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Use of the Mantle Magnitude M_m for the Reassessment of the Moment of Historical Earthquakes.

II: Intermediate and Deep Events

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Abstract—We extend to the case of intermediate and deep earthquakes our application of the mantle magnitude M_m to historical events. Because of the general lack of quantitative studies of deep earthquakes before the initiation of the Centroid Moment Tensor databank in 1977, we regard as historical all non-shallow earthquakes up to and including 1976. An analysis of 57 records from 41 events, using the Uppsala Wiechert seismometer and various long-period instruments at Pasadena, yields new moment estimates for 28 events whose moments had not previously been published. Our results correlate poorly with available traditional magnitudes, as would be expected from early saturation effects for magnitude scales measured at relatively high frequencies. They also suggest that large events (10^{28} dyn-cm and greater) take place in the 100–200 km depth range, but that the depth interval 350–520 km features few if any large earthquakes.

Key words: Deep seismicity, historical seismicity, seismic moment, magnitudes, mantle waves.

Introduction and Purpose

This paper follows in the steps of our previous contributions in which we introduced the concept of a mantle magnitude, M_m (OKAL and TALANDIER, 1989), applied it to intermediate and deep earthquakes (OKAL, 1990), and more recently to historical shallow events (OKAL, 1992; hereafter Paper 1). The motivation of the development of M_m has been to give a simple, single-station, quantification of an earthquake source, directly related to the seismic moment M_0 of the event, and thus providing an estimate of the true size of the source, irrespective of the saturation affecting traditional magnitude scales. Specifically, the measurement of M_m is taken on the Fourier spectrum of mantle Rayleigh waves, using the formula

$$M_m = \log_{10} X(\omega) + C_S + C_D - 0.90 \qquad (1)$$

where $X(\omega)$ is the spectral amplitude at the angular frequency ω in μm-s, C_D a distance correction, and C_S a source correction whose exact expressions for deeper sources are given in OKAL (1990). In particular, C_S must be adapted to the individual depth of the earthquake, which we bin into three broad categories:

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Intermediate (A) from 75 to 200 km; Intermediate (B) from 200 to 400 km; and Deep beyond 400 km. The largest value of M_m over the available Fourier spectrum is retained, and is expected to be an estimate of $[\log_{10} M_0 - 20]$, where the seismic moment M_0 is in dyn-cm. We have verified on a growing dataset now approaching 1000 earthquakes that the method has an accuracy on the order of ± 0.2 units of magnitude (HYVERNAUD *et al.*, 1992). We concentrate here on the application of the mantle magnitude formalism to historical earthquakes with intermediate and deep hypocenters.

Existing catalogues of the size of deep historical earthquakes are at best imprecise. We describe in Paper I some of the problems inherent in the quantification of large shallow historical earthquakes using traditional magnitude scales, and in the unreliable estimation of seismic moments for these events from such data as the extent of aftershock zones. The problem is compounded in the case of deeper sources by the nature of the magnitudes used in the catalogues. The primary source of quantification of non-shallow earthquakes before 1963 remains a "Pasadena" magnitude M_{PAS}, assigned personally by B. Gutenberg and C. F. Richter during the preparation of their monumental work *Seismicity of the Earth* (GUTENBERG and RICHTER, 1954). In many instances, M_{PAS} remains the only magnitude included in the USGS/NEIC database ("the NEIC tape"). While later studies have shown that M_{PAS} was basically identical to present-day M_s for shallow earthquakes (GELLER and KANAMORI, 1977), the exact nature of M_{PAS} for intermediate and deep events is more erratic. In a detailed and careful compilation, ABE and KANAMORI (1979) revised the M_{PAS} estimates by recomputing a long-period body-wave magnitude, m_B, suggested by GUTENBERG (1945), and designed to bring stability and uniformity to the quantification of non-shallow events. However, m_B shares with M_{PAS} the drawback of being a body-wave magnitude measured at the relatively short periods characteristic of body waves, typically $T = 5$ to 10, exceptionally 15, seconds. These magnitude scales are therefore expected to saturate, as a result of source finiteness in time and space, just like M_s (measured at 20 seconds) saturates around 8.3 for events with $M_0 \geq 10^{28}$ dyn-cm (GELLER, 1976). An interpolation of Geller's results shows that a 5-second magnitude is expected to saturate around 7.3 for events with $M_0 \geq 3 \times 10^{26}$ dyn-cm, while a 12-second magnitude would reach 7.8 for $M_0 \geq 10^{27}$ dyn-cm. Unfortunately, we now have modern proof that significant intermediate and deep earthquakes take place with moments greater than these thresholds (e.g., the 1970 Colombian earthquake, and the ten Centroid Moment Tensor [CMT] solutions obtained since 1977 with moments greater than 10^{27} dyn-cm). In this context, the mere fact that m_B is measured over a variable, but limited range of periods, strongly restricts its use for the purpose of comparing the very largest deep shocks. Finally, KANAMORI (1983) proposed the relationship $\log_{10} M_0 = 2.4 m_B + 10.1$ on the basis of GUTENBERG's (1956) observation of an empirical relation between magnitude and energy; however, such a relation and especially the value 2.4 for its slope, are not easily explained in simple theoretical terms.

From a chronological standpoint, and going backwards in time, the present situation regarding the seismic moments of deep sources is as follows:

* Reliable seismic moments start to be regularly available in 1977, thanks to the systematic compilation of CMT solutions by the Harvard group (DZIEWONSKI *et al.*, 1983 and subsequent updates). In particular, it is important to stress that this catalogue is *homogeneous*, i.e., all events are solved using the same kind of data and the same, permanent, algorithm.
* For the period between the implementation of the WWSSN (1963) and the beginning of the CMT solutions (1977), which we will call the WWSSN era, a number of seismic moments have been published. However, these solutions have stemmed from a variety of methods, and may not be mutually comparable. This situation is fundamentally different from that of shallow events, for which the majority of the large shocks have been studied in detail by forward-modeling or inverting abundant datasets of intermediate-to-long period surface waves. The fundamental motivation behind these studies was the estimation of seismic risk and recurrence times along the major subduction zones; this motivation is absent for deeper events, and fewer solutions have been published.

  Specifically, a number of very large deep earthquakes (mostly, but not exclusively, at the bottom of individual subduction zones) have been the subject of detailed studies, often based on the same methods used for shallow shocks, namely long-period surface wave modeling: Peru-Brazil, 1963 (FURUMOTO and FUKAO, 1976); Colombia, 1970 (GILBERT and DZIEWONSKI, 1975); Banda Sea, 1963 (OSADA and ABE; 1981; WELC and LAY, 1987); South Sandwich, 1964 (ABE, 1972). In addition, a number of events were studied by body-wave modeling, often times by fitting a corner-frequency source model to the spectrum of WWSSN long-period seismograms. In general, this method has poor resolution as the corner frequency decreases below 60 mHz (i.e., as the size of the earthquake increases), and the quality of fit, when shown, often suggests an uncertainty of at least half an order of magnitude. The motivation behind these studies was the recovery of such parameters as stress drop at various depths inside the Wadati-Benioff zones. A monumental compilation of such parameters, including published seismic moments, can be found in PURCARU and BERCKHEMER (1982), both for shallow and deep earthquakes.

  On the other hand, a large number of focal mechanisms are available in the literature, either in world-wide compilations such as ISACKS and MOLNAR's (1971) aimed at retrieving the state of stress inside the descending slabs, or as the result of regional studies, such as STAUDER and MUALCHIN's (1976) in the Northwest Pacific. Also, DENHAM (1977) has compiled a catalogue of focal solutions for the Western Pacific and Indonesia, which includes earthquakes of all depths. His catalogue extends back to 1929, but some of the earlier solutions can be inaccurate. The common motivation of all these studies was the retrieval of the directions of displacement or of stress release, and the size (moment) information was either not sought, or lost. More recently, ASTIZ *et al.* (1988) have compiled a large number of focal solutions of intermediate events, including many original ones during the WWSSN era. The only moments listed by ASTIZ *et al.* (1988) are for CMT solutions, i.e., post-1976.

During the WWSSN era, the parameter most frequently available for non-shallow earthquakes is their short-period body-wave magnitude m_b, which is known to saturate as early as $m_b = 6.3$; $M_0 \geq 10^{25}$ dyn-cm (GELLER, 1976). In this respect, and from the point of view of quantification, it would seem appropriate to extend the qualifier "historical" to all intermediate and deep events up to and including 1976, i.e., predating the routine availability of CMT solutions.

* For earthquakes pre-dating the WWSSN (1962 and before), seismic moments are in general not available (a notable exception being the 1954 Spanish earthquake ($M_0 = 7 \times 10^{27}$ dyn-cm (CHUNG and KANAMORI, 1976), but only $M_{\mathrm{PAS}} = 7.0$), and the number and quality of focal solutions drop rapidly with age. A substantial dataset for this period of time remains WICKENS and HODGSON'S (1987) compilation of more than 600 focal solutions, many of them intermediate or deep. These authors were very careful to include a printout of the convergence of their solutions, as documented by the final iterations of their computer code, which gives an estimate of the quality and degree of constraint of the solutions.

