54	0.23E18	5.19	0.10	6	64
1980	Nov	29	0648	35.09	181.63	33R	25	6.2	5.97	0.10E19	5.73	0.07	17	172
1981	Mar	5	1253	37.13	177.32	5R	6	5.5	5.90	0.78E18	5.77	0.08	11	119
1982	Feb	5	1751	40.64	175.92	34R	34	5.3	5.36	0.12E18	5.08	0.13	3	192
1982	Sep	2	1558	39.74	176.93	31R	31	5.5	5.46	0.17E18	5.02	0.13	3	89
1983	Apr	2	2033	37.53	177.80	96	94	5.0	5.00	0.36E17			0	35
1983	Apr	16	2129	39.26	173.70	12R	20	5.3					0	7
1983	Sep	18	1944	35.77	180.81	33R	25	5.2	5.27	0.89E17	4.89	0.09	8	46
1983	Oct	26	0538	36.21	180.61	12R	35	4.8	5.30	0.10E18			0	35
1983	Dec	14	2056	38.36	176.33	5R	3	5.1	5.06^		4.62	0.15	2	4
1984	Jan	3	2255	40.53	174.19	104	104	5.5	5.21	0.72E17			0	98
1984	Mar	5	0207	38.92	175.78	9R	9	5.5	5.27		4.96	0.16	2	30
1984	Mar	8	0041	38.31	177.29	75	80	6.4	5.91	0.82E18	5.40	0.09	6	285
1984	Jun	24	1329	43.60	170.56	5R	13	5.9	6.12	0.17E19	6.07	0.07	13	282
										(0.18E19)				
1984	Dec	30	2136	36.73	177.53	12R	14	6.2	6.71	0.13E20	6.85	0.06	34	382
										(0.18E20)				
1985	Jan	2	2025	36.93	177.33	12R	6	5.3	5.34	0.11E18	5.05	0.11	4	29
1985	Jan	2	2108	36.55	177.54	12R	6	5.5	5.36	0.12E18	5.14	0.09	8	52
1985	Jan	6	1832	36.61	177.57	12R	6	5.6	5.56	0.24E18	5.29	0.07	12	72
1985	Jan	31	0433	46.06	165.03	33R	27	6.0	6.17	0.20E19	6.03	0.06	27	365
										(0.32E19)				

TABLE 1 cont.

yr	mth	dy	hr	°S	°E	h	h_C	M_L	M_W	M_O	M_S	s.e.	n	N
1985	May	6	1710	37.38	179.71	33R	9	5.9	6.27	0.28E19 (0.25E19)	6.03	0.06	21	455
1985	Jun	28	1854	37.46	179.75	33R	10	5.8	5.70	0.40E18 (0.32E18)	5.32	0.07	14	273
1985	Jul	19	1433	38.72	177.30	41	31	5.7	5.92	0.84E18 (0.12E19)	5.90	0.06	25	257
1985	Nov	1	1444	38.73	177.10	52	52	5.1	5.23	0.77E17	4.57	0.16	2	65
1986	Jul	11	0827	46.00	166.22	33R	15	5.5	5.60	0.28E18	5.41	0.07	13	179
1987	Mar	2	0142	37.88	176.84	10R	6	6.1	6.53	0.70E19 (0.64E19)	6.62	0.06	32	405
1987	Jul	3	2258	41.27	178.59	33R	20	5.0	5.10	0.49E17	5.02	0.12	3	59
1987	Aug	8	0748	37.07	179.17	5R	30	5.1	5.70	0.39E18	5.77	0.07	12	223
1988	Apr	12	0503	39.14	178.82	33	20	5.4	5.47	0.18E18	5.50	0.08	9	123
1988	May	15	1826	44.01	168.57	10	10	4.9	5.24	0.80E17	5.18	0.08	9	73
1988	May	18	2307	38.57	175.77	150R	150	4.1	5.15	0.58E17			0	51
1988	Jun	2	1158	36.40	180.00	33R	30	5.6	5.28	0.91E17	5.24	0.13	3	143
1988	Jun	3	2327	45.10	167.17	57	60	6.1	6.69	0.12E20 (0.12E20)	6.50	0.05	48	459
1988	Jul	19	0258	44.97	167.48	137	137	5.7	5.54	0.23E18			0	24
1989	May	31	0554	45.27	166.88	23R	24	6.1	6.33	0.35E19 (0.53E19)	6.26	0.05	58	428
1989	Aug	8	0759	40.12	174.30	122	112	6.0	5.40	0.14E18 (0.26E18)	4.85	0.21	1	202
1990	Feb	10	0327	42.25	172.65	13	8	5.8	5.93	0.87E18 (0.11E19)	6.04	0.05	52	217
1990	Feb	10	0354	42.32	172.74	5R	8	5.5	5.71	0.41E18	5.86	0.09	7	59
1990	Feb	19	0534	40.38	176.22	24	27	6.1	6.23	0.25E19 (0.27E19)	6.45	0.05	49	460
1990	Mar	12	1259	47.56	164.59	10R	10	4.7	5.44	0.16E18	5.42	0.09	7	67
1990	Mar	13	1330	47.64	164.62	11R	11	5.0	5.47	0.18E18	5.34	0.08	9	52
1990	Mar	24	0705	47.96	164.53	10R	10	5.0	5.54	0.23E18	5.26	0.08	10	170
1990	May	13	0423	40.35	176.23	12	11	6.2	6.37	0.40E19 (0.46E19)	6.40	0.05	71	507
1990	Aug	15	1554	40.32	176.44	28	28	5.5	5.17	0.63E17	4.98	0.09	7	161
1990	Oct	4	2348	41.60	175.41	15R	15	5.3	5.57	0.25E18	5.35	0.07	15	160
1990	Oct	6	0241	41.60	175.41	15R	15	5.3	5.46	0.17E18	5.24	0.08	10	121
1991	Jan	28	1258	41.89	171.58	0	10	6.1	5.79	0.53E18 (0.44E18)	5.45	0.06	35	235
1991	Jan	28	1800	41.90	171.67	17	11	6.3	5.93	0.87E18 (0.70E18)	5.79	0.05	43	229
1991	Feb	15	1048	42.04	171.59	7	9	6.0	5.42	0.15E18	5.19	0.07	13	172
1991	Jul	12	0442	39.31	175.97	70	69	6.2	5.30	0.10E18	4.69	0.16	2	80

TABLE 1 cont.

