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Four years of automated measurements of seismic moments at Papeete using the mantle magnitude M_m: 1987–1991

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ABSTRACT

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We report on a 4-year experiment of routine automatic determination of seismic moments using the mantle magnitude M_m. We have developed a system performing automatic detection and location of distant earthquakes, on the basis of three-component broadband records at a single seismic station. This system, which has been operational since 1987 at Papeete, Tahiti, computes M_m from the spectral amplitude of the mantle Rayleigh waves. Based on a dataset of 474 earthquakes, we show that M_m provides a excellent estimate of the quantity $\log_{10}M_0 - 20$, where M_0 is the seismic moment in dyn-cm, as published subsequently by the Harvard and USGS groups. The average residual is 0.07 units of magnitude, and the standard deviation 0.22 units. This method, which necessitates minimal hardware, has powerful applications in the field of tsunami warning.

Introduction and background

We present here a 4-year progress report on a method which we have developed to measure in real time an estimate of the seismic moment of earthquakes at teleseismic distances. This method is based on an automatic detection and location algorithm, coupled to a real-time measurement of the mantle magnitude M_m of the event. It involves a single three-component broadband seismic station, and has been fully operational at the Geophysical Laboratory in Papeete, Tahiti (PPT) since mid-1987.

The concept of the mantle magnitude M_m was introduced by Okal and Talandier (1989). It consists of analyzing the spectral amplitude of mantle Rayleigh waves recorded on a broadband instrument, and of extracting the moment information after effecting both a distance and a source correction: the mantle magnitude is calculated as:

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

where $X(\omega)$ is the spectral amplitude at the angular frequency ω, measured in μm-s. We refer to Okal and Talandier (1989) for the justification of the following expressions for the distance correction:

$$C_D = 0.5 \log_{10} \sin \Delta + \log_{10} e \cdot \frac{\omega a \Delta}{2UQ} \qquad (2)$$

[where Δ is the epicentral distance (in radians), a the radius of the Earth, and U and Q^{-1} the group velocity and attenuation of Rayleigh waves at the angular frequency ω] and for the source correction:

$$C_S = 1.6163\,\theta^3 - 0.83322\,\theta^2 + 0.42861\,\theta + 3.7411 \qquad (3)$$

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where $\theta = \log_{10}T - 1.8209$, $T = 2\pi/\omega$ being the period in seconds. The distance correction C_D can be regionalized to take into account the lateral variations of dispersion and attenuation, although our experience shows that in practice this process has liNe influence on the final results. These corrections, as well as the locking constant, -0.90 in eqn. (1), are rigorously justified on the basis of the theory of excitation and propagation of Rayleigh waves. The mantle magnitude, computed according to eqn. (1), is theoretically expected to approach the value $(\log_{10}M_0 - 20)$, if the seismic moment is expressed in dyn-cm. We keep, however, the general philosophy of the concept of *magnitude*, by performing a rapid measurement at a single station, without the knowledge of the exact focal mechanism and depth of the earthquake. In this respect, C_S represents a correction for an average orientation of the source rupture relative to the station, and for an average depth, taken as 20 km. In practice, M_m is computed at all mantle periods (from 50 to 300 s) and the largest value retained. While much of this material has already been published, we wish to emphasize that the motivation behind the development of M_m was to avoid the saturation of the classical magnitude scales, such as M_s (or worse even, m_b) measured at a constant (and usually relatively short) period. One of the goals of our early studies was to prove that M_m keeps growing linearly with $\log_{10}M_0$, even for the very largest events recorded.

Based on a dataset of more than 250 records, we justified the technique in Okal and Talandier (1989), and showed that M_m recovered the seismic moment of shallow earthquakes ($h \leq 75$ km) with an accuracy of approximately 0.2 units of magnitude, comparable to that of other magnitude scales, and indeed to the scatter of moment determinations of the same earthquake by different investigators. While the concept was initially developed for Rayleigh waves generated by shallow sources, we later extended it to Love waves (Okal and Talandier, 1990), and in the case of Rayleigh waves, to intermediate and deep sources (Okal, 1990). In both cases, the source correction C_S must be adjusted to reflect the change in surface wave excitation, and in the case of Love waves, a new distance correction C_D must be used, to take into account the different values of U and Q.

We also demonstrated in Okal and Talandier (1989) and justified theoretically in Okal (1989), the possibility of making direct time domain measurements, taking advantage of the strong inverse dispersion of Rayleigh waves in the mantle frequency range. This possibility cannot, however, be extended to Love waves, or even to Rayleigh waves at shorter distances; in both cases, the waveform becomes insufficiently dispersed. In further studies, we showed that the use of M_m and in particular its automation could significantly improve tsunami warning procedures (Talandier and Okal, 1989; Reymond et al., 1991), and could also help the reassessment of the seismic moment of old earthquakes, for which datasets are limited, occasionally consisting of a single record (Okal, 1992). In a study targeted at the gigantic events of 1960 (Chile) and 1964 (Alaska), we also showed that the method performs flawlessly even for the very largest earthquakes ever recorded, despite the generally lower quality of the available records (Okal and Talandier, 1991a). Finally, we showed that measurements of M_m could be reliably taken at distances as short as 1.5°, thereby extending the potential of the method in terms of rapid tsunami warning (Okal and Talandier, 1991b).

Our purpose in the present paper is to report on four years of routine real-time computation of M_m, and hence of seismic moment estimates at PPT, and to analyze the resulting dataset. Since the details of the detection and location algorithms, as well as of the automation of the actual computation, have been published elsewhere (Reymond et al., 1991), we will only review rapidly the procedure involved, which is summarized in the flow chart on Figure 1.

Technique

Two detection and location algorithms run concurrently at Papeete: A short-period algorithm takes advantage of the existence of an eleven-station short-period network telemetered in real time to the central observatory in PPT. A

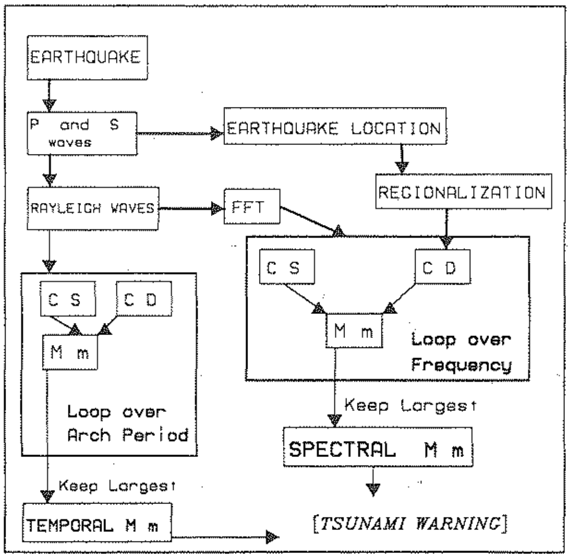

Fig. 1. Flow chart of the automatic procedure of location and moment estimation. See text for details.

second algorithm is based on the single three-component broadband station at PPT. It automatically evaluates the S–P delay to infer the epicentral distance, and analyzes the three-dimensional ground motion during the P phase to obtain the back azimuth to the epicenter. The two algorithms offer a comparable level of precision, the location error vectors being usually on the order of a few hundred kilometers at teleseismic distances (Reymond et al., 1991). By eliminating the need for any telemetry, the long-period algorithm has the potential of significantly reducing acquisition and maintenance costs.

Once an estimate of the epicenter is obtained, the Rayleigh wave time window is defined, and the corresponding time series dumped into the computer. The analysis proceeds through a Fast-Fourier-Transform, and the application of eqn. (1) at each frequency. Simultaneous computations are also performed on Love waves, and directly in the time domain; however, we present in this paper only spectral Rayleigh estimates. The algorithm automatically prints the estimated moments, and an assessment of the tsunami danger at Papeete, only a few minutes after the passage of the first Rayleigh wavetrain R_1. Upon verification by a geophysicist (on call 24 hours a day), the values of M_m and of the estimated seismic moment are transmitted by fax to the United States Geological Survey's National Earthquake Information Center in Golden, Colorado, where they are made available, usually within a few hours, on the "Quick Epicenter Determination (QED)" dial-up line. The moment estimates are also reported (as "Moment (PPT)") in the Weekly Preliminary Determination of Epicenters (PDE), usually published two to three weeks following the event.

Dataset

We report in the present paper on a dataset of 474 earthquakes for which we obtained real-time estimates of the seismic moment, over the period August 1987–May 1991. This represents slightly

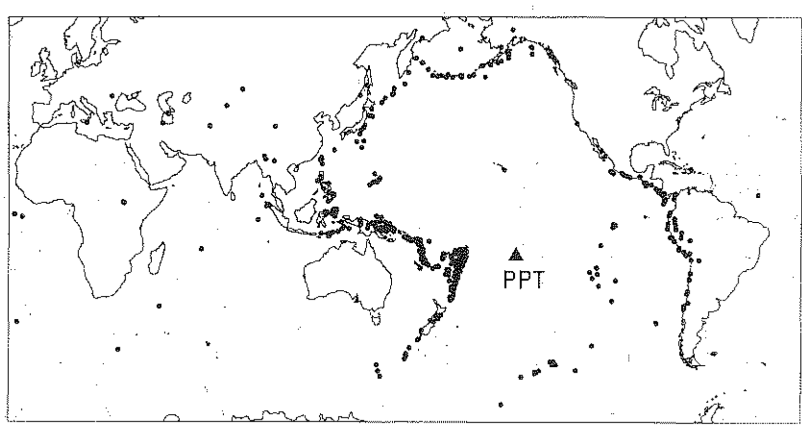

Fig. 2. Map of the 474 earthquakes used in this study. The events are shown as individual dots. The large triangle identifies the station at Papeete, Tahiti.