The generally poor quality of the available dataset of non-shallow earthquake sizes prior to 1977 inhibits any attempts to estimate such factors as seismicity rates and/or recurrence times. The exact mechanism of earthquake genesis for intermediate and deep earthquakes is still poorly understood, and is presently the subject of new and exciting speculation (e.g., KIRBY *et al.*, 1991). It is clear, however that such models cannot be tested on the basis of a reliable dataset extending back only 15 years, and that it is crucial at this point to obtain seismic moments for WWSSN-era and older non-shallow earthquakes.

In the present paper, we compute mantle magnitudes to obtain moment estimates for 41 intermediate and deep events, ranging from 1909 to 1975. We are motivated by our observation on recent earthquakes, that the M_m algorithm provides an acceptable accuracy on the seismic moment, typically on the order of 0.2 units of magnitude, or a factor of 1.6 on the moment. The present study does not purport to provide a full, detailed study of each event studied: the estimates of M_0 obtained remain for the most part single-station determinations, and further constraints could be obtained, especially in the case of WWSSN-era events, from body- and surface-wave modeling of extended datasets.

Dataset and Methodology

Following the strategy in Paper I, we concentrate on Wiechert records from the Uppsala Observatory, and for more recent times, make use of Pasadena records, principally from the Benioff 1–90 seismometer and the various long-period systems developed at Pasadena during the 1950s and 1960s.

As the hypocentral depth of an event is increased, the spectrum of Rayleigh waves shifts towards lower frequencies, which themselves suffer from lessened excitation by seismic sources. As detailed in OKAL (1990), the minimum period at which M_m measurements can be taken grows from 50 s for shallow events to 190 s for deep ones. As a result, only the very largest non-shallow events can be investigated, this limitation being particularly acute for the Wiechert instruments, whose response is biased towards higher frequencies. As described on Figure 1 (which extends the concept of Figure 2 of Paper I), the minimum size for an earthquake to be recorded by the Uppsala Wiechert above noise level grows from $M_m = 6.99$ at shallow depths to $M_m = 7.16$ for Intermediate (A) events, 7.79 for Intermediate (B), and 8.43 for Deep ones. In practice, this means that no Deep event ($h \geq 400$ km) can be adequately recorded above noise level on the UPP

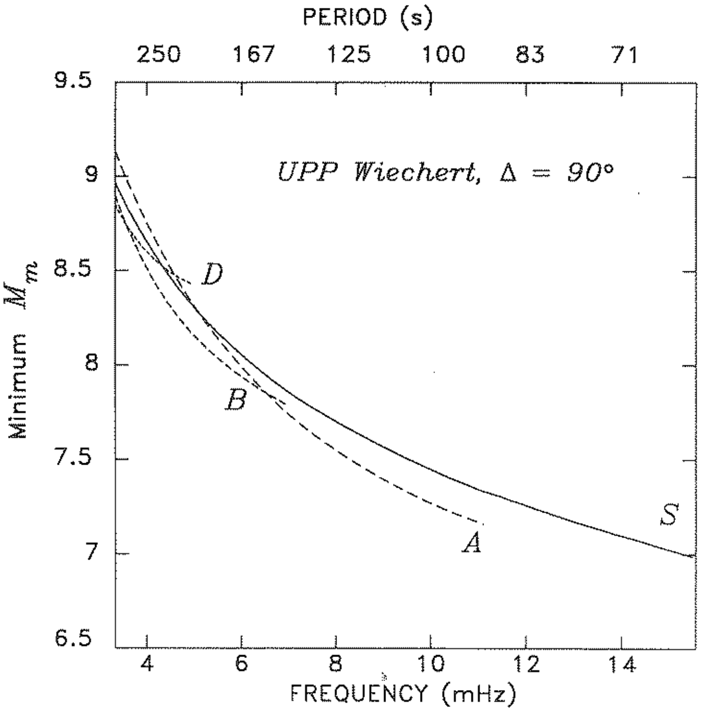

Figure 1
Minimum magnitude M_m measurable as a function of frequency on a horizontal component of the Uppsala Wiechert, for a typical distance of 90°. This figure extends Figure 2 of Paper I (shallow earthquakes; solid trace labeled S) to the case of deeper sources. The various traces correspond to Intermediate (A), Intermediate (B) and Deep (D) sources. Each corresponds to a time-domain noise level of 0.5 mm on the record.

Wiechert, a result which we verified based on the large 1970 Colombian event ($M_m = 8.30$): we could not identify usable surface wave trains at UPP. Of course, starting in the 1930s, improved instrumentation makes it feasible to study smaller events; for example, corresponding thresholds for the Benioff 1–90 system would be: 5.72 (Shallow), 5.87 (Intermediate (A)), 6.54 (Intermediate (B)) and 7.26 (Deep).

We targeted initially all events since 1904 with at least one magnitude (usually M_{PAS}) greater than 7.5 (1904–1962) or 7.0 (1963–1976). The change of standard in 1963 reflects what we believe is a systematic bias of the old scales, and the use of more sensitive instrumentation in the 1960s. Of the 96 such events extracted from the NEIC tape (24 post-1963), we selected by visual inspection of the Uppsala and Pasadena archives 67 records from 44 events, and were able to obtain 57 new determinations of M_m for 41 events. In practice, and whenever possible, we selected the largest events recorded in individual geographic areas. The ten records which were not processed correspond either to spectral amplitudes falling beyond the noise level (see discussion above), or to uncertainty in the instrument magnification, or even, in the case of the 13 January 1960 event in Peru, to an erroneous depth on the NEIC tape (the event is listed as intermediate ($h = 200$ km), but is really shallow, as correctly reported by the ISS ($h = 64$ km)). A geographic map of the events investigated in the present study is shown on Figure 2; a set of typical records is given on Figure 3.

Computation of M_m from First Rayleigh Overtones

In keeping with our experience with modern events (OKAL, 1990), in no instance did we attempt to use Love waves, due to time-domain contamination of their waveforms by overtones. The situation is quite different with Rayleigh overtones: intermediate and deep events are known to generate substantial overtones, in particular the branches ${}_1R$ and ${}_2R$, both well separated from the fundamentals, due to specific group velocities in the mantle period range (typically 70 to 100 s for ${}_1R$). They appear on seismograms as individual "phases," which OKAL (1979) and later OKAL and JO (1983) have used to retrieve the dispersion properties of the first branch ${}_1R$.

The clear recording of Rayleigh overtones from large deep earthquakes (see Figure 4) suggests the possibility of computing a mantle magnitude $M_m^{\mathrm{overt.}}$ from their vertical component. The computation proceeds as in the case of the fundamentals, but the corrections C_S and C_D in (1) must obviously be altered. In the case of C_S the modeling of the excitation of the branch of first higher spheroidal modes, as computed at 550 km from the PREM model (DZIEWONSKI and ANDERSON, 1981), between periods of 70 and 150 s leads to an expression of the form

$$C_S^{\mathrm{overt.}} = 4.5945\theta^3 + 9.5778\theta^2 - 0.7791\theta + 4.4503 \tag{2}$$

where $\theta = \log_{10} T - 1.9560$. As for the distance correction C_D, it simply needs to reflect the relevant values of group velocity and attenuation, which we took from

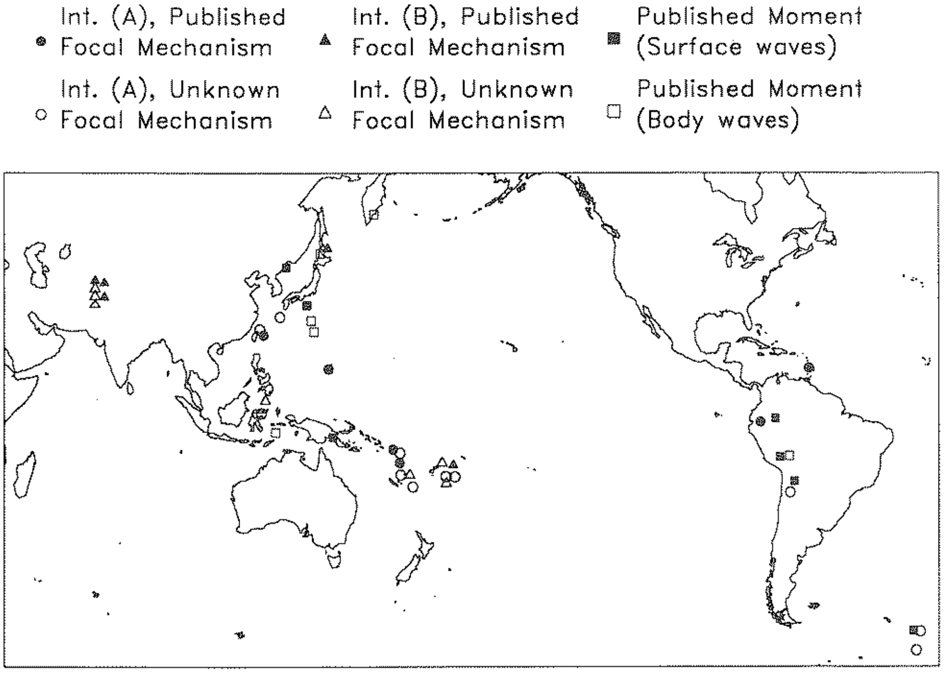

Figure 2
Map of the events investigated in this study. Various symbols are used to identify the depth ranges and the availability of source information (see text for details). In the case of nearby epicenters, some of the symbols have been moved slightly to avoid plotting several events on top of each other.

the PREM model (DZIEWONSKI and ANDERSON, 1981). Also, we did not use any tectonic regionalization in the computation of $M_m^{\text{overt.}}$.