yr	mth	dy	hr	°S	°E	h	h_c	M_L	M_W	M_0	M_S	s.e.	n	N
1991	Sep	8	1350	40.25	175.17	94R	94	6.3	5.61	0.29E18	4.60	0.15	2	196
1991	Nov	16	0035	37.13	176.89	264	264	6.4	5.47	0.18E18			0	147
1991	Nov	20	0923	36.39	178.64	33R	83	6.3	6.09	0.15E19	5.78	0.06	22	279
1992	Mar	2	0905	40.31	176.48	24	26	5.5	5.54	0.23E18	5.34	0.09	6	115
1992	Mar	16	2321	35.22	178.97	168	168	6.1	5.42	0.15E18			0	107
1992	Mar	30	0702	43.05	171.23	5R	5	5.8	5.50	0.20E18	5.29	0.07	15	187
1992	May	16	1757	38.23	178.37	24	22	5.6	5.76	0.49E18	5.62	0.07	13	147
1992	May	27	2230	41.63	173.62	84	67	6.7	5.88	0.75E18	5.32	0.07	18	197
										(0.86E18)				
1992	Jun	21	1743	37.67	176.86	23	4	6.1	6.26	0.27E19	6.31	0.05	71	444
										(0.26E19)				
1993	Apr	11	0659	37.24	176.52	35	26	6.1	5.63	0.30E18	5.54	0.06	30	134
										(0.45E18)				
1993	Aug	10	0051	45.21	166.71	5R	22	6.7	6.81	0.18E20	6.98	0.05	77	591
										(0.33E20)				
1993	Aug	10	0946	38.55	177.92	36	39	6.3	6.19	0.22E19	6.17	0.05	71	446
										(0.44E19)				

TABLE 2: **Number of earthquakes in present study of those listed in New Zealand catalogue of local magnitudes, for epicentres between 37°S and 47°S latitude and up to 179°E longitude.**

	$M_L \geq 5.5$		$M_L \geq 6.0$	
	NZ Catalogue	**This study**	**NZ Catalogue**	**This Study**
$h \leq 45$ km				
1943-1993 Aug 10	186	102	45	36
1961-1993 Aug 10	95	53	22	21
$45 < h \leq 150$ km				
1943-1993 Aug 10	74	8	22	6
1961-1993 Aug 10	41	8	13	6

4.0 ANALYSIS OF STATION MAGNITUDE

The "Prague formula," Equation (1), for estimating M_S is normally used only for data recorded at distances less than 160°, e.g. as practised in the ISC Bulletin. This would exclude M_S data from many stations (in Europe), reducing our data set for New Zealand earthquakes from 2040 observations of M_S to 1577. However, as found previously [2], data at distances > 160° is made admissible by correcting for bias by calculating station corrections using analysis of variance. The same procedure was adopted in the present study, the method used and the resulting station corrections being discussed in a separate paper [15]. With a larger data set than used in 1990, the corrections for the stations in general differ from the previous results, although such differences are mostly small. This means that the corrected magnitudes of events considered in the 1990 study may differ slightly in the two studies even when no additional station observations are used for a given earthquake. However, the larger differences tend to occur when additional station observations are used. Examples of larger differences are provided by the earthquakes of 1975 June 10 and 1988 June 3. The former event was previously estimated to have an M_S of 5.3 based on two observations; now it is estimated at 5.14 based on 10 observations. The latter event was estimated at 6.7 based on 11 observations, and now at 6.50 based on 48 observations.

The corrected mean M_S values and associated standard errors are given in Table 1. For the purposes of comparison, macroseismic magnitudes (designated M^*), local magnitudes (M_L), moments (M_O) and moment magnitudes (M_W) are also given, where available. The M_S and M_W values are given to two decimal places for more precise comparisons, and also for more accurate depth correction for M_S. Table 1 also includes the number of station M_S values used for each event, and also the number of non-New Zealand stations reporting the event. This is usually the number of stations listed by the International Seismological Centre, or its predecessors, though for a few of the earlier events their lists of overseas stations were supplemented by the authors, as it was found that those events were recorded at Riverview and/or Melbourne.

TABLE 3: Earthquakes which have had substantial relocations arising from this study

EVENT				PREVIOUS SOURCE DATA				REVISED SOURCE DATA			
				Epicentre		***h***	M_L	**Epicentre**		***h***	M_L
				°S	**°E**			**°S**	**°E**		
1927	Feb	25	1541	38.00	178.00	50?	-	37.00	179.00	45	-
1934	Mar	5	1146	40.50	175.50	60?	-	40.51	176.29	12	-
1941	Apr	6	1806	41.60	173.0	nor	5.8	NR*	NR	150	NR
1943	Feb	20	1611	36.60	175.83	12R	5.6	37.39	177.03	291	5.2
1943	Mar	1	0744	40.47	173.87	12R	5.8	40.53	173.97	33R	5.7
1944	Aug	13	1053	37.19	178.15	12R	5.6	37.04	177.38	251	5.9
1946	Feb	12	0616	39.79	174.50	12R	6.4	39.77	175.02	132	6.0
1946	Feb	26	0530	38.63	176.35	12R	5.6	38.55	176.98	103	5.6
1946	Sep	29	0835	34.65	177.81	12R	6.1	35.16	178.84	200R	5.3
1947	May	5	0205	39.36	175.35	33R	5.9	39.28	175.51	82	5.8
1948	Oct	03	2158	36.04	175.54	33R	5.5	36.63	176.03	215	5.0
1948	Dec	10	2016	36.57	175.91	33R	5.5	37.32	177.00	250R	4.8
1949	May	27	0854	45.57	167.14	33R	5.9	45.46	167.43	92	6.4
1949	Jun	07	1828	36.42	175.81	33R	5.1	36.74	175.99	164	4.5
1949	Jun	20	0435	34.76	176.98	33R	6.6	35.11	177.18	179	5.3
1949	Dec	18	0935	39.46	176.01	12R	5.5	39.43	176.17	130	5.9
1950	Feb	28	1858	38.88	176.70	30	5.7	38.80	177.05	100R	5.8
1950	Mar	13	0938	40.55	174.04	33R	5.7	40.54	170.00	70	5.6
1954	May	4	0241	44.92	167.60	12R	5.4	44.80	167.75	50	5.1
1955	Mar	3	1602	35.34	179.69	33R	5.5	35.48	179.10	232	5.6
1955	Dec	4	0201	35.51	178.26	33R	5.8	35.67	177.89	150R	5.5
1957	Aug	11	0512	39.09	176.11	33R	6.0	39.05	175.92	99	5.6
1960	Feb	3	0221	37.56	177.99	33R	6.0	37.61	178.04	144	5.9
1960	Feb	21	0046	42.28	173.08	33R	6.2	42.28	173.06	102	5.8
1962	Apr	17	1743	42.81	173.93	12R	5.1	42.85	173.98	33	5.2
1962	Sep	22	1508	36.82	178.59	12R	5.7	37.03	178.44	125	5.5

Notes: * NR= Not revised

5.0 RELATIONSHIPS BETWEEN DIFFERENT MAGNITUDES

We examine relationships between M_S, M_W and M_L using graphical and regression techniques. Because we are interested in predicting one magnitude from another, ordinary least squares regression is used, rather than any technique, such as orthogonal regression, which allows for uncertainties in the predictor variables.