TABLE 1

Dataset and results of the present study

Date	Published Parameters					Measurements at PPT			
D M Y	Epicenter (°N; °E)	Depth (km)	M_m^{pub}	Focal Solution (ϕ, δ, λ)	Ref. †	Δ (°)	M_m	Period (s)	M_c
8 8 1987	-19.19 -70.14	82	6.90	176 20 -87	a	74.70	6.90	102	6.58
6 10 1987	-17.90 -172.29	33	6.95	352 42 -113	b	21.63	7.28	144	6.94
12 10 1987	-7.29 154.39	20	6.53	323 43 -68	b	55.49	6.58	74	6.86
16 10 1987	-6.25 149.09	24	7.10	266 32 90	b	60.83	6.67	273	6.68
25 10 1987	-2.39 138.41	33	6.28	22 32 132	b	72.14	6.54	68	6.52
17 11 1987	58.82 -143.21	10	6.82	262 57 -6	b	76.43	6.56	84	6.66
26 11 1987	-8.29 124.15	32	5.90	91 71 180	b	84.00	5.97	68	6.07
27 11 1987	-16.37 168.10	33	5.37	151 69 3	b	40.43	5.66	51	5.74
30 11 1987	58.68 -142.79	10	7.86	355 70 -172	b	76.31	7.68	205	7.77
12 1 1988	-28.80 -177.46	38	5.90	189 30 88	c	27.89	5.77	205	5.52
15 1 1988	-20.74 -176.13	247	5.67	188 16 64	c	25.26	5.74	137	4.95
19 1 1988	-24.75 -70.60	21	6.55	353 17 87	c	73.06	6.54	205	6.33
5 2 1988	-24.77 -70.37	33	6.82	353 17 82	c	73.26	6.75	205	6.58
24 2 1988	13.42 124.60	21	6.94	153 20 80	c	90.12	6.76	164	6.66
26 2 1988	-37.30 47.97	10	6.26	318 33 89	c	122.84	6.08	164	5.99
29 2 1988	55.10 167.45	33	6.41	131 56 -173	c	81.17	6.00	205	6.40
6 3 1988	57.27 -142.79	10	7.69	182 75 -168	c	74.91	7.20	205	7.77
12 4 1988	-17.32 -72.40	54	6.68	322 11 87	d	73.05	6.48	117	6.31
17 5 1988	-11.50 170.67	62	5.35	248 59 -27	d	38.89	5.32	164	5.34
29 5 1988	-16.75 -172.56	47	4.37	214 21 118	d	21.97	4.36	74	4.12
12 6 1988	-10.78 165.19	33	5.84	305 28 30	d	44.29	5.95	68	5.82
18 6 1988	26.92 -110.94	10	6.03	38 78 -10	d	58.08	5.81	74	5.96
27 6 1988	-20.20 169.34	73	5.10	126 18 4	d	38.88	5.15	59	4.76
28 6 1988	-56.41 147.15	10	5.06	78 74 174	d	60.78	4.90	87	5.80
16 7 1988	-27.26 -176.82	30	4.57	203 25 109	e	26.92	4.34	68	4.23
23 7 1988	-6.55 152.77	34	6.51	97 43 -125	e	57.24	6.34	137	6.77
25 7 1988	-6.12 133.73	30	6.45	29 35 -83	e	75.51	6.56	117	6.23
30 7 1988	-24.42 -116.12	10	4.40	146 90 180	e	31.90	4.43	59	3.99
3 8 1988	18.63 -106.48	33	4.25	286 90 180	e	55.65	4.32	55	4.37
4 8 1988	-42.69 -85.90	10	4.08	181 90 180	e	59.00	4.11	60	4.61
4 8 1988	-33.83 -179.83	33	4.27	315 10 -154	e	31.56	4.04	51	3.91
6 8 1988	-7.15 151.02	30	5.07	267 48 135	e	58.74	4.87	73	4.91
10 8 1988	-10.21 160.77	38	7.40	346 19 116	e	48.64	7.30	74	7.39
14 8 1988	-27.30 -71.03	39	6.06	326 16 31	e	72.18	5.89	82	5.78
15 8 1988	8.74 126.31	52	5.22	177 42 74	e	87.07	5.00	73	5.39
17 8 1988	-27.01 -70.97	39	5.20	49 11 156	e	72.28	5.11	137	5.12
20 8 1988	-16.50 167.12	33	4.95	17 39 134	e	41.34	5.04	117	4.82
21 8 1988	-42.88 -85.84	10	4.38	122 40 42	e	59.06	4.43	91	4.11
26 8 1988	-15.43 -172.88	77	4.66	246 37 -137	e	22.44	4.54	154	4.76
27 8 1988	-19.75 -176.26	33	4.76	26 73 -9	e	25.36	4.79	51	4.97
27 8 1988	-15.88 -172.08	55	4.67	329 27 63	e	21.61	4.64	63	4.38
7 9 1988	30.32 137.37	501	6.01	26 45 166	e	84.92	5.96	208	6.28
10 9 1988	-54.07 -134.05	10	4.72	197 90 180	e	38.39	4.68	51	4.24
15 9 1988	-1.41 -77.87	172	5.37	121 28 -109	e	72.14	5.32	102	5.18
1 10 1988	-35.31 -106.06	10	5.54	186 76 5	e	42.39	5.18	63	5.26
8 10 1988	-18.69 -172.52	65	6.68	196 43 90	f	21.83	6.57	59	6.51
10 10 1988	-28.48 -177.64	63	5.37	200 33 97	f	27.95	5.23	91	5.24
28 10 1988	14.09 146.60	36	3.84	19 39 102	f	70.42	3.99	82	3.90
3 11 1988	13.82 -90.61	68	5.96	96 10 -127	f	66.05	5.92	68	5.51
6 11 1988	22.81 99.77	10	6.56	333 78 174	f	115.25	6.56	91	6.16
14 11 1988	-3.33 150.48	42	6.11	303 73 7	f	60.38	6.11	74	6.32

TABLE 1 (continued)

Date	Epicenter	Depth	M_m^{pub}	Foc. sol.	Ref.	Δ	M_m	Per.	M^c
9 12 1988	-2.83 -77.72	38	4.13	2 11 29	f	71.85	4.18	57	4.70
16 12 1988	-29.78 -177.98	27	5.69	197 28 99	f	28.63	5.66	91	5.48
19 12 1988	-10.79 164.50	33	4.31	292 53 15	f	44.94	4.41	51	4.38
20 12 1988	-27.87 -176.67	37	4.45	201 28 99	f	26.96	4.38	57	4.34
22 12 1988	-13.24 -111.28	10	4.54	189 90 180	f	37.12	4.59	62	4.32
8 1 1989	51.43 -174.77	33	4.23	219 13 69	g	72.29	4.43	82	4.30
12 1 1989	46.77 153.92	33	5.22	191 41 63	g	81.83	5.26	68	5.16
13 1 1989	46.48 153.66	33	4.89	213 43 95	g	81.80	4.80	91	4.57
19 1 1989	-4.01 -105.74	10	5.05	97 74 -4	g	44.99	5.11	68	4.77
21 1 1989	-17.71 -173.32	15	4.56	195 30 86	g	22.62	4.79	55	4.43
22 1 1989	41.79 144.34	17	5.31	248 20 139	g	84.92	5.11	80	4.93
4 2 1989	6.03 -82.64	10	5.51	93 76 10	g	70.12	5.70	164	5.42
10 2 1989	2.26 126.82	33	6.74	26 31 87	g	84.59	6.60	137	6.31
14 2 1989	-10.46 161.39	24	5.76	255 16 -17	g	47.98	5.70	63	5.52
16 2 1989	-56.25 -122.51	10	5.32	191 83 177	g	43.71	5.70	91	5.27
19 2 1989	-14.90 167.17	105	5.13	181 43 174	g	41.54	4.81	117	5.52
22 2 1989	56.27 -153.59	33	5.01	208 13 60	g	73.77	4.78	164	4.90
25 2 1989	-29.85 -177.85	42	6.14	196 29 95	g	28.55	6.11	91	6.11
1 3 1989	43.86 149.01	45	4.85	220 26 89	g	83.03	4.78	164	4.60
6 3 1989	35.56 140.54	59	5.17	201 21 112	g	84.69	5.00	91	4.82
10 3 1989	-4.35 152.79	57	4.74	201 83 178	g	57.87	4.48	74	5.62
11 3 1989	-17.72 -174.81	178	6.40	128 23 18	g	24.04	6.60	164	6.29
16 3 1989	-30.21 -178.06	57	4.97	201 33 98	g	28.84	5.00	205	4.93
17 3 1989	-5.84 146.59	33	4.89	272 45 82	g	63.33	4.52	55	5.19
17 3 1989	-34.41 -178.48	58	5.28	8 47 65	g	30.78	5.00	51	4.98
8 4 1989	-15.71 -173.03	33	5.05	183 21 99	h	22.54	5.11	117	4.95
11 4 1989	49.48 159.18	33	6.18	52 35 -95	h	80.78	6.48	164	6.14
16 4 1989	-20.98 -179.03	609	5.47	127 36 -150	h	27.98	5.48	205	5.45
18 4 1989	-23.81 179.84	554	5.02	85 19 160	h	29.23	5.00	205	4.86
19 4 1989	-31.29 -177.89	33	4.82	206 28 101	h	29.07	4.95	168	4.82
24 4 1989	-17.38 167.82	35	4.76	26 36 122	h	40.56	4.48	102	4.27
25 4 1989	-17.42 167.75	33	4.43	24 46 129	h	40.63	4.53	74	4.41
25 4 1989	16.81 -99.38	20	6.38	276 10 66	h	60.14	6.15	205	6.32
27 4 1989	30.59 140.71	89	5.49	37 12 104	h	82.41	5.78	102	5.55
14 5 1989	-30.55 -178.41	33	6.40	201 29 100	h	29.23	6.40	117	6.27
15 5 1989	-9.77 159.50	25	4.92	15 32 -158	h	49.96	5.11	137	5.16
16 5 1989	-56.32 -139.16	10	4.92	21 74 -167	h	39.51	5.30	55	4.86
19 5 1989	54.30 -165.57	106	5.31	344 9 8	h	73.02	5.48	117	5.22
20 5 1989	-30.36 -178.36	80	5.45	202 31 101	h	29.13	5.54	164	5.69
23 5 1989	-52.24 160.20	10	8.13	34 69 170	h	52.27	8.40	165	8.03
24 5 1989	56.16 164.36	26	5.55	18 80 7	h	83.13	5.78	68	5.63
25 5 1989	-52.24 159.92	10	5.01	255 54 -144	h	52.43	5.08	117	5.09
25 5 1989	-52.02 159.96	10	4.82	159 63 -20	h	52.32	5.26	82	5.22
26 5 1989	-52.65 160.06	10	4.54	68 9 138	h	52.50	4.49	74	4.84
26 5 1989	-4.41 -105.42	10	4.42	187 90 180	h	45.15	4.66	68	4.29
27 5 1989	-54.73 -133.23	10	5.19	72 33 -95	h	39.19	5.70	117	5.19
28 5 1989	-16.46 -173.46	51	4.74	217 49 23	h	22.86	4.66	68	4.70
30 5 1989	-17.42 -173.45	33	4.04	233 14 126	h	22.76	4.11	68	3.95
31 5 1989	-45.16 167.11	38	5.73	41 33 161	h	45.32	5.78	59	5.56
8 6 1989	-19.45 -173.87	24	4.78	196 29 98	h	23.10	5.00	59	4.80
14 6 1989	12.90 143.33	104	4.55	347 46 -53	h	72.85	4.53	91	4.65
16 6 1989	57.84 -154.20	57	4.57	319 28 -176	h	75.36	4.67	164	4.68
25 6 1989	1.15 -79.65	19	5.53	27 25 120	h	71.26	5.48	164	5.26
26 6 1989	19.36 -155.08	9	5.72	238 7 99	h	37.21	5.78	102	5.87
27 6 1989	-63.78 -156.15	10	4.72	196 8 54	h	46.41	5.11	102	5.55
28 6 1989	-57.80 -147.38	10	4.76	28 82 -179	h	40.23	5.23	82	4.83
29 6 1989	-22.88 -175.36	32	4.08	177 37 68	h	24.74	4.30	51	4.43
3 7 1989	51.62 -175.19	33	5.15	249 23 96	i	72.58	5.30	68	5.15
6 7 1989	-16.63 -177.48	33	4.94	325 78 -169	i	26.67	5.20	91	5.03

TABLE 1 (continued)