A total of five overtone measurements were taken; under these conditions, the residuals ($\bar{r} = 0.08$; $\sigma = 0.41$; $\bar{r}_c = -0.03$; $\sigma_c = 0.29$) have little statistical meaning; in particular, the residual population is strongly biased by one event (07 October 1968) whose published moment we believe to be significantly overestimated (see Appendix). When this event is removed, the residuals ($\bar{r} = 0.23$; $\sigma = 0.32$; $\bar{r}_c = 0.10$; $\sigma_c = 0.13$) have generally the same quality as regular M_m values computed on fundamentals. We added to the general dataset the measurements on the fundamentals previously reported in OKAL (1990), for events whose overtones were investigated in the present study.

From M_m to M_c and the Seismic Moment

Once an estimate of M_m was obtained, further study evolved differently depending on the availability of focal mechanism and seismic moment information.

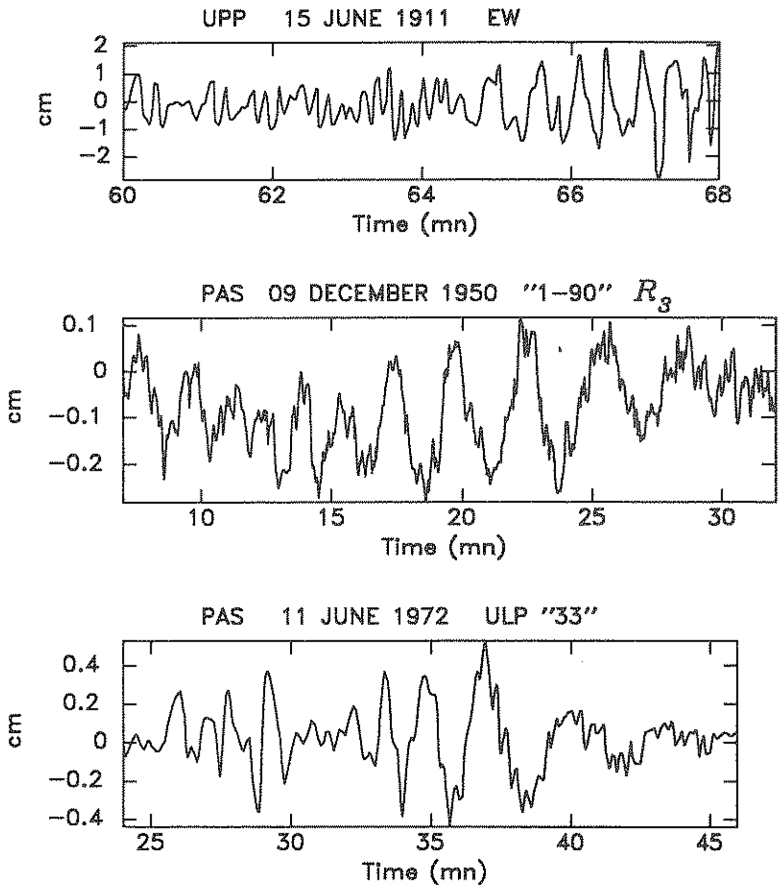

Figure 3

Examples of records used in the present study. The top seismogram is a typical Uppsala record of the 1911 earthquake at the Taiwan corner ($h = 200$ km); the center plot shows the third Rayleigh passage R_3 recorded on the Benioff 1–90 at Pasadena from the 1950 Argentina earthquake (possibly the largest intermediate depth event ever recorded; $h = 128$ km); the bottom trace is an Ultra-long period "33" record at Pasadena from the Celebes Sea event of 1972 ($h = 325$ km). Note different scales for time and amplitudes.

Following the general approach in Paper I, we distinguish between

1. *Events for which a detailed focal solution (focal geometry and seismic moment) is available in the literature.* For these 13 earthquakes (mostly WWSSN-era), we compute the corrected magnitude M_c, along the lines of OKAL and TALANDIER (1989), OKAL (1990) and Paper I, using the published focal mechanism and depth. The resulting M_c can be compared to the equivalent published mantle magnitude, $[M_m^p = \log_{10} M_0 - 20]$ and this comparison gives an estimate of the performance of our method. These events are shown as filled squares on Figure 2.

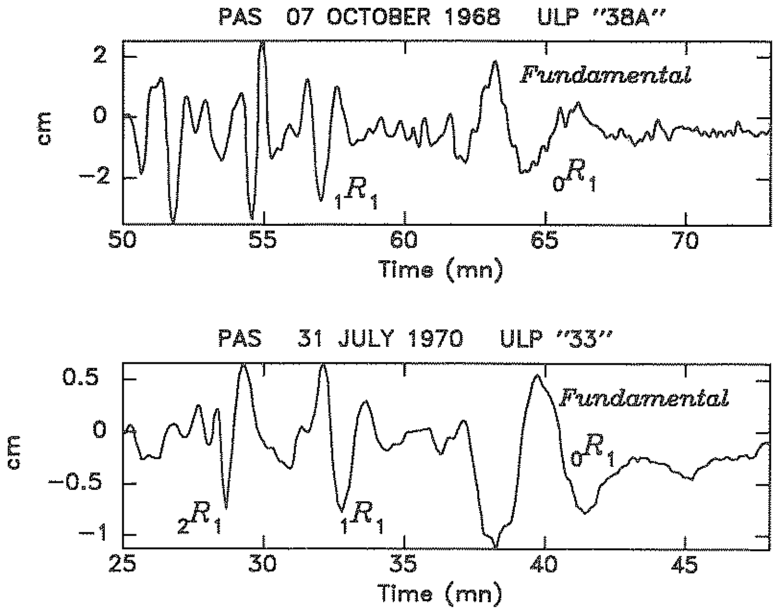

Figure 4

Examples of first Rayleigh overtone passages on ultra-long-period systems at Pasadena. The top trace is a record of the deep Bonin Trench event of 1968 ($h = 516$ km) on the high-gain ultra-long-period instrument; the bottom trace is the 1970 Colombia event recorded on the Number "33" seismometer. In both cases, windows of 4-minute duration centered on $_1R_1$ are used to recover $M_m^{\text{overt.}}$. Note difference in scale between diagrams.

2. *Events for which a focal mechanism is published in the literature, but no seismic moment is available.* These eleven earthquakes (including a new solution computed as part of this study) have intermediate depths and span the years 1949–1975. We similarly used the published focal geometry and depth to compute a corrected M_c, which we in turn converted to a proposed seismic moment M_0. When we processed several records of the same event, we occasionally came up with a range of M_c values; we used their mean to infer a seismic moment. These events are shown as closed symbols on Figure 2.
3. *Events for which we could not find, to the best of our efforts, any reference to their focal mechanism and seismic moment.* For these 17 earthquakes, we attempted to compute a corrected M_c, based on representative focal mechanisms. The latter were obtained from a compilation of available solutions in the vicinity of the hypocenter, both from the CMT dataset and such catalogues as ISACKS and MOLNAR's (1971) and DENHAM's (1977). We want to emphasize the tentative nature of the resulting correction: there is no guarantee that the mechanism of the older (but usually larger) event is identical to that of the newer, better documented (and often times smaller) earthquake. While M_c gives an estimate of

what the seismic moment would have been in a geometry exactly similar to that of the recent event, M_m is a potentially more robust descriptor of the size of the earthquake, irrespective of its particular source orientation. These events are shown as open symbols on Figure 2.

In all cases, the analysis of every single record is detailed in the Appendix, with full references to the events used for comparison.

Results and Discussion

Results are detailed in Tables 1, 2 or 3, depending on the level of documentation of the event in the literature. For reference, these tables include the various magnitudes published for the events. Values of m_b and M_{PAS} are taken from the NEIC tape; m_B was compiled from ABE and KANAMORI (1979).