M_W versus M_S

The relation between moment magnitude M_W, surface-wave magnitude M_S and centroid depth h_C, using data restricted to modern M_W determinations (i.e. from 1964 March 8 onwards), is shown in Figure 3. For earthquakes of $h_C \leq 30$ km, M_S and M_W are close to being equal above magnitude 6.5. At lower magnitudes M_S is consistently smaller than M_W and is as much as a quarter-unit smaller between magnitude 5.0 and 5.5. Depth also influences the discrepancy between M_S and M_W; for deep New Zealand earthquakes ($h_C > 50$ km) M_S is about a half-unit smaller than M_W between magnitude 5.0 and 5.5. The results from the tendency for M_S to decrease with depth for earthquakes of a given seismic moment. In

1969 Karnik [16] dealt with this effect by proposing a focal depth correction term for M_S in relation to M_B for various parts of Europe, while Ambraseys & Free [17] have recently estimated a focal depth correction term for M_S in relation to log M_O for European earthquakes. As we are interested in estimates of M_W rather than M_S our approach is to examine the relationship of M_W to M_S and h_C. First, the linear regression of M_W on M_S and h_C is

$$M_W = 1.45[\pm 0.16] + 0.77[\pm 0.03]M_S + 0.0034[\pm 0.0006](h_C - 25) \qquad (4)$$

where the standard error of each coefficient follows it in square brackets. This relation explains 92% of the variance of M_W and has a residual standard deviation of 0.14. Neglecting the depth term for $h_C<50$ km introduces a bias of less than 0.1 magnitude unit. Second, using a quadratic as well as a linear term in M_S gives a slightly improved fit which explains 93% of the variance:

$$M_W = 1.27[\pm 0.16] + 0.80[\pm 0.03]M_S + 0.087[\pm 0.031](M_S-6)^2 + 0.0031[\pm 0.0006](h_C-25) \qquad (5)$$

Both approximations, of course, apply only within the range of the present data. In Eq. (5) it can be seen that the quadratic term contributes significantly to the regression because the coefficient of this term is more than twice its standard error. It is of interest to note that although their expression is different from ours, Ambraseys & Free [17] obtained a coefficient for their depth term of 0.0036, which is very similar to the coefficient of 0.0034 in Eq. (4) above.

A local regression fit of M_W against M_S for earthquakes restricted to $h_C \leq 50$ km was calculated. This provides a robust smooth trend curve against which the linear and quadratic parametric fits can be compared. As for other local regression analyses presented in this paper, it was fitted using the Splus local regression function "loess" [18]. As can be seen from Figure 3, the trend curve lies within about 0.1 magnitude units of the linear and quadratic fits, being slightly closer to the quadratic fit for most of the range of M_S. The quadratic fit in Eq. (5) is thus considered adequate, and is used to derive an inferred value of M_W, denoted $\hat{M}_W$, for earthquakes for which M_S but no value of M_W is known. Thus the "actual or inferred" moment magnitude is available for any earthquake for which either the moment magnitude or surface-wave magnitude is known. This magnitude is plotted in Figures 1 and 2.

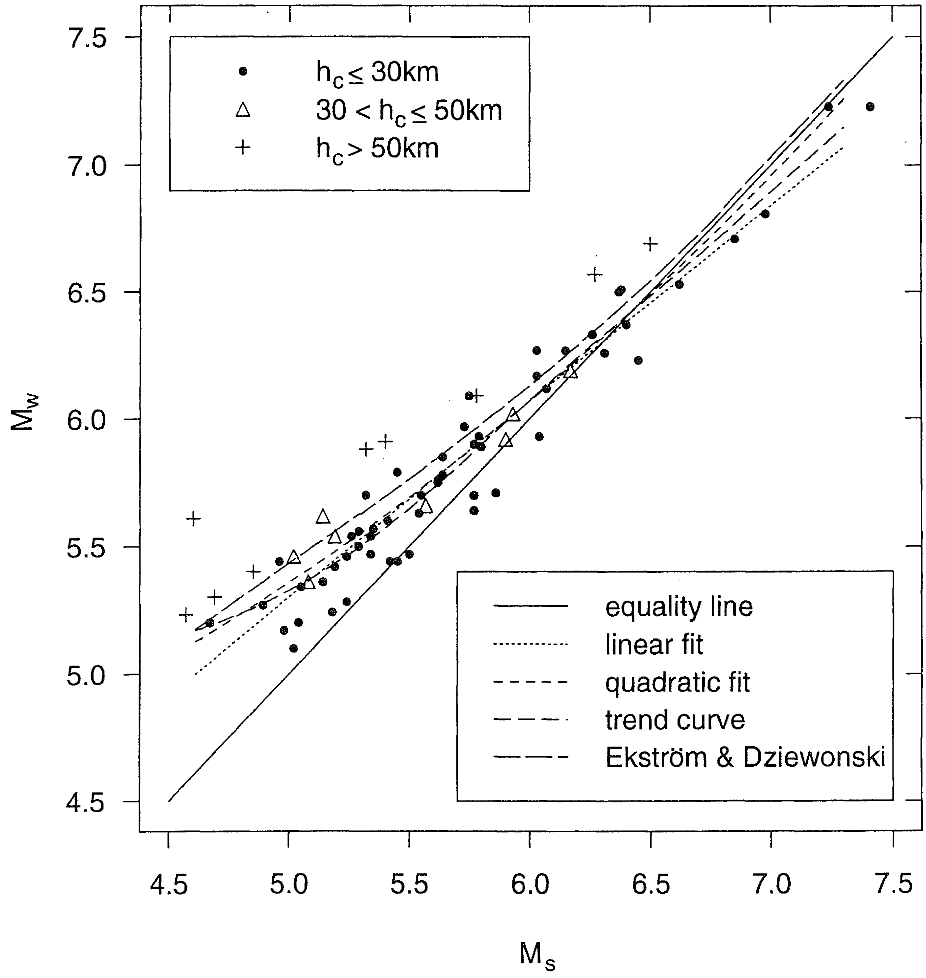

Figure 3: ***Scatter plot of moment magnitude M_W against surface-wave magnitude M_S for earthquakes listed in Table 1, distinguishing events in different classes of centroid depth h_C. Also shown are the linear (Eq. (4)) and quadratic (Eq. (5)) regression fits for M_W evaluated at $h_C = 25$ km, a local regression trend curve of M_W on M_S for events with $h_C \leq 50$ km, and the relation of Eckström and Dziewonski (Eq. (6)).***