Date	Epicenter		Depth	M_m^{pub}	Foc. sol.			Ref.	Δ	M_m	Per.	M^c
8 7 1989	-17.55	-173.41	33	3.98	194	36	73	i	22.72	4.32	51	4.49
14 7 1989	-8.04	125.15	59	6.03	67	33	103	i	83.12	6.11	74	6.05
22 7 1989	2.33	128.19	146	5.71	54	42	79	i	83.31	5.70	102	5.71
22 7 1989	-54.40	-132.74	10	4.43	204	90	180	i	39.02	4.51	63	4.06
24 7 1989	-18.83	176.73	31	4.99	239	83	-3	i	32.00	5.11	59	5.08
24 7 1989	-18.90	176.82	19	4.89	151	87	-177	i	31.91	5.15	63	4.87
24 7 1989	-18.79	176.79	33	4.08	136	69	-175	i	31.94	4.54	55	4.56
31 7 1989	-8.03	121.23	33	6.03	83	45	139	i	86.84	6.11	137	6.02
1 8 1989	-4.50	138.95	33	5.24	7	76	173	i	71.00	5.11	82	5.49
1 8 1989	-11.59	164.67	36	4.94	1	39	-70	i	44.59	5.11	82	5.09
7 8 1989	-4.34	-104.80	10	4.65	100	71	0	i	45.75	4.66	68	4.29
8 8 1989	-40.21	174.22	127	4.42	226	38	82	i	38.52	4.32	91	4.48
9 8 1989	-20.30	-173.91	38	3.92	358	42	61	i	23.17	4.18	74	4.28
10 8 1989	5.90	124.36	37	5.18	339	20	101	i	88.04	5.20	74	5.26
12 8 1989	-20.50	-174.55	33	4.35	226	24	116	i	23.78	4.38	74	4.29
29 8 1989	18.07	-105.63	34	5.84	100	76	170	i	55.95	6.11	164	5.92
4 9 1989	55.56	-156.79	33	6.66	247	8	95	i	73.24	6.48	205	6.60
7 9 1989	-30.18	-178.01	49	4.93	208	39	117	i	28.78	4.72	117	4.74
13 9 1989	-18.94	-175.02	118	4.76	208	37	-58	i	24.19	4.86	117	4.81
14 9 1989	1.69	127.32	109	5.27	339	28	34	i	83.94	5.58	102	5.42
16 9 1989	40.37	51.60	33	5.65	104	36	-132	i	150.81	5.52	68	5.40
16 9 1989	16.51	-93.65	114	5.23	86	44	-178	i	64.71	5.30	117	5.20
17 9 1989	40.19	51.79	33	5.34	292	36	-115	i	150.83	5.08	55	5.07
25 9 1989	-20.32	169.24	55	5.76	333	34	86	i	38.97	5.36	91	5.48
7 10 1989	-20.17	168.97	84	5.24	228	47	116	j	39.23	5.20	91	5.19
7 10 1989	51.28	-179.02	33	6.25	266	21	113	j	73.38	6.48	205	6.26
9 10 1989	51.75	171.90	33	4.66	174	27	-76	j	76.89	4.93	59	5.60
17 10 1989	-4.05	152.40	33	5.14	140	70	17	j	58.34	5.45	117	5.27
18 10 1989	37.04	-121.88	19	6.43	235	41	29	j	60.40	6.60	102	6.44
18 10 1989	-10.14	161.12	33	5.03	103	41	59	j	48.32	5.23	55	5.38
23 10 1989	-25.56	179.79	439	5.25	66	6	153	j	29.52	5.23	273	4.96
26 10 1989	39.79	143.52	27	5.03	174	26	58	j	84.51	5.18	117	4.94
27 10 1989	39.74	143.70	31	5.60	200	6	99	j	84.37	5.41	205	5.62
27 10 1989	-11.00	162.38	29	6.47	272	21	22	j	46.91	6.48	63	6.44
29 10 1989	39.55	143.33	28	5.76	182	19	61	j	84.53	5.82	164	5.64
1 11 1989	39.80	142.84	38	7.13	183	14	69	j	84.98	7.11	273	7.03
3 11 1989	-1.28	148.71	33	5.02	224	40	14	j	62.71	5.04	137	5.43
5 11 1989	-49.66	-115.18	10	4.93	100	77	1	j	42.32	5.18	117	4.86
6 11 1989	-11.31	162.34	52	5.26	262	53	13	j	46.88	5.34	137	5.37
14 11 1989	-9.16	124.76	33	4.82	25	75	-7	j	83.17	4.53	117	4.77
15 11 1989	-52.20	159.87	33	4.62	58	42	180	j	52.44	4.46	82	4.45
16 11 1989	-17.69	-179.06	531	5.37	92	46	27	j	28.08	5.18	205	5.13
17 11 1989	-17.31	167.80	33	4.72	12	34	113	j	40.59	4.68	102	4.45
19 11 1989	-6.54	154.14	33	5.23	321	24	96	j	55.94	5.15	164	5.24
21 11 1989	-28.97	-177.54	57	4.82	202	36	101	j	28.01	4.89	164	4.90
21 11 1989	-50.36	161.56	10	5.42	40	67	177	j	50.77	5.75	74	5.40
23 11 1989	-22.33	-174.91	101	4.32	206	25	98	j	24.26	4.69	102	4.41
25 11 1989	-2.19	138.85	33	5.10	153	24	117	j	71.78	5.18	137	5.40
29 11 1989	-15.78	-73.25	74	5.50	38	22	20	j	72.63	5.60	102	5.66
29 11 1989	-25.39	179.52	527	5.18	92	23	160	j	29.73	5.00	205	4.86
3 12 1989	-7.64	-74.53	154	5.86	192	40	-70	j	73.51	5.98	102	5.87
3 12 1989	-57.66	148.21	10	4.98	344	87	-2	j	60.50	4.60	82	5.36
4 12 1989	-15.35	-173.30	74	4.74	350	24	-33	j	22.85	4.68	273	4.97
7 12 1989	-6.48	146.43	115	5.80	232	51	-180	j	63.30	5.78	117	5.91
9 12 1989	0.18	123.46	154	6.08	196	31	69	j	87.16	6.30	102	6.17
14 12 1989	-10.39	161.25	38	5.09	180	41	125	j	48.14	5.15	137	5.07
15 12 1989	8.39	126.78	33	7.37	176	34	66	j	86.52	7.60	273	7.19
20 12 1989	8.13	126.88	64	5.83	174	26	81	j	86.35	6.11	137	6.06
20 12 1989	-35.04	-179.55	33	4.87	222	16	122	j	31.84	5.08	74	5.03

TABLE 1 (continued)

Date	Epicenter	Depth	M_m^{pub}	Foc. sol.	Ref.	Δ	M_m	Per.	M^c
23 12 1989	17.47 145.73	193	5.54	250 52 -172	j	72.61	5.72	117	5.76
30 12 1989	-3.43 146.13	33	6.03	259 62 -14	j	64.48	6.20	117	6.07
1 1 1990	-19.11 167.27	33	4.02	186 37 -72	k	40.90	4.18	68	4.09
4 1 1990	-15.05 -172.90	83	5.82	274 38 -133	k	22.52	6.00	82	5.79
5 1 1990	18.86 -106.73	33	5.00	284 90 -180	k	55.60	5.48	68	5.41
8 1 1990	52.07 -169.43	33	5.11	218 21 66	k	71.61	5.18	205	4.98
9 1 1990	52.02 -169.36	33	4.78	211 24 60	k	71.55	4.90	117	4.76
9 1 1990	24.75 95.28	118	5.48	140 32 139	k	119.60	5.36	137	5.57
14 1 1990	-29.65 -177.42	33	5.18	207 30 102	k	28.13	5.30	91	5.25
16 1 1990	-31.68 -178.11	33	4.60	218 26 119	k	29.39	4.65	117	4.63
16 1 1990	-31.66 -178.09	33	4.43	217 43 122	k	29.37	4.62	137	4.48
18 1 1990	-30.00 -177.71	26	5.08	206 30 103	k	28.48	5.11	117	4.92
20 1 1990	-15.05 -173.57	33	4.79	130 32 20	k	23.16	4.96	74	4.84
21 1 1990	-21.07 -173.83	33	4.17	184 23 82	k	23.14	4.48	117	4.29
22 1 1990	-20.96 -173.88	38	4.14	38 46 118	k	23.18	4.32	63	4.55
22 1 1990	3.85 96.10	51	5.40	313 27 89	k	114.34	5.36	68	5.49
24 1 1990	14.58 119.46	23	4.93	41 20 133	k	95.23	5.18	63	4.99
25 1 1990	-31.28 -178.00	197	4.18	336 7 -128	k	29.16	4.46	74	4.31
2 2 1990	-18.39 176.93	10	5.12	52 85 -4	k	31.84	5.48	117	5.05
2 2 1990	-5.31 151.17	60	4.79	194 82 180	k	59.12	4.74	102	5.98
8 2 1990	9.69 124.71	31	6.19	237 36 87	k	88.87	6.48	117	6.33
10 2 1990	-42.29 172.80	12	5.03	67 56 -174	k	40.39	5.08	68	5.35
17 2 1990	-5.36 -105.91	10	4.84	10 87 179	k	44.37	5.23	68	4.84
19 2 1990	-40.30 176.04	23	5.42	81 28 -41	k	37.31	5.11	82	5.34
19 2 1990	-15.41 166.30	36	6.22	246 35 -7	k	42.29	6.30	164	6.25
20 2 1990	34.69 139.35	13	5.64	355 79 10	k	85.20	5.85	102	5.48
20 2 1990	-21.54 170.47	159	4.49	98 76 13	k	37.77	4.94	102	5.30
24 2 1990	-15.28 -175.45	33	5.24	27 68 -162	k	24.91	5.20	117	5.48
25 2 1990	-10.57 165.19	33	4.51	243 20 129	k	44.34	4.48	117	4.41
26 2 1990	-26.73 -114.84	10	5.16	117 36 -108	k	33.34	5.48	68	5.35
3 3 1990	-22.04 175.16	33	7.48	228 68 4	k	33.42	7.60	117	7.43
5 3 1990	-18.13 167.95	33	6.53	350 28 104	k	40.36	6.78	205	6.50
11 3 1990	-20.58 168.21	38	4.48	206 48 -44	k	39.92	4.69	68	4.80
12 3 1990	-48.05 165.45	33	4.21	207 90 -180	k	47.52	4.63	102	4.45
12 3 1990	51.39 -174.97	33	5.58	229 21 76	k	72.31	5.63	164	5.43
13 3 1990	-47.90 165.76	33	4.26	207 90 -180	k	47.27	4.45	91	4.29
15 3 1990	-15.15 167.25	131	5.75	358 43 70	k	41.42	5.98	117	5.95
16 3 1990	24.93 -109.10	20	5.26	304 90 -180	k	57.88	5.34	68	5.38
21 3 1990	-31.12 -179.21	153	5.92	131 12 93	k	30.07	6.38	102	6.20
24 3 1990	-16.25 -173.02	33	4.14	39 40 146	k	22.46	4.18	68	4.08
25 3 1990	9.89 -84.89	19	7.04	303 11 104	k	69.50	6.78	183	6.91
2 4 1990	-32.57 -71.97	39	4.55	6 36 106	l	70.47	4.93	102	4.78
3 4 1990	-5.89 147.69	99	5.29	51 47 157	l	62.27	5.30	117	5.47
3 4 1990	11.40 -86.39	53	6.25	310 19 105	l	68.75	6.30	164	6.34
5 4 1990	15.23 147.53	32	7.21	185 31 -108	l	70.09	7.48	164	7.16
6 4 1990	-21.78 -174.16	33	4.22	213 24 101	l	23.51	4.64	82	4.57
6 4 1990	15.21 147.56	33	5.37	35 32 -50	l	70.06	5.66	74	5.57
6 4 1990	-25.85 -176.12	66	4.72	273 22 167	l	25.96	4.63	82	4.30
7 4 1990	-25.59 -176.11	33	4.14	278 45 -168	l	25.89	4.26	63	4.18
9 4 1990	-25.66 -176.10	56	4.99	353 31 -102	l	25.90	5.48	82	5.46
11 4 1990	-30.65 -177.75	48	4.81	220 29 125	l	28.73	4.77	102	4.71
16 4 1990	-14.78 167.22	119	4.56	343 47 40	l	41.51	4.65	117	4.74
18 4 1990	1.16 122.84	28	7.52	112 31 122	l	88.05	7.30	82	7.63
18 4 1990	1.28 123.05	33	5.82	98 24 99	l	87.88	5.62	59	5.98
19 4 1990	1.12 123.48	31	5.54	85 48 -168	l	87.42	5.60	59	5.55
21 4 1990	-36.95 -73.25	30	4.82	352 17 80	l	68.84	5.04	137	4.89
22 4 1990	-38.01 -73.36	33	4.55	347 16 81	l	68.64	4.41	164	4.29
26 4 1990	36.01 100.27	33	5.47	90 40 19	l	116.27	5.82	164	6.21
28 4 1990	8.86 -83.56	28	5.62	317 30 118	l	70.31	5.70	205	5.48