For the 13 earthquakes with published moments, and as in the case of our previous studies, we define the residuals $r = M_m - M_m^p$ and $r_c = M_c - M_m^p$. The average value and standard deviation of the 23 residuals r are $\bar{r} = -0.13$; $\sigma = 0.29$, and the corresponding values for r_c are $\bar{r}_c = -0.16$; $\sigma_c = 0.26$. As noted in Paper I, these figures are not necessarily representative of the performance of our method, inasmuch as the published moments themselves may be erroneous. In particular, if we exclude from the dataset those events for which only a body-wave moment (probably not representative of source size at frequencies lower than 60 mHz) was published, we obtain $\bar{r} = -0.09$; $\sigma = 0.26$; $\bar{r}_c = -0.10$; $\sigma_c = 0.16$, more in line with our previous results (OKAL and TALANDIER, 1989; OKAL, 1990; Paper I). At any rate, these results clearly confirm that adequate estimates of M_0 can be obtained from the M_m algorithm *including through the use of overtones.*

Based on published or estimated focal geometries, we propose 28 new seismic moments for intermediate and deep events covering the period 1909–1975, and ranging from 1.2×10^{26} to 2.6×10^{28} dyn-cm. These moments, obtained as $M_0 = 10^{(M_c + 20)}$ dyn-cm, are given in the last column of Tables 2 and 3. In one instance (11 June 1972, Celebes Sea), we could not select a representative focal mechanism because of the wide variety of geometries available in the immediate vicinity of the hypocenter, and as a result our proposed moment is largely unconstrained between 2 and 7 times 10^{27} dyn-cm. It is clear that this event, which features a body-wave magnitude of only 5.8, should be targeted for a full seismological investigation. In addition, we propose to revise MIKUMO's (1972) estimate of the deep Mariana earthquake of 07 October 1968 from 1.54×10^{27} dyn-cm to 3.2×10^{26} dyn-cm.

Figure 5a plots the seismic moments (either published or proposed in the present study) as a function of the Pasadena magnitude M_{PAS} assigned to the earthquake. While a general trend is certainly present, the correlation coefficient is only $\alpha = 0.62$, with $\chi^2 = 8.43$. Furthermore, the slope of the straight line best-fitting

Table 1

Events for which a published moment and focal geometry are available from a detailed seismological study

Date	Epcienter		Depth (km)	Magnitudes			Published Moment			M_m	M_c
	°N	°E		m_b	m_B	M_{PAS}	M^p_m	Method	Reference		
						Intermediate (A)					
29 NOV 1957	−21.0	−66.0	200		7.4	7.8	7.80	B, S	a, b	7.65–7.74	7.69–7.73
26 FEB 1963	−7.5	146.1	156		7.3	$7\frac{3}{8}$	7.40	G	c	7.49	7.11
26 MAY 1964	−56.2	−27.8	120	5.9	7.5	$7\frac{3}{8}$	7.79	S	d	7.29	7.43
24 NOV 1971	52.90	159.19	106	6.3	7.4	7.5†	7.41	B	e, f	7.13–7.34	7.09–7.29
						Intermediate (B)					
21 MAR 1964*	−6.4	127.9	367	5.4		7.0	6.04	B	g	6.06–6.54	6.16–6.22
19 JAN 1969	45.01	143.17	204	6.4	7.3	7.0	6.70	B	h	6.80	6.84
27 MAY 1970	27.22	140.12	382	6.2		7.1	6.90	B	i	6.75	6.70
						Deep					
26 JUL 1958	−13.5	−69.00	609			7.5	7.45	B	a, b	7.20–7.51	7.17–7.48
15 AUG 1963	−13.8	−69.3	591	6.0	7.3	$7\frac{3}{4}$	7.84	S	j	7.69	7.71
07 OCT 1968*	26.29	140.60	516	6.1		7.5	7.19	B	i	6.51–6.71	6.38–6.63
31 JUL 1970*	−1.46	−72.56	651	7.1	7.5	7.0†	8.30	S, C	j, k, l	7.97–8.00	8.18–8.22
29 SEP 1973*	41.89	130.91	575	6.5	7.4	7.0	7.83	S	j	7.58–8.08	7.58–8.06
07 MAR 1978*	31.96	137.61	434	6.9		7.0	6.73	C	m	6.88–7.19	6.54–6.85

* Overtone mantle magnitude $M_m^{\mathrm{overt.}}$ computed for this event

† Berkeley magnitude

Key to methods of moment determination:
B: Body-wave modeling;
C: Centroid moment tensor inversion;
G: Overtone Love wave modeling;
S: Surface-wave modeling.

References for Published Moments:
a: WICKENS and HODGSON (1967); b: WYSS (1970); c: FUKAO and ABE (1971); d: ABE (1972); e: STAUDER and MUALCHIN (1976); f: ZAKHAROVA and CHEPKUNAS (1977); g: TENG and BEN-MENAHEM (1965); h: LUNDGREN and GIARDINI (1990); i: MIKUMO (1972); j: FURUMOTO and FUKAO (1976); k: OKAL and GELLER (1979); l: GILBERT and DZIEWONSKI (1975); m: DZIEWONSKI *et al.* (1987).

Table 2

Events for which a focal geometry (but no seismic moment) is available from a detailed seismological study

Date	Epicenter		Depth (km)	Magnitudes			Reference for Focal Geometry	M_m	M_c	Proposed M_0 (10^{27} dyn-cm)
	°N	°E		m_b	m_B	M_{PAS}				
				Intermediate (A)						
19 MAR 1953	14.00	−61.20	134			7.3	a	7.01	7.07	1.2
26 APR 1959	24.85	122.75	113		7.5	7.5	b	6.57–6.77	6.34–6.53	0.27
09 JUL 1964	−15.5	167.6	121	6.6	7.4	7.2	c	6.87	6.84	0.69
27 JUL 1971	−2.75	−77.43	135	6.3	7.3	7.5	d	7.00	7.06	1.1
14 FEB 1972	−11.36	166.34	102	6.2	7.3	7.4	e	7.03	7.14	1.4
01 NOV 1975	13.84	144.75	113	6.1		7.1	e	6.36	6.08	0.12
				Intermediate (B)						
04 MAR 1949	36.0	70.5	230		7.4	7.5	f	7.36–7.65	7.09–7.65	2.2
28 FEB 1950	46.0	144.0	340		7.5	7.9	b	7.45	7.49	3.1
14 MAR 1965	36.3	70.7	219	6.6	7.5	7.5	f	7.65	7.47	3.0
22 MAY 1972	−17.69	−175.19	227	6.2		7.1	b	6.84	6.88	0.76
30 JUL 1974	36.35	70.76	211	6.5		7.4	g	6.83–7.00	6.60–6.77	0.48

References for published focal solutions:
a: RUSSO *et al.* (1992); b: DENHAM (1977); c: ISACKS and MOLNAR (1971); d: STAUDER (1975); e: ASTIZ *et al.* (1988); f: RITSEMA (1966); g: This study.

Table 3

Events for which no focal geometry (or seismic moment) is available from a detailed seismological study (to the best of our knowledge)

Date	Epicenter		Depth (km)	Magnitudes			Reference for Focal Geometry	M_m	M_c	Proposed M_0 (10^{27} dyn-cm)
	°N	°E		m_b	m_B	M_{PAS}				
				Intermediate (A)						
12 APR 1910	25.5	122.5	200		7.6	8.3	a	8.16	8.23	17
15 JUN 1911	29.0	129.0	160		8.1	8.7	b	7.97	7.92	8.3
01 JAN 1919	−19.5	−176.5	180		7.7	8.3	c	7.95	7.80	6.3
21 DEC 1939	0.0	123.0	150		7.8	8.6	d	8.37–8.46	8.23–8.29	18
05 OCT 1944	−22.5	172.0	120		7.3	7.5	e	6.77	6.56–6.72	0.44
24 NOV 1944	−19.0	169.0	170		7.4	7.5	f	6.98	6.69	0.69
09 DEC 1950	−24.2	−67.5	128		7.7	8.3	g	8.24–8.39	8.36–8.80	26
14 DEC 1950	−19.6	−175.79	188		7.5	7.9	c	7.81–7.93	7.76–7.80	6.0
17 DEC 1957	−12.37	166.73	120			7.8	h	7.50	7.73	5.4
01 SEP 1961	−59.5	−27.3	131			7.5	i, j	6.78–6.85	6.96–7.26	1.2
08 SEP 1961	−56.3	−27.1	125		7.6	$7\frac{5}{8}$	i, j	6.43–6.75	6.66–7.06	0.62
				Intermediate (B)						
07 JUL 1909	36.5	70.5	230		7.6	8.1	k, l	7.71	7.65	4.5
15 NOV 1921	36.5	70.5	215		7.6	8.1	k, l	7.84	7.73	5.4
16 APR 1937	−20.51	−177.35	323		7.5	8.1	a	6.98	7.10	1.3
02 JUL 1953	−19.0	169.0	223		7.4	7.5	f	7.18	6.94	0.87
23 MAY 1956	−15.41	−178.73	396			7.5	m	6.95	6.98	0.98
11 JUN 1972	3.94	124.32	325	5.8	7.4	7.5	n, o	7.27–7.34	7.29–7.86	2–7

References for focal mechanisms:
a: 26 April 1959 (DENHAM, 1977); b: 21 September 1965 (KATSUMATA and SYKES, 1969); c: 22 May 1972 (DENHAM, 1977); d: 09 December 1989 (DZIEWONSKI *et al.*, 1990); e: 15 November 1984 (DZIEWONSKI *et al.*, 1985); f: 12 August 1990 (DZIEWONSKI *et al.*, 1991a); g: 03 August 1965 (ISACKS and MOLNAR, 1971); h: 14 February 1972 (ASTIZ *et al.*, 1988); i: 26 May 1964 (ISACKS and MOLNAR 1971); j: 26 May 1964 (ABE, 1972); k: 30 December 1983 (DZIEWONSKI *et al.*, 1984); l: 30 July 1974 (this study); m: 07 December 1990 (DZIEWONSKI *et al.*, 1991b); n: 04 June 1982 (DZIEWONSKI *et al.*, 1983); o: 07 September 1967 (FITCH and MOLNAR, 1970).