Also shown in Figure 3 is the relation of Ekström and Dziewonski [19], derived from global data, between log M_O and M_S for events with h < 50km. In terms of M_W this relation is equation (6)

$$M_W = \begin{cases} 2.13 + \frac{2}{3} M_S & M_S < 5.3 \\ 9.40 - \sqrt{41.09 - 5.07\, M_S} & 5.3 \le M_S \le 6.8 \\ 0.03 + M_S & M_S > 6.8 \end{cases} \qquad (6)$$

As seen in Figure 3, there is no great difference between this relation and the linear and quadratic fits of Eqs (4) and (5) for shallow events over the magnitude range of the data, but the latter also describe the effect of depth.

M_L versus M_S

The relation between M_L, M_S and h_C, using all available M_L/M_S data (i.e. from 1940 March 19 onwards), is shown in Figure 4. In general the correlation between M_L and M_S is weak. Below magnitude 6, M_L tends to exceed M_S; above magnitude 6, the reverse is the case. Despite the wide scatter of the data, the effect of depth is quite marked, with a strong tendency for M_L to exceed M_S for deep earthquakes. The regression of M_L on M_S and h_C explains only 54% of the variance of M_L, and is given by

$$M_L = 3.13[\pm0.21] + 0.47[\pm0.04]\, M_S + 0.0059[\pm0.0009](h_C - 25) \qquad (7)$$

the residual standard deviation being 0.29. This linear relation is shown for $h_C = 25$ km in Figure 4, together with a local regression trend curve of M_L against M_S for earthquakes with $h_C \le 50$ km. The closeness of these two lines shows that the linear relation in Eq. (7) is about as adequate as any fit could be.

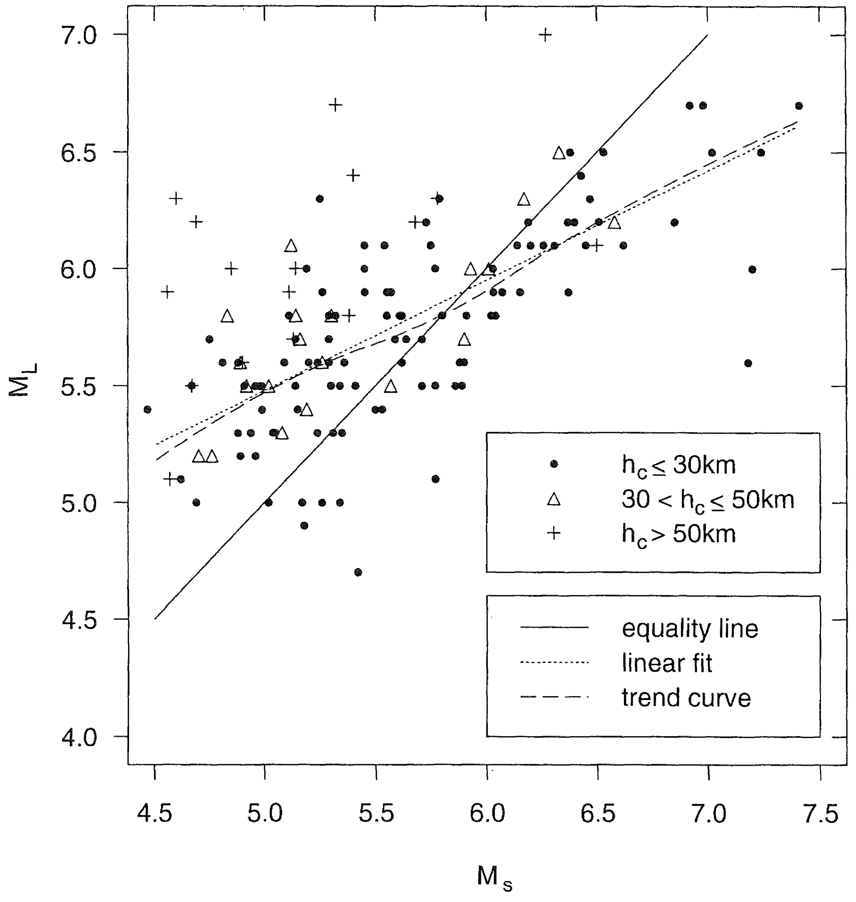

Figure 4: *Scatter plot of local magnitude M_L against surface-wave magnitude M_S for earthquakes listed in Table 1, distinguishing events in different classes of centroid depth h_C. Also shown are the regression fit for M_L evaluated at h_C = 25 km and a local regression trend curve of M_L on M_S for events with $h_C \le 50$ km.*

The residuals from model (7) are denoted R_L^S, i.e.,

$$R_L^S = M_L - [3.13 + 0.47\, M_S + 0.0059(h_C - 25)] \qquad (8)$$

In Figure 5 are plotted the residuals (ie. the differences between the actual and fitted values of M_L in Equation (9)) as a function of earthquake location. There is some regularity in the distribution of the residuals with respect to location, as Figure 5 shows. The larger positive values of R_L^S tend to occur in a central region incorporating the western parts of the northern South Island and southern North Island. Both shallow and deep earthquakes occur in this region. On the other hand, the largest negative values tend to occur in an eastern North Island region which has only relatively shallow events. It appears then that M_L tends to be overestimated relative to M_S in the former region and underestimated in the latter, with a systematic difference of up to a half-unit of magnitude.

In comparing M_L and M_S, two tsunami producing earthquakes should be mentioned, i.e. those of 25 March 1947 (M_L 6.0, M_S 7.2) and 17 March 1947 (M_L 5.6, M_S 7.2). Their very large discrepancies between M_L and M_S were noted by Eiby [20, 21], but in these two events the intensity patterns correspond to M_L rather than M_S. The anomalously high M_S values are thought [18,19] to be the consequence of these earthquakes having "slow" ruptures, ie. rich in long-period energy, but poor in short-period energy. These two events have therefore been omitted from the above analyses and the figures in this paper.