TABLE 1 (continued)

Date	Epicenter	Depth	M_m^{pub}	Foc. sol.	Ref.	Δ	M_m	Per.	M^c
30 4 1990	-25.09 -112.51	10	4.46	156 90 -180	l	35.23	4.90	164	4.57
1 5 1990	14.03 -91.79	33	4.75	284 32 69	l	65.13	4.73	164	4.55
1 5 1990	58.82 -156.85	217	5.94	177 54 -148	l	76.48	5.94	205	5.67
2 5 1990	-5.62 150.15	96	5.70	307 18 -18	l	60.00	5.77	117	5.64
8 5 1990	6.95 -82.64	6	5.76	265 68 8	l	70.45	5.90	166	5.75
10 5 1990	-54.87 146.56	10	4.84	259 90 -180	l	60.78	4.43	82	6.49
12 5 1990	49.04 141.88	611	6.91	172 29 -151	l	89.88	6.78	218	6.75
13 5 1990	-40.26 176.14	30	5.66	220 28 149	l	37.23	5.70	102	5.68
14 5 1990	-35.84 -71.38	81	5.27	273 40 19	l	70.48	5.32	117	5.24
15 5 1990	1.11 123.78	33	5.04	65 29 106	l	87.14	4.78	68	4.76
15 5 1990	-31.83 -178.05	48	4.55	210 32 112	l	29.40	4.76	91	4.77
20 5 1990	5.04 32.11	7	6.72	224 67 176	l	167.40	6.91	68	6.49
20 5 1990	-18.09 -175.34	232	5.43	260 32 -25	l	24.52	5.58	205	5.18
24 5 1990	5.34 31.91	10	6.68	232 43 -131	l	167.72	7.04	59	6.53
28 5 1990	-20.76 -178.08	497	4.94	142 31 -123	l	27.09	5.15	205	4.90
29 5 1990	56.97 -153.52	33	5.20	212 9 61	l	74.47	4.81	164	4.99
30 5 1990	-6.03 -77.27	33	5.88	188 24 122	l	71.35	6.11	164	5.89
30 5 1990	45.87 26.67	90	6.48	33 29 70	l	151.57	6.85	193	6.88
31 5 1990	17.25 -100.75	26	4.87	265 35 71	l	59.28	5.23	222	5.04
1 6 1990	35.53 140.45	62	5.43	214 23 118	l	84.75	5.32	102	5.16
7 6 1990	-3.59 144.49	28	5.76	176 84 179	l	65.99	6.04	117	5.94
7 6 1990	-16.03 -176.92	33	4.48	249 31 0	l	26.21	4.65	68	4.54
8 6 1990	-18.70 -178.90	499	5.76	73 34 -143	l	27.87	5.75	273	5.73
14 6 1990	11.33 122.17	15	6.67	224 78 -169	l	91.75	6.78	117	6.56
16 6 1990	-22.49 -176.80	142	4.50	333 13 41	l	26.02	4.67	137	4.44
20 6 1990	36.96 49.41	10	7.13	200 59 160	l	154.42	7.30	137	6.99
22 6 1990	-14.88 167.82	193	4.24	175 45 83	l	40.93	4.40	82	4.20
23 6 1990	-0.63 146.44	40	5.34	161 62 -159	l	65.07	5.65	205	5.37
23 6 1990	-21.36 -176.58	209	6.34	264 12 -26	l	25.72	6.70	137	6.43
24 6 1990	-21.50 -176.54	193	4.76	216 32 -72	l	25.69	4.94	117	4.80
6 7 1990	45.32 150.23	42	4.52	232 36 126	m	83.09	4.46	74	4.48
9 7 1990	5.36 31.66	10	5.52	28 44 -149	m	167.77	5.70	68	5.31
10 7 1990	-10.29 161.14	69	5.65	145 12 152	m	48.26	5.38	63	5.34
11 7 1990	-25.22 178.22	600	5.11	250 56 -180	m	30.87	5.38	205	5.52
14 7 1990	0.00 -17.41	10	5.93	79 70 177	m	129.80	5.82	205	5.86
15 7 1990	-23.11 -175.36	68	4.15	239 26 122	m	24.77	4.18	74	3.91
16 7 1990	15.66 121.23	25	7.61	243 86 178	m	93.90	7.90	164	7.59
17 7 1990	16.37 120.86	12	5.16	45 83 180	m	94.45	5.15	74	4.80
17 7 1990	16.41 121.02	7	5.80	213 41 82	m	94.32	6.20	68	5.64
22 7 1990	-23.48 179.93	565	5.48	62 25 130	m	29.11	5.32	205	5.23
27 7 1990	-15.32 167.40	133	6.86	332 39 55	m	41.25	7.08	102	6.99
2 8 1990	-31.61 -71.58	41	5.12	2 27 95	m	70.95	5.30	164	5.08
3 8 1990	47.95 84.96	19	5.30	113 53 173	m	126.47	5.26	164	5.07
5 8 1990	36.30 141.08	42	5.18	205 26 99	m	84.63	5.20	68	5.08
5 8 1990	-1.01 -13.96	10	5.73	260 77 -168	m	132.54	5.70	63	5.53
6 8 1990	-16.15 -173.45	83	4.39	18 9 92	m	22.89	4.60	164	4.43
10 8 1990	-20.17 168.28	47	4.76	186 43 -70	m	39.88	5.20	82	5.51
10 8 1990	0.31 126.16	38	5.40	231 50 128	m	84.63	5.71	59	6.01
10 8 1990	-19.68 -177.52	392	4.84	130 37 -147	m	26.55	4.95	205	4.59
12 8 1990	-19.42 169.05	144	6.64	327 17 72	m	39.20	6.78	137	6.53
17 8 1990	-11.18 162.02	33	6.12	278 24 32	m	47.21	6.00	55	5.87
21 8 1990	-33.16 -178.03	33	4.91	35 38 -69	m	29.91	5.20	91	5.22
21 8 1990	-27.58 -104.40	10	5.04	200 33 -96	m	42.67	5.48	82	4.99
25 8 1990	0.49 126.02	44	5.60	212 47 117	m	84.81	5.90	59	7.29
26 8 1990	-33.98 -179.02	33	4.01	225 20 114	m	31.00	4.30	63	4.29
27 8 1990	-26.11 -177.54	33	4.61	195 79 173	m	27.26	4.90	68	4.90
28 8 1990	-19.43 -175.83	243	4.50	275 8 -25	m	24.95	4.60	205	4.18
2 9 1990	-0.12 -80.24	25	5.41	22 27 115	m	70.29	5.48	137	5.23
2 9 1990	-3.10 148.04	41	4.73	111 82 -4	m	62.77	4.78	68	5.29

TABLE 1 (continued)

Date	Epicenter	Depth	M_m^{pub}	Foc. sol.	Ref.	Δ	M_m	Per.	M^c
8 9 1990	-24.41 -177.16	133	4.66	147 26 -126	m	26.60	4.93	91	4.75
8 9 1990	-20.50 -174.33	57	5.09	191 26 83	m	23.57	5.26	102	5.18
9 9 1990	-5.16 151.79	37	5.09	239 31 67	m	58.58	4.95	205	4.94
14 9 1990	51.44 -164.10	33	4.46	20 72 -174	m	70.02	4.81	273	4.54
17 9 1990	-53.30 159.44	10	5.65	29 77 175	m	53.09	6.04	74	5.60
18 9 1990	51.43 177.98	41	4.67	215 19 22	m	74.47	4.30	74	4.21
21 9 1990	-12.89 165.81	33	4.47	2 21 110	m	43.22	4.62	82	4.53
23 9 1990	-15.04 -173.65	33	4.99	109 35 5	m	23.24	5.00	74	4.92
23 9 1990	-17.80 167.61	33	5.58	8 16 113	m	40.71	5.78	102	5.68
23 9 1990	33.22 138.73	10	5.85	36 86 -1	m	85.05	5.78	82	5.73
24 9 1990	-17.51 167.68	59	4.91	14 22 115	m	40.68	5.20	117	5.08
28 9 1990	-13.43 166.97	180	6.08	5 37 100	m	42.00	6.20	137	6.05
2 10 1990	-23.96 -174.77	43	4.71	11 35 -104	n	24.38	5.00	102	5.05
4 10 1990	-41.45 175.00	39	4.40	190 21 58	n	38.54	4.26	68	4.65
7 10 1990	-28.81 -176.93	60	4.13	182 21 72	n	27.45	4.43	102	4.35
10 10 1990	-19.34 -66.55	271	5.84	237 31 -28	n	77.95	6.04	205	5.62
10 10 1990	-23.35 178.87	594	5.14	278 38 -112	n	30.07	4.90	273	4.93
13 10 1990	15.70 147.97	38	4.88	30 24 -85	n	69.91	5.30	205	5.04
15 10 1990	-2.20 92.28	34	6.13	19 70 -2	n	115.98	5.86	117	7.12
17 10 1990	-25.59 -176.30	33	4.79	177 18 85	n	26.06	5.00	117	4.87
17 10 1990	-10.99 -70.78	624	6.50	350 34 -90	n	76.16	6.48	273	6.37
21 10 1990	-4.01 -77.31	116	4.18	354 32 -69	n	71.89	4.45	125	4.38
22 10 1990	-16.31 -173.16	31	4.42	108 22 17	n	22.59	4.30	63	4.16
25 10 1990	8.30 126.50	53	5.56	163 42 55	n	86.76	5.70	273	5.38
1 11 1990	-3.53 139.27	33	4.67	347 59 167	n	70.98	4.68	117	4.72
1 11 1990	-4.54 -104.89	10	4.23	185 90 -180	n	45.60	4.53	164	4.24
2 11 1990	-21.16 -174.50	33	4.47	217 29 113	n	23.77	4.81	205	4.56
6 11 1990	53.47 169.93	32	6.76	308 23 159	n	78.98	6.73	68	6.60
12 11 1990	42.94 78.08	5	5.52	211 65 23	n	132.50	5.51	273	5.37
13 11 1990	46.10 138.67	28	4.92	196 45 83	n	90.52	5.30	205	4.85
15 11 1990	3.95 97.56	56	6.08	122 67 178	n	112.98	6.20	102	6.29
20 11 1990	-18.19 -174.75	87	4.52	234 46 -56	n	23.96	4.74	137	5.04
21 11 1990	51.60 -171.23	33	5.03	17 66 -178	n	71.57	5.26	71	5.17
22 11 1990	-5.61 151.09	45	5.45	241 37 72	n	59.11	5.23	164	5.36
23 11 1990	-4.94 145.80	57	4.65	324 81 -180	n	64.34	5.15	117	5.26
25 11 1990	-23.34 -175.95	33	4.58	187 17 70	n	25.34	4.75	137	4.83
25 11 1990	-23.54 -176.03	115	4.78	192 25 73	n	25.45	4.82	117	4.77
25 11 1990	-2.70 -77.79	25	4.11	20 35 98	n	71.83	4.18	91	3.93
29 11 1990	-27.81 -179.94	416	5.14	125 55 171	n	29.73	4.67	273	4.74
3 12 1990	-22.75 166.74	33	4.47	343 43 -127	n	41.21	4.95	273	4.52
5 12 1990	-5.26 131.42	89	5.16	333 80 -172	n	77.96	5.15	137	5.98
7 12 1990	-16.82 -177.36	412	4.96	243 52 -23	n	26.54	5.04	273	4.96
10 12 1990	-5.96 142.29	33	5.00	312 43 102	n	67.39	5.46	273	5.45
11 12 1990	-22.25 -174.27	38	4.09	187 20 63	n	23.66	4.23	74	4.19
11 12 1990	-15.18 -173.40	30	5.39	140 16 46	n	22.97	5.51	102	5.46
11 12 1990	-15.15 -173.39	33	4.69	141 20 38	n	22.97	4.76	59	4.57
13 12 1990	37.20 15.50	10	4.51	274 64 174	n	156.41	4.83	51	4.41
13 12 1990	24.03 121.67	14	5.50	225 19 85	n	95.93	5.52	273	5.29
13 12 1990	1.12 123.98	33	5.17	321 41 81	n	86.95	5.52	74	5.70
13 12 1990	23.74 121.69	10	5.56	212 23 104	n	95.83	6.08	55	5.68
13 12 1990	23.58 121.66	10	4.95	212 14 95	n	95.81	5.15	55	4.91
14 12 1990	-9.66 -78.90	41	4.45	191 57 140	n	68.81	4.54	91	4.52
16 12 1990	-19.68 -173.18	33	4.59	199 28 81	n	22.46	4.96	205	4.68
17 12 1990	6.65 -82.03	23	5.45	354 63 171	n	70.91	5.34	273	5.22
18 12 1990	-42.60 -16.17	10	4.05	163 33 -107	n	106.25	4.66	63	4.30
19 12 1990	23.75 121.57	10	4.44	190 15 72	n	95.94	4.52	59	4.25
19 12 1990	-26.75 -175.91	41	3.77	8 57 -41	n	26.00	4.20	82	4.26
19 12 1990	52.60 160.83	33	4.98	207 35 79	n	82.10	5.11	59	5.08
21 12 1990	-16.45 -177.70	33	4.84	318 72 -171	n	26.90	5.20	137	4.97