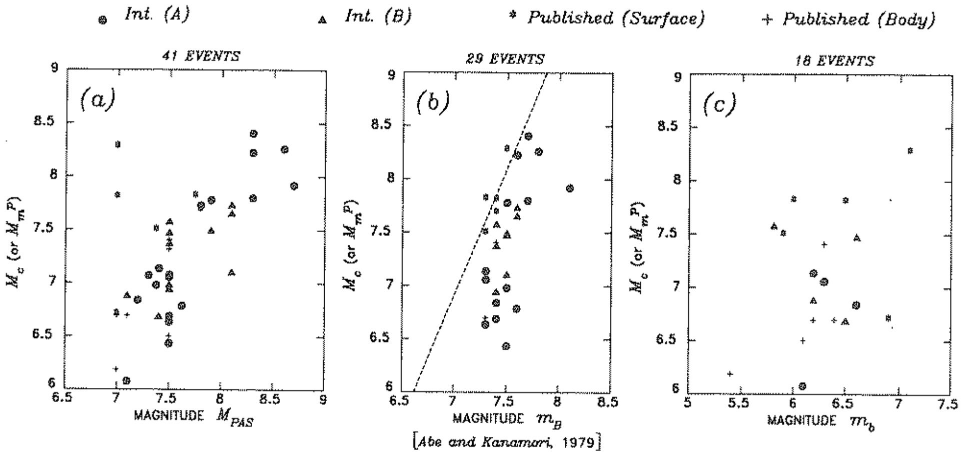

Figure 5

Correlation between seismic moment and various magnitudes. In all diagrams, the seismic moment is estimated either from its published value (asterisks or plus signs; expressed as $M_m^P = \log_{10} M_0 - 20$), or from the corrected magnitude M_c as computed in the present study (filled symbols, keyed to source depth). (a): Correlation with Pasadena magnitude M_{PAS}; (b): Correlation with ABE and KANAMORI's (1979) magnitude m_B; the dashed line is KANAMORI's (1983) proposed relation between m_B and M_0; (c): Correlation with standard body-wave magnitude m_b. Note that neither magnitude scale correlates well with seismic moment.

$\log_{10} M_0$ vs. M_{PAS} is only 0.83; it should if anything be larger than 1, to reflect the saturation of M_{PAS}. Not surprisingly, the correlation is generally worse for the deeper events. Intermediate (A) earthquakes would yield $\alpha = 0.83$; $\chi^2 = 2.57$ and a slope of 1.14, while Intermediate (B) and Deep events, treated as a single dataset, would yield $\alpha = 0.33$; $\chi^2 = 4.96$ and a slope of 0.46. The latter dataset is heavily influenced by the published moments of recent earthquakes (e.g., Colombia, 1970), for which Pasadena (and other) magnitudes are strongly deficient.

As expected, the situation is not improved by the use of the body-wave magnitude m_b. As shown on Figure 5c for the restricted dataset of post-1963 events for which m_b is available, the correlation between m_b and moment is mediocre: $\alpha = 0.34$; $\chi^2 = 5.43$, and the slope drops to 0.51. These numbers are in fact totally controlled by the extreme values of m_b (the 1964 Banda Sea and 1970 Columbia events); if these are eliminated, α takes a negative value, which would indicate that M_0 actually *decreases with* m_b!

It is also interesting to test the correlation between our population of moments and ABE and KANAMORI's (1979) longer-period body-wave magnitude, m_B. As shown on Figure 5b, the 29 events for which this measurement is available also give a poor correlation ($\alpha = 0.49$; $\chi^2 = 6.37$). The excessive best-fitting slope of M_c vs. m_B (1.50) expresses the saturation of m_B. Indeed, the maximum variation of m_B in this dataset is only 0.8 units, while M_c varies by more than two full units.

Figure 5b also shows a lot of scatter in KANAMORI's (1983) proposed relation $\log_{10} M_0 = 2.4 m_B + 10.1$.

The bottom line is that traditional magnitudes, whether m_b, m_B or M_{PAS}, are not reliable descriptors of the true size of large non-shallow historical earthquakes.

Finally, it is interesting to comment on the repartition of events of large seismic moments with depth. For this purpose, on Figure 6, we compare our results to a database of previously published moments. Specifically, the filled squares represent the 53 large non-shallow CMT solutions ($h \geq 100$ km; $M_0 \geq 2 \times 10^{26}$ dyn-cm), and the triangles are 15 additional solutions, published in the literature, but predating the CMT era (TENG and BEN-MENAHEM, 1965; WYSS, 1970; FUKAO and ABE, 1971; ABE, 1972; MIKUMO, 1972; GILBERT and DZIEWONSKI, 1975; SASATANI, 1976; CHUNG and KANAMORI, 1976; FURUMOTO and FUKAO, 1976; ZAKHAROVA and CHEPKUNAS, 1977; LUNDGREN and GIARDINI, 1990). The open circles are 28 new moments estimated in the present study. A number of conclusions are apparent from this figure:

1. The present CMT dataset, limited to a little less than 15 years of data, underestimates the level of seismic moment release, especially for very deep earthquakes ($h \geq 500$ km). Indeed, this result is obvious when considering such events as the Brazilian earthquake of 1963 ($M_0 = 6.9 \times 10^{27}$ dyn-cm) and the

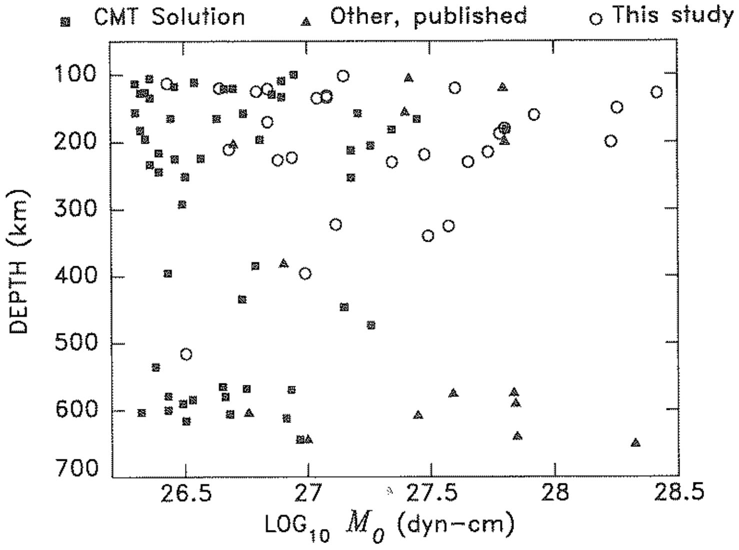

Figure 6

Seismic moment of 96 large, non-shallow earthquakes plotted as a function of source depth. The 53 squares are all CMT solutions 100 km or deeper and with a moment of at least 2×10^{26} dyn-cm. The 15 triangles are additional moments published in the literature, but predating the CMT solutions. The open circles are the 28 moments greater than 2×10^{26} dyn-cm obtained in the present study.

1970 Colombia event (2×10^{28} dyn-cm). Incidentally, the situation is identical for shallow events: the largest CMT published to date is the Indonesian event of 1977 ($M_0 = 3.6 \times 10^{28}$ dyn-cm, approximately 100 times smaller than the 1960 Chilean earthquake, and 20 times smaller than the largest earthquake recorded during the WWSSN era (Alaska, 1964; $M_0 = 8.2 \times 10^{29}$ dyn-cm)).

2. Significant moment release takes place between 200 and 300 km, principally in connection with the Hindu Kush intermediate focus. This fascinating region is the locus of abundant seismicity, in a relatively regular pattern of large events reaching up to 5×10^{27} dyn-cm, and clustered around 36.5°N, 70.5°E, at depths between 210 and 235 km.
3. Historical data suggest the existence of events at the level 10^{28} dyn-cm and above, in the depth range 100–200 km for which the maximum moment in the CMT dataset is presently 6.4×10^{27} dyn-cm (Kuriles, 1978). The unambiguous recording of multiple passages R_2 on the Uppsala Wiechert for the Minahassa earthquake of 1939, and up to R_3 on the Pasadena Benioff 1–90 for the 1950 Argentina event, clearly confirm their exceptional size. Relocation efforts based on travel times published by the ISS confirm the intermediate depth of these two events: 150 km for Minahassa and 128 km for Argentina. The third event reaching over 10^{28} dyn-cm (Taiwan corner, 12 April 1910) is less favorably recorded at Uppsala (only on the NS component), and its depth could not be confirmed independently. Its moment estimate is generally more tentative.