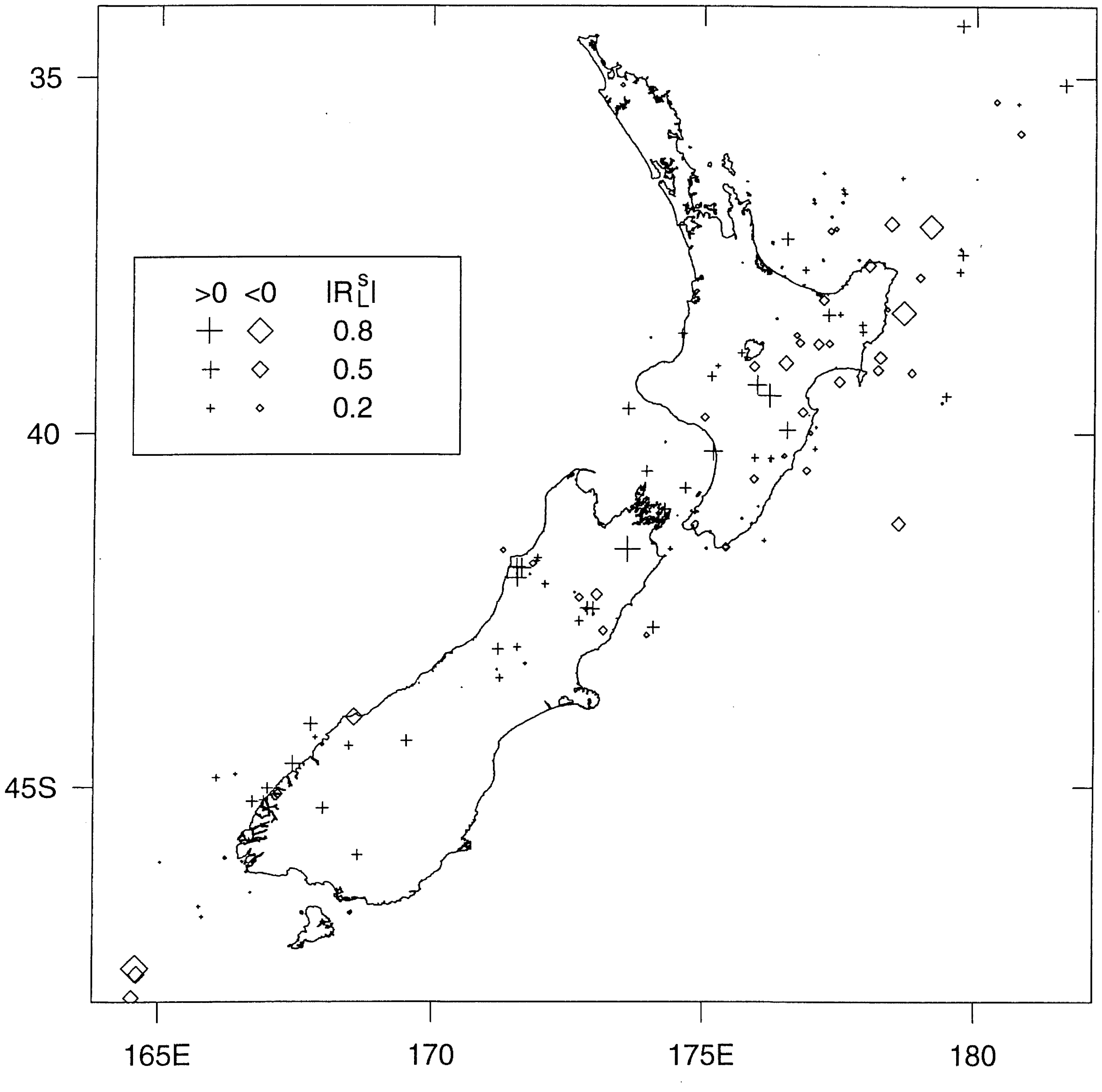

Figure 5: ***Distribution of residuals R_L^S from linear regression (7) of local magnitude M_L on surface-wave magnitude M_S and centroid depth h_C with respect to epicentral location.***

M_L versus M_W

The graph of M_L against M_W is also quite scattered and the pattern of the shallow event data and the trend line are somewhat curvilinear (Figure 6). Depth again has a marked effect, with M_L tending to exceed M_W for deep earthquakes. Above magnitude 6, M_W tends to exceed M_L, especially for shallow earthquakes. This is consistent with the tendency of M_L to saturate at values of about 7. For M_W in the range 5.0-5.5, the scatter of M_L values is particularly wide. The regression of M_L on M_W and h_C, using data from 1964 onwards, explains only 65% of the variance of M_L, and is given by

$$M_L = 1.65[\pm0.41] + 0.71[\pm0.07]\, M_W + 0.0065[\pm0.0013]\,(h_C - 25) \quad (9)$$

the residual standard deviation being 0.29. It can be seen from the size of the standard error of the coefficient of M_W that this coefficient is significantly less than unity, again reflecting the tendency of M_L to saturate for larger earthquakes. Adding a quadratic term in M_W improves the fit marginally, (in the sense of reducing the residual mean square, but not significantly so) making the proportion of variance explained 66%. The quadratic fit is

$$M_L = 1.62[\pm0.41] + 0.72[\pm0.07]\, M_W - 0.16[\pm0.11](M_W - 6)2+0.0065[\pm0.0013](h_C - 25) \quad (10)$$

In Figure 6 the above linear and quadratic relations are compared with a local regression trend curve of M_L against M_W for earthquakes with $h_C \leq 50$ km. The quadratic curve is seen to lie within about 0.1 magnitude unit of the trend curve and, given the scatter of the data, is nearly as adequate a fit as can be obtained over the present data range of M_W.

A similar regression to the above was also carried out, using all available M_L/M_W data, i.e. from 1943 Feb 17 onwards, thus including the more variable pre-1964 M_W data of "historic" South Island earthquakes [13]. The resulting expression equivalent to Equation (9), not presented here, explained only 54% of the variance.