TABLE 1 (continued)

Date	Epicenter	Depth	M_m^{pub}	Foc. sol.	Ref.	Δ	M_m	Per.	M^c
21 12 1990	-20.36 -174.21	33	5.26	210 21 100	n	23.45	5.40	137	5.27
22 12 1990	9.91 -84.30	13	5.01	147 67 -179	n	70.04	5.18	273	5.27
22 12 1990	-14.93 168.04	33	4.64	203 26 124	n	40.71	5.04	273	4.73
23 12 1990	-0.70 127.40	33	4.40	186 55 -144	n	83.14	4.87	59	4.97
24 12 1990	-19.88 -173.08	33	3.98	214 29 111	n	22.37	4.41	91	4.27
24 12 1990	-5.36 151.49	49	4.96	216 43 46	n	58.80	4.51	51	4.76
24 12 1990	-5.66 146.42	65	4.12	62 37 2	n	63.54	4.18	74	3.99
27 12 1990	-19.61 168.95	45	4.14	352 42 81	n	39.28	3.89	63	4.42
28 12 1990	-14.95 66.75	10	4.94	168 42 -48	n	131.69	4.86	91	5.43
29 12 1990	8.23 94.02	21	5.18	347 86 179	n	117.56	5.38	205	5.12
30 12 1990	-5.09 150.98	188	7.25	204 38 16	n	59.37	6.96	164	7.37
31 12 1990	-21.99 174.95	33	4.45	253 32 -33	n	33.61	4.26	137	4.31
1 1 1991	18.04 -105.69	10	5.44	275 90 -180	o	55.89	5.74	137	5.33
1 1 1991	17.91 -105.77	10	4.70	275 90 -180	o	55.75	5.11	137	4.70
1 1 1991	55.17 -158.41	33	4.16	255 15 137	o	72.98	4.08	74	4.15
1 1 1991	-21.40 -174.20	29	5.03	188 23 80	o	23.51	5.20	164	4.96
3 1 1991	-7.16 148.49	40	4.35	82 28 -78	o	61.15	4.43	102	4.62
3 1 1991	-29.67 -111.95	10	4.89	316 77 -171	o	36.35	5.23	273	4.87
3 1 1991	-7.15 148.49	32	5.18	72 37 -93	o	61.15	5.40	137	5.40
5 1 1991	23.48 95.98	20	6.49	2 68 166	o	118.80	6.57	82	7.29
8 1 1991	-18.02 -173.66	43	5.30	342 31 107	o	22.93	5.36	205	5.17
9 1 1991	-5.43 151.85	38	5.32	240 19 73	o	58.44	5.18	273	5.21
10 1 1991	-5.53 151.91	35	4.78	234 18 69	o	58.36	4.40	137	4.54
10 1 1991	-17.95 -173.73	33	4.60	170 38 88	o	23.00	4.80	164	4.44
12 1 1991	-18.14 -173.64	120	4.52	167 42 79	o	22.91	4.79	164	4.90
12 1 1991	-17.34 -172.91	33	3.95	195 25 76	o	22.26	4.20	68	4.11
14 1 1991	18.08 -101.68	52	4.28	87 44 47	o	59.01	4.32	117	4.37
15 1 1991	-6.00 154.42	88	5.09	135 44 87	o	55.83	4.76	82	4.76
16 1 1991	13.73 -90.72	68	4.31	209 21 -11	o	65.92	4.53	137	4.35
18 1 1991	23.70 121.36	11	4.56	125 16 -85	o	96.11	4.53	51	4.87
18 1 1991	15.14 147.61	33	3.95	13 30 -108	o	69.98	4.00	102	3.77
19 1 1991	-5.61 148.33	178	4.52	321 20 -103	o	61.74	4.72	102	4.64
20 1 1991	-21.24 169.97	88	5.03	18 41 -168	o	38.25	4.57	102	4.87
23 1 1991	52.02 178.86	116	5.71	112 48 171	o	74.68	5.66	117	5.48
24 1 1991	2.26 126.74	33	4.10	32 36 92	o	84.67	4.34	91	4.13
25 1 1991	-2.15 138.94	33	5.27	135 22 92	o	71.71	5.36	102	5.63
27 1 1991	-10.73 164.21	33	4.09	253 24 -12	o	45.23	3.98	91	3.91
28 1 1991	-42.02 171.71	28	4.64	66 42 136	o	41.00	4.48	91	4.74
28 1 1991	-42.02 171.75	29	4.85	229 34 121	o	40.97	4.92	164	4.92
29 1 1991	-14.90 -75.69	36	3.80	311 40 50	o	70.55	4.15	117	3.93
29 1 1991	12.79 -90.85	37	4.12	99 48 -123	o	65.39	4.34	82	4.39
31 1 1991	0.49 126.16	33	4.70	7 44 62	o	84.68	4.65	137	4.33
31 1 1991	36.06 70.48	152	6.34	247 17 68	o	140.13	6.20	137	6.36
1 2 1991	-19.86 -173.12	23	4.09	170 24 52	o	22.41	4.53	117	4.32
1 2 1991	-57.07 -141.13	10	4.60	204 90 -180	o	39.97	4.85	73	4.41
5 2 1991	-24.41 -115.95	10	4.34	155 80 -177	o	32.06	4.91	82	4.51
7 2 1991	51.67 174.28	33	4.59	294 15 134	o	75.95	4.54	74	4.41
9 2 1991	-15.52 -177.16	28	5.16	272 58 -7	o	26.51	5.04	273	5.34
9 2 1991	-9.86 159.09	10	6.44	279 34 -89	o	50.33	6.38	273	6.34
10 2 1991	8.72 -39.84	10	4.94	183 81 -7	o	111.33	5.23	91	4.98
10 2 1991	14.03 144.74	159	5.08	183 72 1	o	72.04	4.94	63	5.24
14 2 1991	-6.24 154.65	52	4.96	310 41 94	o	55.54	4.56	74	4.97
14 2 1991	-22.56 -112.82	10	5.09	142 90 -180	o	34.81	5.48	102	5.05
15 2 1991	-42.10 171.56	33	4.18	213 37 90	o	41.14	3.89	68	4.25
16 2 1991	48.22 154.37	44	5.18	204 32 86	o	82.45	5.23	205	4.94
17 2 1991	-21.06 169.72	60	5.00	73 47 -37	o	38.49	5.11	63	4.93
18 2 1991	8.82 126.60	57	6.20	186 23 88	o	86.83	6.28	205	6.15
18 2 1991	-19.01 168.44	72	4.57	154 50 -175	o	39.81	4.48	91	4.56
20 2 1991	-22.47 -112.97	10	4.87	168 90 -180	o	34.67	4.79	91	4.69

TABLE 1 (continued)