   However, these historical events are not unique in their depth/moment combination, in view of the Tonga event of 22 June 1977 (1.7×10^{28} dyn-cm): while the latter is listed in the CMT catalogue as shallow ($h = 65$ km), LUNDGREN and OKAL (1988) have argued, in particular based on the excitation of the earth's radial modes, that its rupture area had to extend downwards, possibly as deep as 125 km. Similarly, the Banda Sea event of 04 November 1963, whose catalogue depth is only 80 km and which reached as much as 3.1×10^{28} dyn-cm, probably ruptured down to 170 km (OSADA and ABE, 1981; WELC and LAY, 1987).
4. Historical data confirm a significant low in moment release in the depth range 350–520 km, where the maximum seismic moment reported is 1.8×10^{27} dyn-cm (Banda Sea, 1982; $h = 478$ km). Two historical events, with well-constrained depths, suggest activity at the 3 to 4 times 10^{27} dyn-cm level around 325 km.

Conclusion

In conclusion, the concept of the mantle magnitude M_m can be successfully applied to historical events of intermediate or greater depth. This study proposes the assignment or revision of moments for 29 earthquakes with depths between 100 and 609 km, ranging from 1.2×10^{26} to 2.6×10^{28} dyn-cm, and covering the years

1909–1975. Their values, and those for a few large, deep, events individually studied in the literature, clearly demonstrate that the presently available CMT dataset underestimates the level of seismicity inside the slabs, especially below 500 km depth.

Before we can achieve any understanding of the mechanism controlling earthquake rupture at intermediate and greater depths, it is clear that a careful quantitative compilation of seismic moment release in the various subduction zones is warranted. Our study shows that the available magnitudes m_b, m_B or M_{PAS} are not reliable estimates of the seismic moment, the only parameter representing the true size of the earthquake source. It is therefore imperative that seismic moments be determined for events predating 1977. For WWSSN-era earthquakes, an adequate analog dataset exists, and a combination of body- and surface-wave techniques could be employed; for older earthquakes postdating the development of high-magnification long-period instrumentation (Benioff 1–90; strainmeters, etc.), the task is more difficult but can be achieved; for earthquakes in the 1920s and earlier, the available instruments (either Wiechert-type mechanical or Golytsin-type electromagnetic seismographs) will not record surface waves above noise level for very deep events below a prohibitively large moment of several times 10^{28} dyn-cm. The seismic moments of large, very deep shocks will have to be estimated on the basis of the deconvolution of their body waves.

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Appendix: Discussion of Individual Events

We present a detailed analysis of all measurements obtained in this study. The events are listed in chronological order, but are regrouped geographically whenever several hypocenters are clustered. All focal mechanisms are described by their strike (ϕ), dip (δ), and slip (λ) angles, in the conventions of KANAMORI and CIPAR (1974), which are also those of the Harvard CMT files.

- *07 July 1909 ($M_{PAS} = 8.1$), 15 November 1921 ($M_{PAS} = 8.1$), 04 March 1949 ($M_{PAS} = 7.5$), 14 March 1965 ($m_b = 6.6$; $M_{PAS} = 7.5$) and 30 July 1974 ($m_b = 6.5$; $M_{PAS} = 7.4$); Hindu Kush*

The intermediate depth seismicity of the Hindu Kush has been noted for a long time, and a review given by RITSEMA (1966). We gathered records from the five shocks listed above. They include the largest three historical events, and the largest two from the WWSSN era. RITSEMA (1966) gave somewhat different focal solutions for the 1949 event ($\phi = 290°$; $\delta = 16°$; $\lambda = 90°$) and the 1965 one ($\phi = 305°$; $\delta = 30°$, $\lambda = 90°$). The only recent earthquake in the cluster, for which a CMT mechanism is available, is the noted 30 December 1983 shock ($M_m^p = 7.18$), whose mechanism is practically identical to that for 1949. On the other hand, we obtained a first-motion mechanism for 1974 ($\phi = 310°$; $\delta = 25°$; $\lambda = 90°$) approaching that of 1965.

M_m values are 7.71 (UPP) for 1909; 7.84 (UPP) for 1921; 7.65 (UPP), 7.56 (PAS, R_1) and 7.36 (PAS, R_2) for 1949; 7.65 (PAS, R_1) for 1965; and 7.0 (PAS, R_1) and 6.83 (PAS, R_2) for 1974. It is possible to compute M_c values for 1949 and 1965 using the published mechanisms: 7.65 (UPP, 1949); 7.29 (PAS R_1, 1949); 7.09 (PAS R_2, 1949) and 7.47 (PAS R_1, 1965). For the 1974 event, our new mechanism results in $M_c = 6.77$ (R_1) and 6.60 (R_2). For the older events, we use the 1983 mechanism, and obtain $M_c = 7.65$ (UPP, 1909) and 7.73 (UPP, 1921). The use of the other focal mechanisms would in general change these values by only ± 0.2 units.

- *12 April 1910 and 26 April 1959; Taiwan-Ryukyu Corner*

These events have the largest magnitudes recorded in the area ($M_{\text{PAS}} = 8.3$ and 7.5, respectively). Only the NS record (poorly polarized) was available at Uppsala for the 1910 earthquake, yielding $M_m = 8.16$. The 1959 event was well recorded, including R_2, on the Pasadena Press-Ewing, yielding $M_m = 6.77$ (R_1) and 6.57 (R_2). DENHAM (1977) gives two very close focal solutions for the 1959 event; in their average geometry ($\phi = 131°$; $\delta = 76°$; $\lambda = 93°$), the 1959 record yields $M_c = 6.53$ and 6.34, respectively. A similar mechanism for the 1910 earthquake would yield $M_c = 8.23$, making it one of the largest intermediate events ever recorded. Moment release in the area has been very weak since 1977, with the largest CMT solution a meager 6×10^{24} dyn-cm.

- *04 May 1911; Northern Kurile Islands, and 24 November 1971; Kamchatka*

We consider together these two events, whose epicenters differ only by a few degrees. The 1971 earthquake occurred at 106 km depth, and yields $M_m = 7.34$ (R_1) and 7.13 (R_2) based on the Ultra-long Period "33" instrument at Pasadena. The focal mechanism ($\phi = 37°$; $\delta = 85°$; $\lambda = 86°$) was given by STAUDER and

MUALCHIN (1976), and suggests $M_c = 7.29$ and 7.09, respectively. The event was also studied by APTEKMAN *et al.* (1981), who computed estimates of the seismic moment based on the source spectrum of intermediate-period body waves. Their results are scattered between 1.3 and 8 times 10^{27} dyn-cm. Using the long-period system at Obninsk, ZAKHAROVA and CHEPKUNAS (1977) obtained a body-wave moment of 2.6×10^{27} dyn-cm, which we use as a reference.

Despite a large reported magnitude ($M_{\mathrm{PAS}} = 7.6$), the only record for the 1911 earthquake, the NS component at Uppsala, remains below noise level. In general, there is an absence of significant moment release since 1977 in the vicinity of its hypercenter (the largest CMT being 4×10^{25} dyn-cm).

• *15 June 1911; Ryukyu Islands*

This event has the largest magnitude ever reported for a non-shallow shock: $M_{\mathrm{PAS}} = 8.7$. The mantle magnitude measured from the NS record at UPP is 7.97. A large event ($m_b = 6.1$; $M_{\mathrm{PAS}} = 6\tfrac{3}{4}$) occurred in the immediate vicinity on 21 September 1965, with a mechanism ($\phi = 139°$; $\delta = 35°$, $\lambda = -149°$) determined by KATSUMATA and SYKES (1969). This mechanism also agrees with a CMT solution (02 January 1981) at slightly greater depth, and suggests $M_c = 7.92$ for the 1911 event.

• *01 January 1919, 16 April 1937, 14 December 1950, and 22 May 1972;*
South of Fiji

The exact locations and depths of the older events are somewhat in doubt. For the 1919 earthquake, and on the basis of a relocation using 10 P times listed in the ISS, we prefer GUTENBERG and RICHTER's (1954) solution (19.5°S; 176.5°W; $h = 180$ km), to the ISS solution, further to the Southwest and deeper. The NS record at Uppsala yields $M_m = 7.95$, a rather large value in agreement with the reported magnitude ($M_{\mathrm{PAS}} = 8.3$).

The depth of the 1937 earthquake is controversial, since it is listed in the ISS as 223 km, but given as 400 km by GUTENBERG and RICHTER (1954). However, the latter is inconsistent with Apia arrivals. Our relocation, based on 43 good quality arrivals converges on 20.51°S, 177.35°W and 323 km. The event is clearly Intermediate (B). From an EW record on the Benioff 1–120 instrument (prototype to the 1–90), we obtain $M_m = 6.98$. As expected from this low value, no readable record was found at Uppsala.