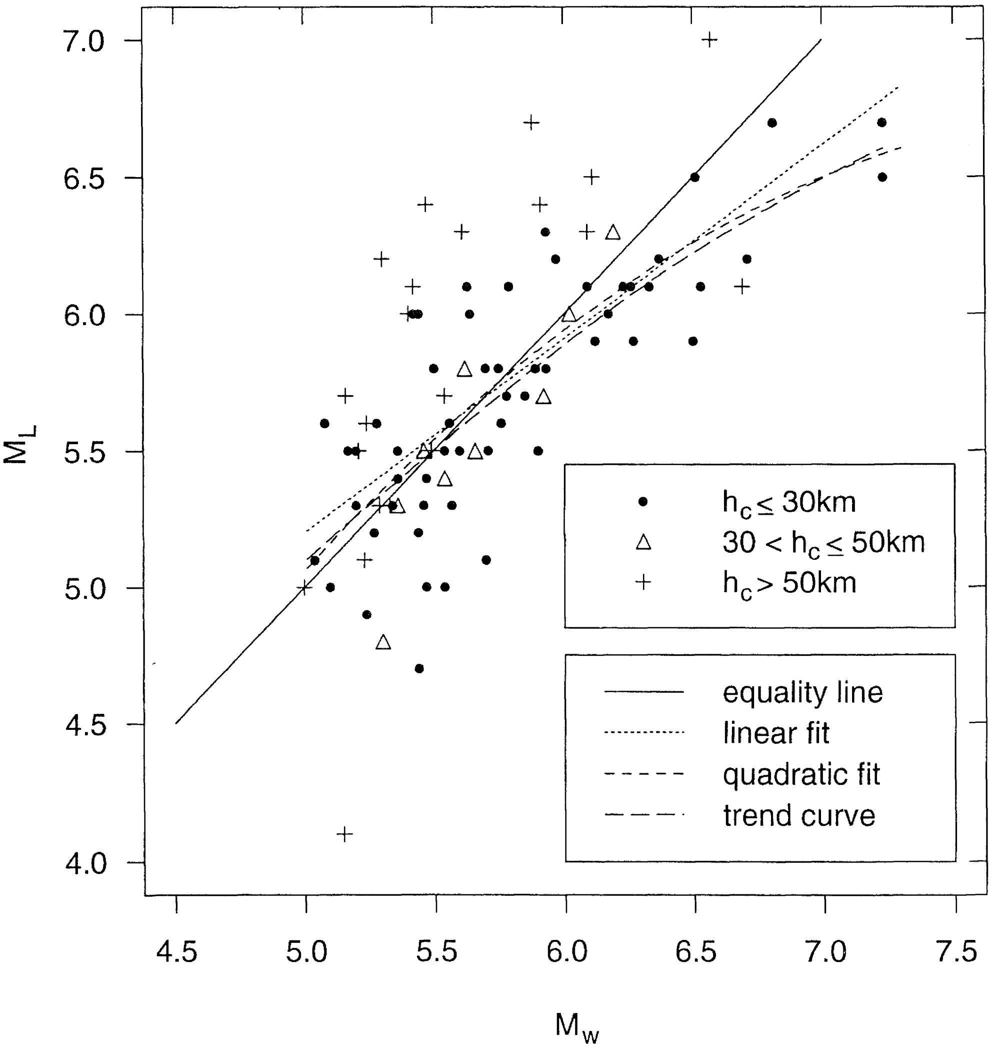

Figure 6: ***Scatter plot of local magnitude M_L against moment magnitude M_W for earthquakes listed in Table 1, distinguishing events in different classes of centroid depth h_C. Also shown are the linear and quadratic regression fits for M_L evaluated at h_C = 25 km and a local regression trend curve of M_L on M_S for events with $h_C \leq 50$ km.***

For estimating M_W from M_L and h_C, the best linear regression is

$$M_W = 0.96[\pm 0.49] + 0.84\,[\pm 0.08]\,M_L - 0.0055\,[\pm 0.0015]\,(h_C - 25) \qquad (11)$$

The regression explains 59% of the variance and has a residual standard deviation of 0.31.

Harvard *versus* local M_W

The Harvard estimates of seismic moment [5], M_O (Harvard), are available for the larger recent earthquakes and are listed in Table 1 together with the larger set of locally determined values [3,4]. The corresponding moment magnitudes are denoted M_W (Harvard), defined by Kanamori [22, 23] as

$$M_W = \tfrac{2}{3}\,\log_{10} M_O - 6.03 \qquad (12)$$

where M_O is expressed in Nm.

There are small differences between M_W determined from body-wave modelling and M_W from CMT inversion (ie M_W(Harvard) as illustrated in Figure 7, but no apparent systematic differences. The correlation between them is 0.98. A regression of one variable on the other does not vary significantly from the line of equality and has a residual standard deviation of 0.08 magnitude units.

