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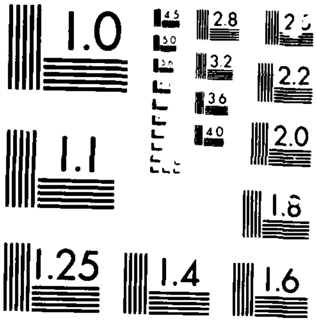

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ATOMIC WEAPONS RESEARCH ESTABLISHMENT

AWRE REPORT No. O 12/85

Body Wave Magnitudes and Locations of French Underground Explosions at the Mururoa Test Site

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Recommended for issue by

A Douglas, Superintendent

Approved by

B L Elphick, Head of Division

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SUMMARY

Since 1975 the French have conducted underground nuclear weapon tests beneath the Mururoa atoll in the Tuamotu Archipelago in the Southern Pacific. A least squares joint estimate of origin time and epicentre together with a least squares joint estimate of magnitude is presented for presumed explosions in this area. These are based on data taken from bulletins of the International Seismological Centre. Some seismograms, recorded in Canada, are included to illustrate the nature of the P waves from these presumed explosions.

1. INTRODUCTION

Basic source information (location, origin time, depth, yield, etc) about underground nuclear explosions is important to seismologists interested in fundamental properties of the structure of the earth, as well as those interested in discrimination between earthquake and explosion from their seismic signals. Numerous scientists have appealed for the release of epicentral details of explosions to aid research programmes (Bullen, 1958, Griggs and Press, 1961, Teller, 1963). In response, Springer and Kinnaman (1971, 1975) published the basic epicentre details for all underground nuclear explosions, US and British, detonated in the USA from 1961 to 1973. Numerous yield estimates were also included. The origin time and precise epicentres of French underground nuclear explosions in the Sahara between 1961 and 1966 have been published by Duclaux and Michaud (1970). However no comparable data are available for underground explosions in the USSR or the French Pacific Test Site at the Tuamotu Archipelago.

Several international data centres collect seismic wave arrival times from all over the world and compute estimates of the origin time, epicentre, depth and size for seismic disturbances. Bulletins containing these data are published by the US National Earthquake Information Centre (NEIC) in Colorado, USA, and the International Seismological Centre (ISC) in Newbury, UK. A similar service is provided by the Institute of Physics of the Earth in Moscow, but the Soviet bulletin does not report data on Soviet nuclear explosions. The French produce a bulletin for their metropolitan and Polynesian seismological networks but the bulletin contains no information on French explosions.

To provide seismologists with improved estimates of some of the basic source information about French presumed underground nuclear explosions, seismic wave arrival time and amplitude data collected by the ISC have been analysed using a joint epicentre technique (JED) to relocate the epicentres, and a least squares analysis (LSMF) of amplitude data to provide consistent estimates of the seismic magnitude. A similar study has already been made for explosions at the Soviet test site near Semipalatinsk, East Kazakh and has been published by Marshall et al (1984).

It is planned to carry out a similar study of other Soviet test sites such as Novaya Zemlya, North Caspian Sea region and the Nevada Test Site (NTS) USA.

2. JOINT EPICENTRE RELOCATIONS

The Joint Epicentre Determination (JED) method described by Douglas (1967) was employed to relocate the events using P & PKP arrival time data taken from International Seismological Centre (ISC) bulletins. To fix the overall location of the group, one of the epicentres must be restrained to a predetermined value. The restrained epicentre chosen was that for the event on 25 July 1979, the largest and most widely recorded. No true epicentre has been published and so the location must be fixed using other evidence. The strategy used here was to shift the restrained epicentre until the overall pattern fitted centrally over the island (figure 1). Taking the median latitude and longitude as representative of the group, only when the restrained epicentre is located near the southern coast does this median lie on the island and its central lagoon. The adopted epicentre (21.88S, 138.94W) gives the minimum deviation of the median location from the lagoon centre (taken as 21.83S, 138.91W). Confidence in the restrained location is gained by the fact that the ISC location (21.86S, 139.0W) is approximately 6 km WNW of the chosen position, a bias similar to that expected when station travel time corrections are not used (Lilwall and Underwood, 1970).

Arrival time readings were weighted to remove gross errors and allow for variation in the quality of arrival time measurement between stations. The effects of gross errors were reduced using the method of uniform reduction (Jeffreys, 1961). Where a station reported sufficient events (here set at 10) the standard deviation of the residuals was calculated and the station's arrival time readings weighted to account for variation in this. This technique also permitted the incorporation of a large body of PKP data which would all normally be given zero weight.

Table 1 gives the relocated epicentres, origin times and the 95% confidence limits. All depths were constrained to a surface focus source. Figure 1 shows the epicentres plotted on a map of the atoll. Although the standard deviation of the residuals (0.28s) is small the poor azimuthal distribution of stations results in relatively large limits, the majority (22 out of 28) however are less than 10 km. All but three (events 11, 22, 24) have 95% limits which intersect the island.