Based on 46 P and S times published by the ISS, we relocated the 1950 earthquake to 19.60°S, 175.79°W and 188 km depth, in the immediate vicinity of the 1919 event. M_m values are 7.93 (UPP) and 7.81 (PAS).

The 1972 event ($h = 227$ km; $m_b = 6.2$; $M_{\mathrm{PAS}} = 7.1$) is well recorded on the Ultra-long Period "33" instrument at Pasadena, yielding $M_m = 6.84$. The focal mechanism listed by DENHAM (1977) ($\phi = 55°$; $\delta = 60°$; $\lambda = -118°$) leads to $M_c = 6.88$. Assuming the same mechanism for the older events, we obtain $M_c = 7.80$ (1919), 7.10 (1937) and 7.76 (UPP) and 7.80 (PASS) for the 1950 event. The latter was also studied by WICKENS and HODGSON (1967). However, their focal mechanism ($\phi = 355°$; $\delta = 89°$; $\lambda = -90°$) cannot reconcile the magnitudes at PAS ($M_c = 7.49$) and UPP ($M_c = 8.58$).

- *21 December 1939; Minahassa Peninsula*

This event ($M_{\mathrm{PAS}} = 8.6$) is exceptionally large for its depth, a fact confirmed by well-recorded second passages R_2 at Uppsala, M_m values are 8.37 (R_1) and 8.46 (R_2). WICKENS and HODGSON (1967) propose two widely different mechanisms. An event with $M_0 = 1.2 \times 10^{26}$ dyn-cm occurred on 09 December 1989, at an identical hypocenter. Its mechanism yields $M_c = 8.29$ (R_1) and 8.23 (R_2), but it is clear that further study of the 1939 event is desirable.

- *05 October 1944; Loyalty Islands*

This event has the largest conventional magnitude ($M_{\mathrm{PAS}} = 7.50$) reported at non-shallow depths in the Loyalty Islands. The vertical Benioff 1–90 instrument yields $M_m = 6.77$. Representative focal mechanisms in the vicinity (e.g., $\phi = 122°$; $\delta = 83°$; $\lambda = 63°$ on 15 November 1984) would yield $M_c = 6.56$ to 6.72, a range typical of the moment values of the CMT solutions, in the area.

- *24 November 1944 and 02 July 1953; Southern Vanuatu*

Both events are reported with $M_{\mathrm{PAS}} = 7.5$. Benioff 1–90 records yield $M_m = 6.98$ and 7.18, respectively. Several CMT solutions in the area are well represented by the largest shock among them: 12 August 1990 ($\phi = 327°$; $\delta = 17°$; $\lambda = 72°$; $M_m^P = 6.63$), which leads to $M_c = 6.69$ (1944) and 6.94 (1953). The 1953 event is listed in WICKENS and HODGSON (1967), but their solution fails to converge.

- *28 February 1950 and 19 January 1969; Southern Kurile Islands*

We discuss both events together, since there epicenters are close by, even though their depths (340 and 204 km, respectively) and mechanisms are significantly different. The 1950 event yields $M_m = 7.45$ at Pasadena based on a Benioff 1–90 record. A focal mechanism ($\phi = 184°$; $\delta = 54°$; $\lambda = 340°$) is available for this event from DENHAM (1977), leading to $M_c = 7.49$. No comparable levels of moment release are documented in the recent seismicity, as discussed by LUNDGREN and GIARDINI (1990).

For the 1969 event, we use a first passage on the Ultra-long Period "38B" instrument, resulting in $M_m = 6.80$. The event was studied in detail by LUNDGREN and GIARDINI (1990) who obtained the geometry ($\phi = 155°$; $\delta = 80°$; $\lambda = 30°$), leading to $M_c = 6.84$, in excellent agreement with their $M_m^p = 6.70$. The earthquake is reminiscent of the larger 06 December 1978 event ($M_m = 7.81$) studied by LUNDGREN *et al.* (1988) and included in our earlier compilation (OKAL, 1990).

- *09 December 1950 and 29 November 1957; Argentina*

At $M_{\mathrm{PAS}} = 8.3$ and 7.8 respectively, these events have the largest conventional magnitudes for intermediate shocks in the area since 1918. The 1950 shock produced Rayleigh waves well recorded up to R_3 on the 1–90 Benioff at Pasadena (see Figure 3). M_m varies from 8.24 (R_1) to 8.39 (R_3). The smaller 1957 shock yielded $M_m = 7.74$ on the 1–90 Benioff, and 7.65 on the 70-s strainmeter. WYSS (1970) studied the 1957 event based on a focal solution by WICKENS and HODGSON (1967): ($\phi = 85°$; $\delta = 74°$; $\lambda = 197°$), and obtained moments of 5.1 and 7.8×10^{27} dyn-cm, respectively from body- and surface-wave modeling. The corresponding mechanism yields $M_c = 7.73$ (1–90) and 7.69 (strainmeter). The same mechanism applied to the 1950 event yields $M_c = 8.36$ (R_1); 8.38 (R_2) and 8.52 (R_3)

- *19 March 1953; St. Lucia*

This event ($M_{\mathrm{PAS}} = 7.3$) is by far the largest intermediate earthquake recorded in the Lesser Antilles since 1916. We measured $M_m = 7.01$ on the Benioff 1–90 at Pasadena. The earthquake was studied by RUSSO *et al.* (1992), who constrained the focal mechanism to $\phi = 299°$; $\delta = 50°$; $\lambda = 261°$. In this geometry, $M_c = 7.07$. No comparable seismicity has occurred since 1953 at this location.

- *23 May 1956; Northeast of Fiji*

This earthquake occurred at the extreme northern end of the Tonga slab, at a depth (ISC) of 396 km. At $M_{\mathrm{PAS}} = 7.5$, it is the largest event ever reported in the area. However, M_m reaches only 6.95 on the 1–90 at Pasadena. WICKENS and HODGSON (1967) list the earthquake but their focal solution fails to converge. Very few focal mechanisms are available in the area. None are reported at adequate depths by ISACKS and MOLNAR (1971), and only small events (typically below 10^{25} dyn-cm) have their CMT solutions published. The largest CMT available is the 07 December 1990 earthquake at 441 km ($\phi = 243°$; $\delta = 52°$; $\lambda = -23°$; $M_0 = 9.2 \times 10^{24}$ dyn-cm), leading to $M_c = 6.98$.

- *17 December 1957 and 14 February 1972; Santa Cruz Islands*

These earthquakes have the largest Pasadena magnitudes reported in the area for intermediate shocks ($M_{\mathrm{PAS}} = 7.8$ and 7.4, respectively). For the 1957 event, the North-South Pasadena strainmeter yields $M_m = 7.50$; for the 1972 event, we obtain $M_m = 7.03$ from the Pasadena "33" instrument. The mechanism of the 1972 event was studied by ASTIZ *et al.* (1988) ($\phi = 15°$; $\delta = 55°$; $\lambda = 100°$); it leads to $M_c = 7.14$ (1972) and $M_c = 7.73$ (1957). WICKENS and HODGSON (1967) list the 1957 event, but their mechanism fails to converge.

- *26 July 1958 and 15 August 1963; Peru-Brazil*

These two earthquakes ($M_{\mathrm{PAS}} = 7.5$ and $7\frac{3}{4}$, respectively) have the largest Pasadena magnitudes in that section of the bottom of the South American slab. Their epicenters are identical, and upon relocation, the 1958 event moves to 609 km, approximately 20 km below the 1963 source. M_m values are obtained from the 1–90 Benioff at Pasadena (7.20 for 1958; 7.69 for 1963). The latter event was studied by FURUMOTO and FUKAO (1976), who retained a mechanism published by STAUDER and BOLLINGER (1966) ($\phi = 184°$; $\delta = 65°$; $\lambda = -59°$), and assigned the event a moment $M_0 = 6.9 \times 10^{27}$ dyn-cm ($M_m^p = 7.84$). This mechanism leads to $M_c = 7.71$ for the 1963 event, and 7.30 for 1958.

Both events are mentioned by WYSS (1970) who suggest a body-wave moment of 2.8×10^{27} dyn-cm ($M_m^p = 7.45$) for the 1958 earthquake, based on a solution by WICKENS and HODGSON (1967) ($\phi = 76°$; $\delta = 63°$; $\lambda = -96°$), and a surface-wave moment of 1.4×10^{28} dyn-cm ($M_m^p = 8.15$) for the 1963 event, based on a solution by STAUDER and BOLLINGER (1966). It is not exactly clear which mechanism WYSS (1970) used in his modeling, since the earthquake was a complex event resulting in different focal solutions for P waves (CHANDRA, 1970) and S (STAUDER and BOLLINGER, 1966 give two such mechanisms). At any rate, Wyss' moment appears too large by about a factor of 4.