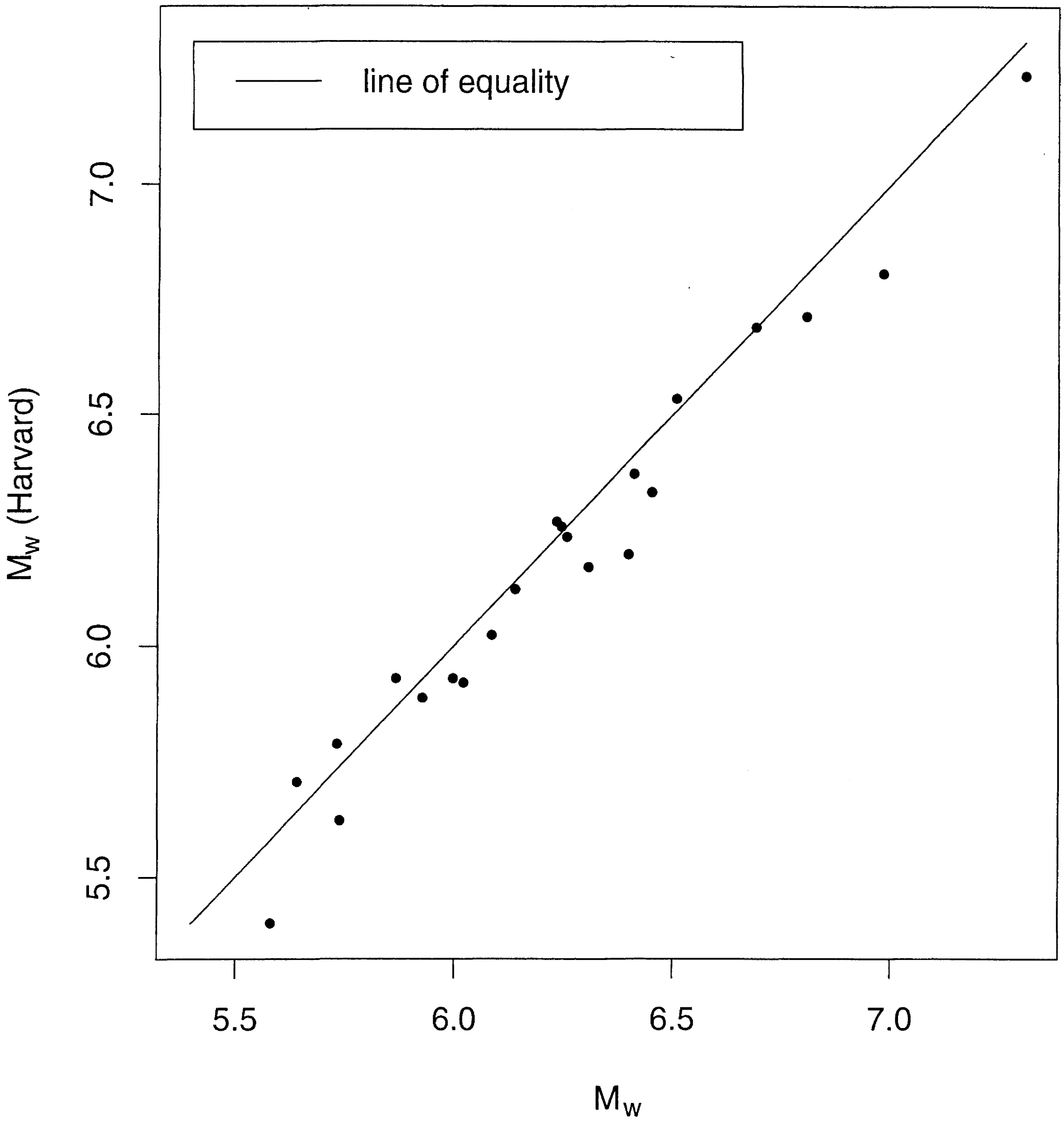

Figure 7: Comparison of moment magnitudes M_W(Harvard) and M_W (determined from body-wave modelling) for earthquakes listed in Table 1.

Magnitude *versus* number of observations

The number of stations outside of New Zealand (N) at which an earthquake of given M_W was observed has increased steadily over the period 1901-1990. In Figure 8 a local regression fit of N against actual or inferred M_W and year of occurrence is presented, with curves showing the expected number of stations observing an earthquake as a function of magnitude M_W in a given year. Also shown are the $\pm 2\sigma$ (approximate 95%) tolerance limits for the actual number of stations when the expected number of stations observing an earthquake is 10.

These curves and tolerance limits can be used to infer an (approximate) upper limit on the magnitude of any earthquake which was not recorded at any non-New Zealand station. The moment magnitude of such an earthquake is most unlikely to have been so large that the expected number of observations was 10 or more. On this basis the moment magnitude of a shallow earthquake which was not observed at any station outside of New Zealand is almost certainly less than 6.0 if it occurred after 1920, 5.8 if it occurred after 1930, 5.7 if it occurred after 1940, 5.5 if it occurred after 1950 and 5.2 if it occurred after 1960. Thus, for example, for the crustal earthquake of 1940 Feb 26, which is assigned a magnitude of M^*6 in the New Zealand Seismological Observatory Catalogue, the moment magnitude was almost certainly less than 5.7.

In some cases the upper limits derived by this method are highly conservative. For example, in 1922 between June 9 and September 5 a series of very shallow events, known as the Taupo swarm, occurred at about 38.60°S and 176.10°E. Only three of these events were recorded at any non-New Zealand station, and the largest M_S was for the event of 1922 September 5, at 5.14, giving an $\hat{M}_W$ of 5.40. The events with $N = 0$, on June 9 and 18 and July 14,16,17 and 26, may therefore safely be given upper limits for M_W of 5.4, rather than 6.0 as arises out of the analysis described above. In addition, the earthquakes of 1913 April 12 and 1928 March, not reported overseas, were originally assigned M^* 5¾ and 6 respectively. From their intensity maps (Dowrick, unpublished work) these events are estimated to have been of magnitude ~5.8 and ~5.5 respectively.

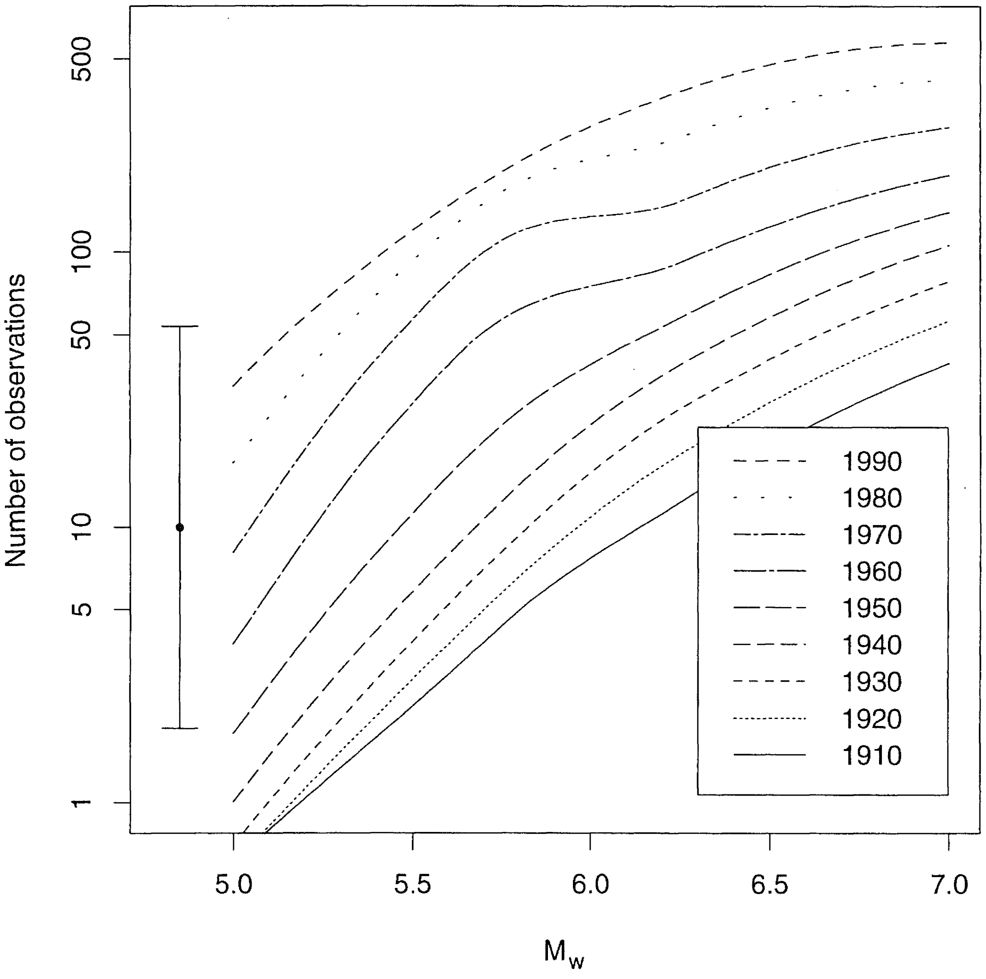

Figure 8: ***Curves of expected number of stations outside New Zealand at which an earthquake was observed as a function of the actual or inferred moment magnitude M_W and date of occurrence. This relation was determined from a local regression analysis of number of observations on actual or inferred M_W and date. The error bar shows approximate 95% tolerance limits for the number of observations when the expected number of observations is 10.***

6.0 CONCLUSION

The data assembled for this study have allowed surface-wave magnitudes to be estimated on a consistent basis for 192 New Zealand earthquakes in the period 1901-1993, including 69 earthquakes for which surface-wave magnitudes have previously been presented based on a smaller data set. The number of usable station observations of earthquakes of a given size has increased steadily over this period, with a corresponding improvement in the quality of the estimates over time.