Date	Epicenter	Depth	M_m^{pub}	Foc. sol.	Ref.	Δ	M_m	Per.	M^c
20 2 1991	9.02 126.58	41	4.32	200 37 112	o	86.91	4.30	117	4.15
21 2 1991	58.42 -175.45	10	6.04	302 55 -45	o	78.80	6.38	63	5.97
24 2 1991	-22.71 166.78	33	3.87	312 51 -177	o	41.17	4.08	91	3.96
24 2 1991	-15.12 -173.58	33	4.67	150 21 124	o	23.16	4.43	164	4.67
25 2 1991	-7.34 128.94	33	4.40	4 32 128	o	79.73	4.54	68	4.67
27 2 1991	-22.88 172.49	33	4.42	230 22 62	o	35.91	3.97	102	4.47
28 2 1991	-19.99 -175.94	220	4.68	56 19 153	o	25.06	4.81	273	4.54
1 3 1991	10.80 -84.70	209	5.26	291 26 85	o	70.03	5.30	117	5.23
3 3 1991	-21.83 -175.18	43	5.31	209 26 75	o	24.46	5.38	273	5.25
6 3 1991	-29.86 -178.87	229	4.44	219 23 157	o	29.39	4.54	137	4.34
8 3 1991	60.83 167.12	33	6.01	37 34 84	o	85.61	6.08	164	5.74
9 3 1991	-54.84 -131.55	10	5.04	111 74 -2	o	39.72	5.36	117	4.95
10 3 1991	-3.81 144.40	23	4.56	155 80 -174	o	66.01	4.73	137	4.54
11 3 1991	-50.88 29.35	10	5.65	207 84 -176	o	111.69	5.94	51	5.60
13 3 1991	4.94 -82.73	10	4.56	180 90 -180	o	69.65	4.52	137	4.29
14 3 1991	51.80 -175.25	40	4.61	246 18 105	o	72.76	4.58	117	4.46
15 3 1991	-17.67 -173.28	140	4.20	186 9 77	o	22.59	4.59	91	4.17
16 3 1991	10.19 -85.15	30	5.51	295 17 81	o	69.38	5.41	205	5.35
20 3 1991	-5.80 -80.98	33	5.04	13 14 114	o	67.88	5.08	205	5.02
21 3 1991	-9.68 -79.75	33	5.28	344 16 92	o	67.99	5.54	91	5.41
21 3 1991	-11.67 166.51	33	4.69	168 38 72	o	42.82	4.73	51	4.82
24 3 1991	-16.85 177.38	22	4.23	272 70 -5	o	31.54	4.30	51	4.52
26 3 1991	21.64 121.82	18	5.48	157 73 -8	o	95.11	5.62	164	5.33
26 3 1991	19.72 -70.38	33	4.79	104 84 -4	o	86.15	5.11	51	5.21
28 3 1991	-18.12 167.71	26	4.76	2 18 118	o	40.58	4.67	117	4.55
29 3 1991	-3.94 -80.89	33	4.43	55 27 151	o	68.50	4.30	102	4.29
30 3 1991	-15.69 -175.14	18	4.31	287 68 176	o	24.56	4.28	82	4.44
31 3 1991	-16.68 -172.49	33	4.18	199 19 93	o	21.91	4.15	117	4.00
1 4 1991	-16.55 -172.81	33	4.32	203 17 89	p	22.23	4.63	102	4.53
1 4 1991	16.23 -98.23	22	4.80	40 51 40	p	60.77	4.54	55	4.57
2 4 1991	-30.63 -177.93	39	4.07	206 38 179	p	28.87	4.11	91	4.06
4 4 1991	6.98 -78.15	39	5.31	316 28 110	p	74.63	5.38	59	5.48
4 4 1991	-6.01 -77.15	33	5.66	171 20 77	p	71.47	5.73	273	5.48
5 4 1991	-5.95 -77.09	33	6.47	183 33 106	p	71.54	6.71	164	6.38
5 4 1991	-14.20 -75.61	56	5.48	13 21 -22	p	70.79	5.41	68	5.19
5 4 1991	-54.03 -132.66	10	4.80	109 83 0	p	38.71	5.08	117	4.66
6 4 1991	-15.02 -175.59	14	6.05	289 72 -8	p	25.09	5.94	137	6.10
7 4 1991	-3.14 130.31	31	4.94	105 18 53	p	79.64	4.45	117	4.77
9 4 1991	-9.83 -74.78	135	4.73	338 45 -96	p	72.68	4.36	102	4.29
11 4 1991	-5.31 151.74	55	4.70	233 25 68	p	58.58	4.23	117	4.67
11 4 1991	-10.98 166.75	23	4.43	166 45 -75	p	42.75	4.95	68	4.86
12 4 1991	13.13 -88.41	68	4.26	2 22 152	p	67.68	4.04	102	3.85
13 4 1991	-20.06 169.06	31	4.78	351 35 98	p	39.15	4.93	137	4.62
14 4 1991	27.12 127.40	105	5.13	136 14 176	p	91.93	5.26	205	5.07
19 4 1991	-14.92 -175.15	33	5.20	267 73 -6	p	24.68	5.15	91	5.30
22 4 1991	9.68 -83.08	10	7.52	103 25 58	p	71.06	7.60	205	7.36
24 4 1991	9.00 126.79	13	5.42	173 16 95	p	86.70	5.62	205	5.45
24 4 1991	9.64 -83.60	10	5.26	145 78 -174	p	70.57	5.46	82	5.34
29 4 1991	-20.70 -174.28	34	4.00	212 23 101	p	23.53	4.11	102	4.01
29 4 1991	-11.31 -77.75	57	4.97	72 14 16	p	69.48	5.23	63	4.83
30 4 1991	6.13 -82.68	10	5.00	86 76 10	p	70.12	4.83	117	4.65
1 5 1991	62.53 -151.52	116	5.48	252 24 92	p	79.98	5.48	137	5.34
2 5 1991	-21.84 -173.88	33	4.23	203 19 86	p	23.26	4.48	205	4.35
2 5 1991	9.32 -77.40	47	4.90	173 75 -178	p	76.14	4.88	82	5.32
3 5 1991	28.06 139.57	459	6.13	107 22 -133	p	82.24	5.78	205	5.66
4 5 1991	9.49 -82.47	15	5.32	138 21 105	p	71.55	5.45	205	5.20
7 5 1991	39.38 144.76	10	5.05	359 42 -80	p	83.48	5.00	273	4.58
10 5 1991	-16.07 -174.20	135	5.41	197 14 -75	p	23.61	5.60	137	5.34
12 5 1991	-21.81 -174.02	33	4.19	199 23 64	p	23.38	4.41	91	4.47

TABLE 1 (continued)

Date	Epicenter		Depth	M_m^{pub}	Foc. sol.			Ref.	Δ	M_m	Per.	M^c
17 5 1991	-4.38	142.62	47	5.58	327	69	177	p	67.54	5.57	205	5.41
19 5 1991	1.08	122.90	33	6.39	92	24	72	p	87.97	6.04	164	6.44
21 5 1991	-7.53	126.57	31	5.94	74	34	65	p	81.92	5.61	68	6.29
22 5 1991	-33.97	-179.44	33	4.18	189	31	104	p	31.31	4.15	117	3.94
22 5 1991	51.78	175.91	33	4.21	272	22	90	p	75.46	4.43	137	4.35
24 5 1991	-16.48	-70.72	125	6.33	129	34	-110	p	74.82	6.60	102	6.50
26 5 1991	-22.27	174.18	33	4.18	241	22	21	p	34.33	4.23	59	4.17
30 5 1991	54.53	-161.59	47	6.49	249	11	113	p	72.68	6.26	205	6.32
31 5 1991	-6.03	130.63	33	4.82	117	47	130	p	78.49	5.00	68	5.15
31 5 1991	-56.76	-140.93	10	4.49	27	67	-164	p	39.69	4.74	102	4.29

† References for published values of M_0 and focal geometry:
a: *Dziewonski et al.*, [1988]; b: *Dziewonski et al.*, [1989*a*]; c: *Dziewonski et al.*, [1989*b*]; d. *Dziewonski et al.*, [1989*c*] e: *Dziewonski et al.*, [1989*d*]; f: *Dziewonski et al.*, [1989*e*]; g: *Dziewonski et al.*, [1990*a*]; h: *Dziewonski et al.*, [1990*b*]; i: *Dziewonski et al.*, [1990*c*] j: *Dziewonski et al.*, [1990*d*]; k: *Dziewonski et al.*, [1991*a*]; l: *Dziewonski et al.*, [1991*b*]; m: *Dziewonski et al.*, [1991*c*]; n: *Dziewonski et al.*, [1991*d*]; o: *Dziewonski et al.*, [1992*a*]; p: *Dziewonski et al.*, [1992*b*].

over one earthquake every three days. While this number is smaller than its counterpart for the CMT dataset of Dziewonski et al. (1983, and subsequent quarterly updates), it reflects the limited detection capabilities of a single Pacific station for low-magnitude earthquakes outside the Pacific Basin. Figure 2 shows a map of the epicenters. In general, most of the events were located in the Pacific Basin, but a few occurred at larger distances, up to 168° in the case of three earthquakes in the Sudan in May and July, 1990. The shortest distance was 21.6° from Samoa. The largest event in the dataset during the time window under study is the Macquarie Ridge Earthquake of May 23, 1989 ($M_m = 8.4$). The smallest events were in Vanuatu and New Zealand ($M_m = 3.9$). Thus, the present dataset covers more than four orders of magnitude in seismic moment; it must be borne in mind, however, that the method was successfully tested over two additional orders of magnitude using seismograms from the 1960 Chilean and 1964 Alaskan earthquakes (Okal and Talandier, 1991a).

All earthquakes in the dataset were later ana-

TABLE 2

Performance of M_m at Papeete

Dataset	Number of records	$\bar{r}$	σ	Slope	$\bar{r}_c$	σ_c
Whole dataset	474	0.07	0.22	1.02	0.02	0.27
Shallow only	399	0.08	0.22	1.03	0.02	0.28
Intermediate and Deep	75	0.06	0.19	0.94	0.01	0.25
For reference						
Full teleseismic Rayleigh dataset [a]	456	0.14	0.24	1.07	0.10	0.18
Intermediate and deep Rayleigh dataset [b]	200	0.14	0.23	0.92	0.12	0.15
Teleseismic Love dataset [c]	307	0.12	0.29	0.36	0.19	0.25
Regional dataset [d]	149	0.13	0.28	1.01	0.17	0.28

[a] This dataset combines the original records from shallow earthquakes (Okal and Talandier, 1989) and those from the intermediate and deep study (Okal, 1990).
[b] (Okal, 1990).
[c] From Okal and Talandier (1990).
[d] (Okal and Talandier, 1991b).

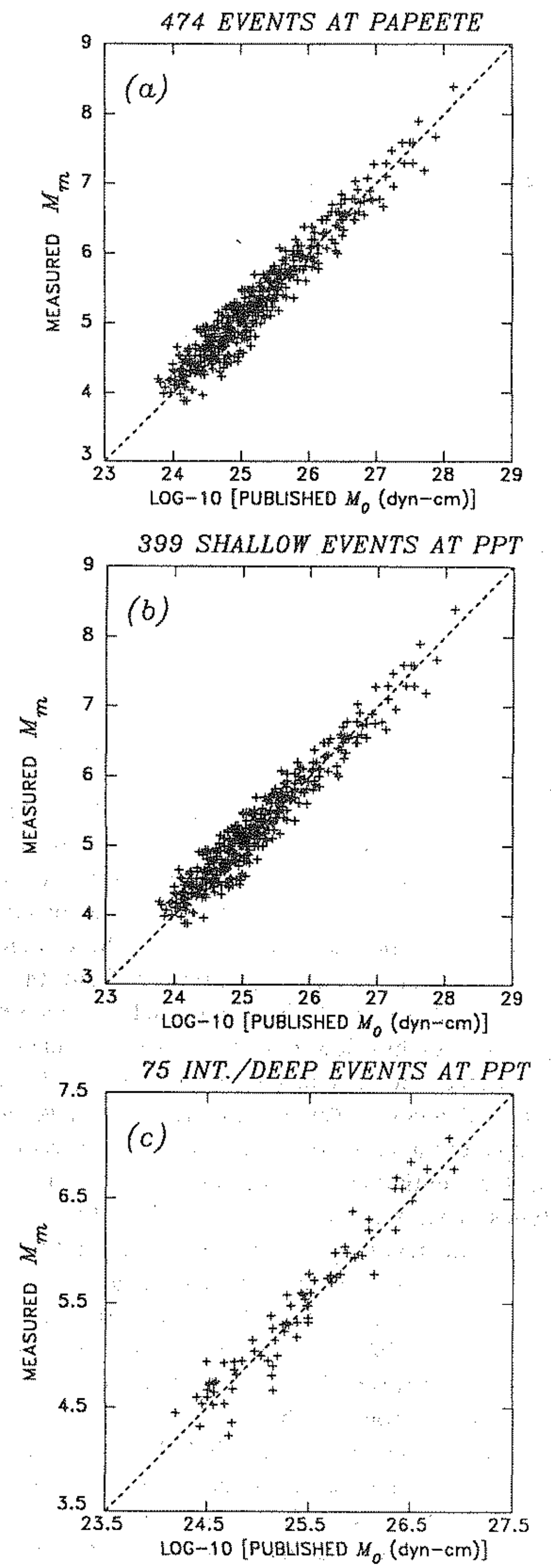

Fig. 3. Measured M_m vs. published moment for the full dataset (a), only the shallow events (b), and only the intermediate and deep events (c). The dashed lines represent the relationship $M_m = \log_{10} M_0 - 20$ predicted by the theory.

lyzed through moment tensor inversion by the Harvard and USGS groups, and the resulting focal parameters published by these authors. Following in the steps of Okal and Talandier (1989), we define for each event a residual $r = [M_m - \log_{10} M_0 + 20]$, where M_m is the value measured at Papeete, and M_0 the moment subsequently computed and published by the Harvard group.