- *01 September 1961, 08 September 1961 and 26 May 1964; South Sandwich Islands*

With Pasadena magnitudes of $7\frac{1}{2}$, $7\frac{5}{8}$ and $7\frac{3}{8}$, respectively, these events are the largest intermediate shocks ever reported in the South Sandwich Islands. The hypocenters of the last two events are very similar, but the 01 September 1961 shock occurred 3 degrees further south. We use Press-Ewing records for the 1961 earthquakes, and a Benioff 1–90 record for the 1964 one. M_m values are 6.78 (R_1) and 6.85 (R_2) for 01 September 1961; 6.43 (R_1) and 6.75 (R_2) for 08 September; and 7.29 (R_1) for the 1964 event. The latter was studied by ISACKS and MOLNAR (1971) who give the mechanism $\phi = 179°$; $\delta = 53°$; $\lambda = 159°$, and by ABE (1972), who computed a seismic moment of 6.7×10^{27} dyn-cm for the slightly different mechanism $\phi = 200°$; $\delta = 48°$; $\lambda = 134°$. These mechanisms lead to $M_c = 7.52$ and 7.43, respectively. ISACKS and MOLNAR'S (1971) geometry gives a generally better agreement between M_c values for R_1 and R_2 in the case of the 1961 events (6.96–7.07 and 6.66–6.95) than do ABE'S (1972) (7.02–7.26 and 6.50–7.06). Tentative moments for the 1961 events would be 1.2×10^{27} dyn-cm (01 September) and 6.2×10^{26} dyn-cm (08 September). The 01 September event is listed by WICKENS and HODGSON (1967), but their mechanism fails to converge.

- *26 February 1963; New Guinea*

This event has the largest magnitude ($M_{\mathrm{PAS}} = 7\frac{3}{8}$) assigned to an intermediate shock in New Guinea. M_m is 7.49 on the Benioff 1–90 at Pasadena. The event was the subject of an original study by FUKAO and ABE (1971), who modeled the interference of several modes of Love waves. They reported a moment $M_0 = 2.5 \times 10^{27}$ dyn-cm ($M_m^p = 7.40$) for a pure dip-slip mechanism ($\phi = 355°$; $\delta = 90°$; $\lambda = 90°$), which yields $M_c = 7.11$.

- *21 March 1964; Banda sea*

This is the first event for which Ultra-long Period records are available at Pasadena. We were able to process not only the fundamental Rayleigh wave ($M_m = 6.06$), but also the very prominent first overtone ($M_m = 6.54$). The latter figure is overestimated because of the relatively shallow character of the event (367 km), as compared to the standard depth used for the computation of $M_m^{\mathrm{overt.}}$ (550 km). The body waves from this earthquake were modeled in detail by TENG and BEN-MENAHEM (1965), who proposed the mechanism $\phi = 94°$; $\delta = 83°$; $\lambda = 310°$, and obtained a moment $M_0 = 1.1 \times 10^{26}$ dyn-cm ($M_m^p = 6.04$). This mechanism reconciles our two measurements ($M_c = 6.16$ for the fundamental, 6.22 for the overtone). ISACKS and MOLNAR (1971) also gave a very similar mechanism ($\phi = 86°$; $\delta = 83°$; $\lambda = 315°$).

- *09 July 1964; Central Vanuatu*

This event ($m_b = 6.6$; $M_{\mathrm{PAS}} = 7\frac{1}{4}$) is the largest intermediate depth earthquake ever recorded in Central Vanuatu (other events assigned $M_{\mathrm{PAS}} = 7\frac{1}{4}$ are reported in 1911–1919, but could not be independently verified). The Pasadena Benioff 1–90 record yields $M_m = 6.87$. The focal mechanism was determined by ISACKS and MOLNAR (1971) ($\phi = 173°$; $\delta = 54°$; $\lambda = 90°$), and leads to $M_c = 6.84$.

- *07 October 1968; Bonin Islands*

This event ($m_b = 6.1$; $M_{\mathrm{PAS}} = 7.5$) has the largest Pasadena magnitude ever assigned to a deep shock in the Marianas subduction zone. We processed both first and second passages of the fundamental, obtaining $M_m = 6.71$ and 6.51 respectively, and the first passage of the ${}_1R$ overtone ($M_m^{\text{overt.}} = 6.69$). The earthquake was studied by MIKUMO (1972). His geometry ($\phi = 119°$; $\delta = 63°$; $\lambda = 46°$) leads to $M_c = 6.58$, 6.38, and 6.63, respectively. On the basis of P-wave modeling, MIKUMO (1972) has proposed a much larger moment, $M_0 = 1.56 \times 10^{27}$ dyn-cm ($M_m^P = 7.19$). We currently do not have an explanation for the discrepancy.

- *27 May 1970; Bonin Islands*

This relatively large earthquake ($m_b = 6.2$; $M_{\text{PAS}} = 7.1$) was well recorded on the Pasadena "33" instrument, with $M_m = 6.75$. The event was studied by MIKUMO (1972), who gave the mechanism $\phi = 110°$; $\delta = 66°$; $\lambda = 74°$, and obtained a moment of 8×10^{26} dyn-cm based on P-wave modeling. His mechanism yields $M_c = 6.70$, a reasonable agreement.

- *31 July 1970; Columbia*

At 651 km depth, and with $M_0 = 2 \times 10^{28}$ dyn-cm (GILBERT and DZIEWONSKI, 1975; FURUMOTO and FUKAO, 1976; OKAL and GELLER, 1979), this earthquake features the largest seismic moment release ever recorded at the bottom of a subduction zone. The only other events known to occur in the immediate vicinity of its hypocenter are the double shocks on 18 December 1921 and 17 January 1922. We attempted to obtain an estimate of the moment of these earthquakes, but no mantle surface waves could be identified on the Uppsala records. A more detailed study of their body waves will be published elsewhere (OKAL and BINA, in preparation), but preliminary results indicate that the 1970 earthquake was indeed larger. We reported on its mantle magnitude ($M_m = 7.97$; $M_c = 8.22$) in OKAL (1990). We confirm on an overtone passage ($M_m^{\text{overt.}} = 8.00$; $M_c^{\text{overt.}} = 8.18$) the gigantic character of this event.

- *27 July 1971; Ecuador*

This event ($m_b = 6.3$; $M_{\text{PAS}} = 7.5$) has the largest reported magnitude in the area since 1906. We obtained a relatively low $M_m = 7.00$ from the Pasadena "33" instrument. The focal mechanism of the event was studied by STAUDER (1975) ($\phi = 208°$; $\delta = 44°$; $\lambda = -55°$), resulting in $M_c = 7.06$.

- *11 June 1972; Eastern Celebes Basin*

Despite a relatively low body-wave magnitude ($m_b = 5.8$), this earthquake was assigned $M_{\text{PAS}} = 7.5$, a value confirmed by well-recorded R_2 wavetrains on the Pasadena "33" instrument. We obtained $M_m = 7.34$ (R_1) and 7.27 (R_2). Two very different focal mechanism are available in the area: a CMT solution (04 June 1982, $\phi = 213°$; $\delta = 9°$; $\lambda = -102°$) of small moment, and the 07 September 1967 event studied by FITCH and MOLNAR (1970) ($m_b = 5.8$; $\phi = 51°$; $\delta = 45°$; $\lambda = -127°$) which is 50 km shallower. The corresponding M_c values would range from 7.29–7.36 in the second geometry to 7.79–7.86 in the first one. In any case, the earthquake definitely has a moment greater than 10^{27} dyn-cm; its relatively low magnitude m_b could suggest a "slow" mechanism, and warrants further study of the event.

- *29 September 1973; Sea of Japan*

This earthquake was studied in detail, notably by FURUMOTO and FUKAO (1976), who obtained a moment of 6.8×10^{27} dyn-cm ($M_m^p = 7.83$). We reported its mantle magnitude measured on the fundamental Rayleigh wave ($M_m = M_c = 7.58$) in OKAL (1990). This event generated substantial Rayleigh overtones, which were studied independently in OKAL (1979) and OKAL and JO (1983). The mantle magnitude measured from the first passage ${}_1R_1$ at Pasadena yields $M_m^{\text{overt.}} = 8.08$; $M_c^{\text{overt.}} = 8.06$.

- *01 November 1975; Mariana Trench*

With a Pasadena magnitude of 7.1, this is the largest intermediate depth event reported in the Guam-Saipan area. We obtain $M_m = 6.36$ from the Pasadena "33" instrument. A focal solution was given by ASTIZ *et al.* (1988) ($\phi = 132°$; $\delta = 84°$; $\lambda = 90°$), leading to $M_c = 6.08$.

- *07 March 1978; Izu-Bonin Trench*

In addition to the measurement on the fundamental R_1 reported in OKAL (1990) ($M_m = 6.88$; $M_c = 6.54$), we performed an overtone measurement, yielding $M_m^{\text{overt.}} = 7.19$; $M_c^{\text{overt.}} = 6.85$. The published value is $M_0 = 5.6 \times 10^{26}$ dyn-cm ($M_m^p = 6.73$).

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