Comparisons of M_S, M_W and M_L have clarified the relations between these different types of magnitude estimate. Depth has been shown to contribute significantly to the relations, and epicentre location also appears to affect the relation between M_L and M_S. However there remains much unexplained variation in the relations between M_L and M_S, and between M_L and M_W. Since M_L is likely to remain, in the foreseeable future, as the only magnitude routinely available for small earthquakes, it is important to try to gain a greater understanding of the reasons for this variation. The possibility that M_W may become routinely estimated in New Zealand for events of M_W 5 is to be encouraged. At present, estimates of M_W from M_S and M_W from M_L have standard errors of about 0.15 and 0.3 respectively.

As a bi-product of the study, a sizeable number of earthquakes have had their source locations substantially relocated, and upper limits have been placed on the lowest magnitude of other events. This has implications for regional seismic hazard modelling, particularly for the low seismicity Auckland/Coromandel area.

ACKNOWLEDGEMENTS

Much of the surface-wave data used in this study was not available in New Zealand and this necessitated visits by the first author to Australia and England in order to obtain sufficient data. The authors wish to express their gratitude for the friendly co-operation during these trips, and subsequently, of the following people and organisations: M. Leiba and K. McCue (Australian Seismological Centre, Canberra); N. Ambraseys (Imperial College, London); R. Adams and A. Hughes (International Seismological Centre, Thatcham, England).

This study was funded by the Foundation for Research, Science and Technology under Contract No. Co5405. We wish to thank W.D. Smith and T. H. Webb for carrying out special determinations of magnitude and location for a number of earthquakes, and M.W. Stirling and T.H. Webb for their helpful in-house reviews of this paper. Finally we thank E.G.C. Smith for his constructive external review.

REFERENCES

1. Dowrick, D.J., and E.G.C. Smith (1990). Surface-wave magnitudes of some New Zealand earthquakes 1901-1988, *Bulletin N.Z. National Society for Earthquake Engineering*, **23**, 198-210.

2. Dowrick, D.J. (1991). Magnitude reassessment of New Zealand earthquakes, *Earthquake Engineering and Structural Dynamics*, **20**, 577-596.

3. Anderson, H., T. Webb and J. Jackson (1993). Focal mechanisms of large earthquakes in the South Island of New Zealand: implications for the accommodation of Pacific-Australia Plate motion, *Geophysical Journal International*, **115**, 103-1054.

4. Webb, T.H. and H. Anderson (1998). Focal mechanisms of large earthquakes in the North Island of New Zealand: slip partitioning at an oblique active margin, *Geophysical Journal International,* **134**, 40-86.

5. Dziewonski, A.M. *et al.* Centroid moment tensor solutions, *Physics of the Earth and Planetory Interiors,* various issues.

6. Vanek, J., A. Zatopek, V. Karnik, N. Kondorskaya, Y. Riznichenko, E. Savarenski, S. Solviev ad N. Shebalin (1962). *Standardisation of Magnitude Scales,* Izvestia Academy of Sciences, USSR, Geophysics Series 2: 108.

7. *Bulletin of the International Seismological Centre* (England), various issues.

8. Ambraseys, N.N., and C.P. Melville (1982). *A History of Persian Earthquakes,* Cambridge University Press.

9. Doser, D.I. and Webb, T.H., Source parameters of large historic (1918-1962) earthquakes, South Island, New Zealand, (submitted to Geophysical Journal International).

10. Downes G. L. (1995). *Atlas of Isoseismal Maps of New Zealand earthquakes,* Monograph 11, Institute of Geological Sciences, Lower Hutt.

11. Ansell, J., and S. Bannister (1996). Shallow morphology of the subducted Pacific plate along the Hikurangi margin, New Zealand, *Physics of the Earth and Planetary Interiors*, **93**, 3-20.

12. Anderson, H., and T. Webb (1994). New Zealand seismicity: patterns revealed by the upgraded national seismograph network, *New Zealand Journal of Geology and Geophysics,* **37**, 477-493.

13. Downes, G.L., D.J. Dowrick, E.G.C. Smith, and K.R. Berryman. The 1934 Pahiatua earthquake sequence: Analysis of observational and instrumental data, (in prep.).

14. Doser, D.I. and Webb, T.H., Source parameters of large historic (1917-1961) earthquakes, North Island, New Zealand, (in prep.).

15. Rhoades, D.A., and D.J. Dowrick. (1999) Station correction analysis for surface-wave magnitudes of New Zealand earthquakes. Bulletin N.Z. National Society for Earthquake Engineering (in press).

16. Karnik, V. (1969). *Seismicity of the European Area, Part 1*, D. Reidel Publishing Company, Dordrecht, Holland.

17. Ambraseys, N. N. and M. W. Free (1997). Surface-wave magnitude calibration for European region earthquakes, *Journal of Earthquake Engineering*, **1(1)**, 1-22.

18. Chambers, J. M., and T. J. Hastie (1992). *Statistical Models in S*, Wadsworth & Brooks/Cole, Pacific Grove, California, 608pp.

19. Ekström, G., and A. M. Dziewonski (1988). Evidence of bias in estimations of earthquake size, *Nature,* **332**, 319-323.

20. Eiby, G.A. (1982). Earthquakes and tsunamis in a region of diapiric folding, *Tectonophysics,* **85 (3-4)** T1-T8.

21. Eiby, G.A. (1982). Two New Zealand tsunamis, *Journal of the Royal Society of New Zealand,* **12(4)**, 337-351.

22. Kanamori, H. (1997). The energy release in great earthquakes, *Journal of Geophysical Research*, **82**, 2981-2987.

23. Hanks, T.C., and H. Kanamori (1979). A moment magnitude scale, *Journal of Geophysical Research,* **B 84**, 2348-2350.