The most far-reaching assumption made in computing the mantle magnitude M_m is the "averaging" of the focal mechanism and of the depth of the earthquake. These parameters are deemed not to be known in real time. In order to investigate the systematic error that this approximation can induce on the performance of M_m, we also compute a "focal mechanism contribution" C_{FM} in the following way: suppose we knew the exact focal mechanism and depth of the event; instead of using eqn. (3) to compute a source correction, we could compute the exact excitation of the Rayleigh spectrum at each frequency (the difference between the two source corrections, C_{FM} being detailed in Okal and Talandier, 1989). We would then have computed a value of M_m "corrected" for focal mechanism: $M_c = M_m + C_{FM}$. We want to stress that M_c necessitates the knowledge of the focal geometry, and therefore in general cannot be obtained quickly. We also define $r_c = r + C_{FM}$. The analysis of the populations r and r_c is discussed in the next sections of the paper. In particular, one of our goals will be to see if and to which extent the performance of M_m is degraded, with respect to the results reported in our previous studies, by its extension to a smaller range of magnitudes. We conclude that it is not degraded.

Results

The entire dataset, comprising epicentral information, M_m measurements and the Harvard solutions, subsequently published by Dziewonski

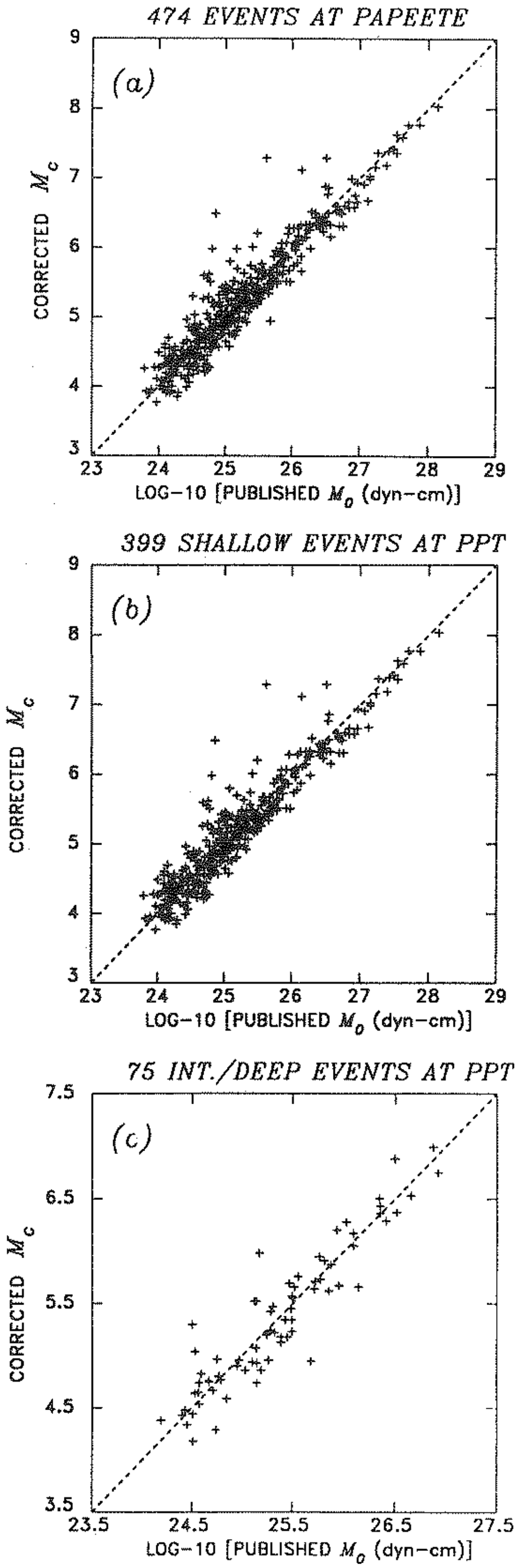

Fig. 4. Same as Figure 3 for the corrected values M_c. Note the presence of a few very large residuals (see text for details).

et al. (1988, 1989a–e, 1990a–d, 1991a–d, 1992a,b), is given in Table 1. The published seismic moment M_0 is given in the form of an equivalent mantle magnitude:

$$M_m^{pub} = \log_{10} M_0 \text{ (published)} - 20 \quad (4)$$

Figure 3 presents plots of the individual M_m measurements, as a function of the published moment. The dataset is presented as a whole, and also split into shallow events ($h \leq 75$ km), and intermediate and deep ones ($h > 75$ km). It is immediately apparent from Figure 3 that the performance of M_m on this dataset is comparable or superior to that on the smaller datasets obtained at generally larger moments, which were used in the earlier studies. The quality of the estimate of the seismic moment provided by M_m can be assessed in several ways. A statistical analysis of the residuals r shows that their average value is only $\bar{r} = 0.07$ units of magnitude with a standard deviation $\sigma = 0.22$ units. These results are also compiled separately for the shallow and intermediate/deep datasets in Table 2, where they are compared to the performance of our previous studies.

A further test of the performance of M_m is the study of the slope of the regression of M_m against the published values of M_0. Specifically, we list in Table 2 the slope of the best-fitting straight line across the populations on Figure 3. These numbers are not significantly different from their theoretical value, 1. The non-shallow dataset yields a slightly lower slope (0.94), a situation comparable to that in our previous study (Okal and Talandier, 1989), and for which we have no simple explanation; this does not, however, represent an initiation of saturation at large magnitudes (since the sub-dataset for $M_0 \cong 10^{25.5}$ dyn-cm would feature a slope of 0.97), but rather a concentration of slightly larger residuals r at the very low range of magnitudes for non-shallow earthquakes. We conclude that in all cases, M_m grows linearly with $\log_{10} M_0$, its slope being unity, as expected from the theory.

The population of residuals $\{r_c\}$ is pictured on Figure 4. It has statistical characteristics comparable to those of $\{r\}$: $\overline{r_c} = 0.02$ for the whole dataset, 0.02 for the shallow events and 0.01 for the intermediate and deep earthquakes. The apparent improvement from r to r_c is, however, not significant since the standard deviation of the residuals actually deteriorates, to $\sigma_c = 0.25$–0.28. This is due to the presence of a few very large residuals r_c, clearly apparent on Figure 4. As mentioned in Okal and Talandier (1989), this situation occurs when the station sits in a near-perfect node of the published focal mechanism, and yet some energy finds its way into the seismogram. This can be due either to a slight error in the focal geometry or the location of the event, or to multipathing away from the great circle path, resulting in an erroneous take-off azimuth to the station. Under such conditions, the magnitude approach provides a more robust estimate of the seismic moment of the event than the use of the full published focal mechanism.

Figure 5 shows that no specific trend with distance of the residuals r could be identified. The slope of the regression of r vs. $\log_{10}\Delta$ was -0.125; when compared to our original study in Okal and Talandier (1989), this number is somewhat higher than for that dataset (-0.057), but comparable to the sub-dataset involving only Pasadena records (-0.129). The absence of a systematic trend in r with Δ was to be expected since it would have reflected an inappropriate distance correction, probably stemming from inadequate Q models, which would have also produced correlations between r and Δ in our earlier studies.

Similarly, as shown on Figure 6, no significant trend with period could be identified. The slope of the regression of r with $\log_{10}T$ was -0.057, comparable to values obtained in previous studies. Again, this result was expected since a correlation between r and T would indicate an inadequate correction C_S, a situation which would have been detected in the earlier studies. Figure 6b shows that the extravagantly large residuals r_c mentioned earlier all occur at the shorter end of the period range, indicating that they could be due to multipathing effects, expected to become more important at higher frequencies.

Finally, we investigate in several ways the possible existence of "regional anomalies" or systematic trends in the residuals r with the geographic

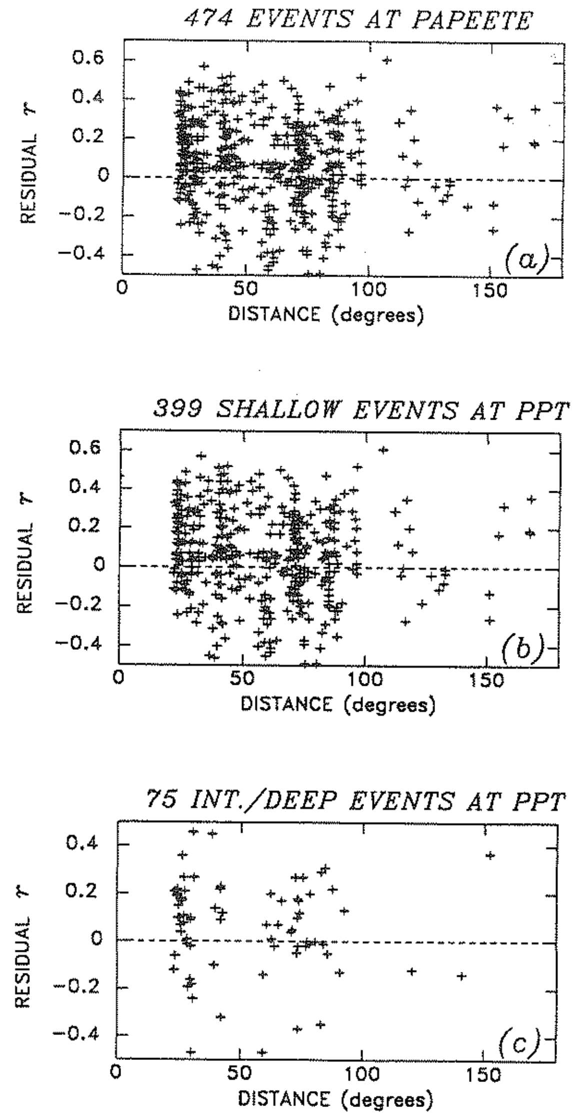

Fig. 5. Residuals $r = M_m - \log_{10} M_0 + 20$ plotted as a function of epicentral distance to PPT. (a) Whole dataset. (b) Only shallow events. (c) Only intermediate and deep events. Note the absence of any significant trend with distance.

location of the epicenter. We first show, on Figure 7, the residuals r plotted as a function of back azimuth at PPT. In this figure, the radius vector is a function of the residual, with the dashed circle corresponding to $r = 0$. The distance information is lost. The existence of any trend could be due to the interaction of the surface wave with a regional structure upon arrival in Polynesia. It is clear that no significant trend exists, with the exception of systematically positive residuals for events arriving from the south and southeast. However, when the corrected residuals r_c are plotted, this trend disappears (Fig. 7b). The relevant earthquakes are all located at the transform faults of the Southeast Pacific Rise, and have a strike-slip geometry for which PPT sits in a strong lobe of Rayleigh radiation; the focal corrections C_{FM} for these events range from -0.32 to -0.51 units. Thus, the presence of systematically negative residuals at this azimuth is entirely an artifact of the combined focal mechanism and source-receiver geometry; it is not a reflection of lateral heterogeneity.

More generally, in Figure 8, we plot the geographic location of all earthquakes with an absolute value of the residual, $|r| \geq 0.35$. There are 67 such events. On this map, the radius vector is now proportional to distance, and the residual information is represented by different symbols. The general trend of positive residuals observed in the Southern Pacific continues north along the East Pacific Rise, while a number of systematically negative residuals are located in the Aleutian–Alaska areas (note, however, that many more events with smaller residuals occur in that area, and are therefore not plotted on Fig. 8). In most other areas, such as Tonga, the Solomons and Indonesia, residuals vary widely and do not show any systematic geographic trends. On Figure 8b, we have plotted the corresponding r_c, for those events plotted on Figure 8a. Note that for 45 earthquakes (or about 2/3 of those plotted on Fig. 8a), $|r_c|$ falls below 0.35 units; in other words a substantial part of the largest residuals is simply due to the influence of the true focal geometry.

Conclusion

In conclusion, the rapid determination of M_m, introduced and tested in Okal and Talandier

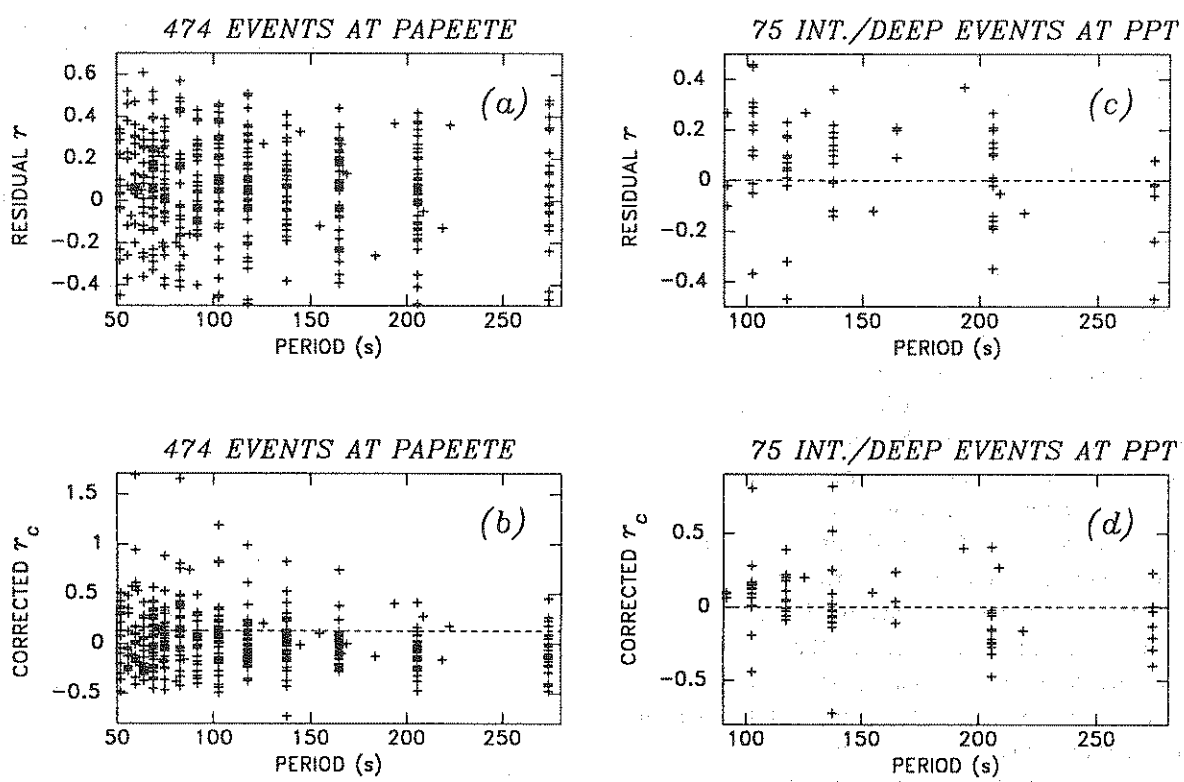

Fig. 6. (a) Residuals r plotted as a function of the period T at which the measurement of M_m is retained, for the whole dataset. (b) Same as (a) for the corrected residuals r_c; note that the extreme residuals occur at the shorter periods. (c, d) Same as (a) and (b) for the intermediate and deep events.

(1989) on an initial dataset of 256 earthquakes in the range $M_m = 5.9$–8.26, has been automated and now provides routine, real-time determinations of the estimate of the seismic moment of distant earthquakes. At the time of writing, we have obtained in this manner more than 550

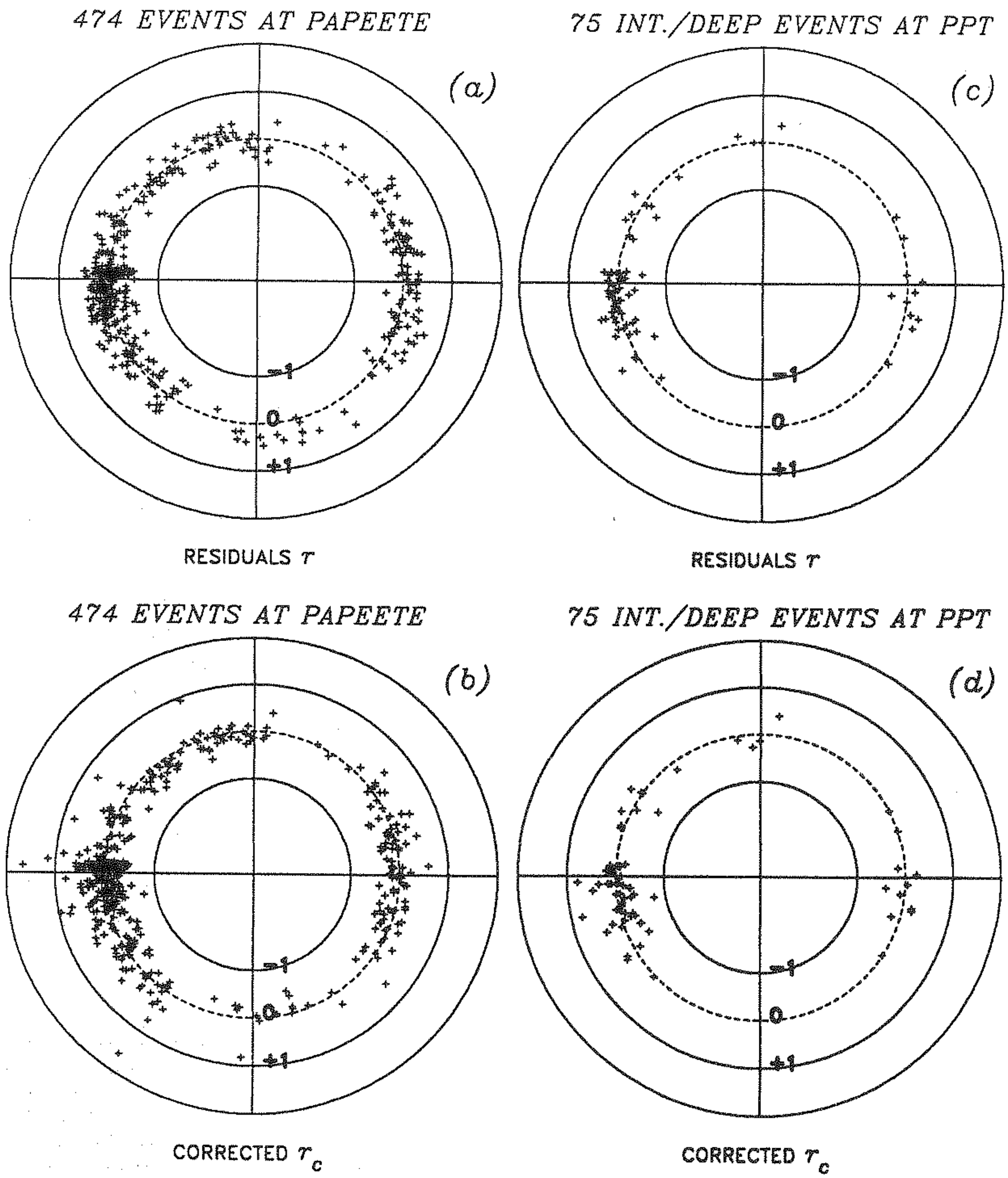

Fig. 7. (a) Residuals r plotted as a function of the back azimuth to the epicenter at PPT: The dashed circle corresponds to $r = 0$. Note the general absence of a systematic pattern, except for events from the south and southeast. (b) Same as (a) for the corrected residuals r_c. (c), (d) Same as (a) and (b) for the intermediate and deep events.

moments. The study of a database of 474 earthquakes shows that the quality of the determinations ($\bar{r} = 0.07$; $\sigma = 0.22$) is comparable to that achieved in the original study, even though the size of the events measured has been lowered by a full unit of magnitude. A number of statistical analyses on the dataset fail to reveal any systematic bias or deterioration of the quality of the measurements.

Our method can rely entirely on a single three-component broadband seismic station. It can work even in the absence of a local or regional short-period network, and can be implemented on a personal computer. Because it provides in quasi-real time an accurate estimate of the seismic moment of an earthquake, even at regional distances, it appears as a very powerful tool in the field of tsunami warning (Talandier and Okal, 1989; Okal and Talandier, 1991b).

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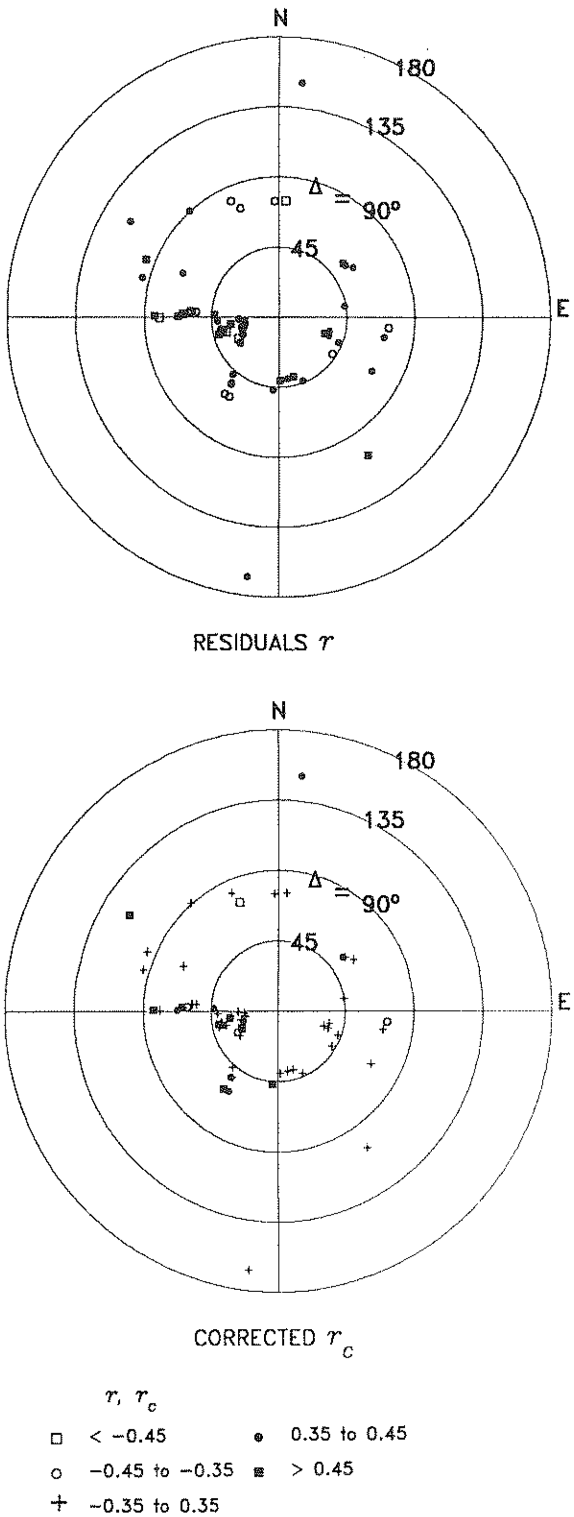

Fig. 8. (a) Azimuthal equidistant plot of those residuals r for which $|r| > 0.35$ units. The map is centered on PPT and various symbols are used to plot the residual information. Note the presence of positive residuals along the Pacific Rise, and of negative residuals in the Aleutians. (b) Plot of the corrected residuals r_c for those events plotted on (a). The crosses show the earthquakes for which a significant fraction of the residual can be explained by the influence of the true focal mechanism.

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