3. DETERMINATION OF MAGNITUDE

The size of a seismic source is measured by its magnitude. For short period (SP) seismic P wave data the Gutenberg and Richter definition is used:-

$$m_b = \log_{10} A/T + B(\Delta) + S, \qquad \ldots \quad (1)$$

where A is the amplitude of the P wave in nm, T its predominant period in seconds, $B(\Delta)$ a distance normalising term and S a station correction.

Consider n explosions recorded at some or all of q stations. Then if m is the magnitude of the ith explosion recorded at station j, we can write

$$m_{ij} = b_i + s_j + \epsilon_{ij}, \qquad \ldots \quad (2)$$

where b_i depends on the seismic size of the explosion, s_j is a station term and ϵ_{ij} is an error term. Least squares can be used to estimate b_i and s_j if it is assumed that

$$\sum^{i} b_i = \sum^{j} s_j = 0.$$

By making the further assumption that the errors ϵ_{ij} are normally distributed, confidence limits can be determined for b_i and s_j. This is the procedure used to obtain the least squares estimate of the magnitude of explosions (Douglas, 1966).

The basic input data are taken from the ISC bulletins, either as m_b or in the form of $\log_{10} A/T$ from which m_b is calculated. The stations used are located in the distance range 60 to 90°. The mean magnitude, (a least squares estimate) of the explosions is given in table 1. Station corrections are given in table 2 together with the 95% confidence limits and the number of observations. The statistics associated with the least squares analysis are given in table 3.

4. SEISMOGRAMS

The short period seismological array station located at Yellowknife, Canada, appears to be well placed to detect explosions at Mururoa. Several examples of the beamed-array P wave are illustrated in figure 2. It would appear that the seismograms fall into one of two categories. For example, explosion number 19 has no large second trough whereas explosion number 24 has a clear, large second trough; the presence or absence of the second large amplitude trough defines the two categories. The presence of the second trough may be a "depth" effect caused by the interaction of the direct P with the free-surface reflection (pP) since most of the explosions which exhibit this feature are of relatively large magnitude compared to the lower magnitude explosions for which the second trough is absent.

5. ACKNOWLEDGMENTS

The authors would like to express their appreciation to Mrs E Bradley for her help in the preparation of the data for subsequent analysis.

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TABLE 1

JED Epicentres and least Squares Estimates of m_b for Explosions at Mururoa

	Date	Origin Time	± secs	Latitude ^oS	± km	Longitude ^oW	± km	Area of Confidence Region sq km	n	$m_b^{(1)}$	±95% CL	n	$m_b^{(2)}$
1	11. 7.76	00 29 59.05	0.19	21.859	5.32	138.768	9.47	207.5	53	5.01	0.16	9	5.00
2	19. 2.77	23 29 58.94	0.21	21.834	5.57	138.846	6.69	151.24	64	5.00	0.16	9	5.01
3	19. 3.77	23 00 58.36	0.10	21.891	2.83	138.913	2.73	34.39	221	5.73	0.12	25	5.86
4	6. 7.77	22 59 58.52	0.26	21.780	6.91	138.954	14.61	414.73	36	4.92	0.21	4	4.92
5	24.11.77	16 59 58.37	0.12	21.896	3.53	138.884	3.50	48.43	159	5.80	0.14	14	5.83
6	22. 3.78	17 29 58.95	0.44	21.714	12.10	138.926	11.68	381.52	16	4.77	0.22	4	4.78
7	30.11.78	17 31 58.48	0.10	21.866	2.88	138.949	2.77	34.11	219	5.80	0.11	28	5.82
8	19.12.78	16 56 59.98	0.22	21.769	6.61	138.945	7.07	171.53	42	4.97	0.14	9	4.95
9	24. 3.79	16 27 58.79	0.17	21.830	4.86	138.909	6.06	120.01	58	4.89	0.15	8	4.85
10	4. 4.79	18 06 59.10	0.37	21.812	10.38	138.741	12.45	339.23	23	4.89	0.18	5	4.88
11	18. 6.79	23 26 58.02	0.21	22.140	7.24	138.456	5.99	183.08	21	4.81	0.23	3	4.79
12	29. 6.79	18 55 58.75	0.15	21.798	4.62	138.927	5.35	89.67	66	5.17	0.16	7	5.17
13	25. 7.79•	17 56 58.50	0.0	21.880		138.940			318	6.03	0.12	29	6.06
14	28. 7.79	19 55 58.77	0.31	21.808	8.80	138.808	8.10	226.26	27	4.76	0.27	2	4.71
15	23. 3.80	19 36 58.49	0.11	21.864	3.23	138.928	3.37	44.64	152	5.62	0.12	16	5.60
16	1. 4.80	19 30 58.68	0.18	21.854	6.30	138.763	6.19	116.16	65	5.10	0.15	8	5.07
17	4. 4.80	18 32 58.61	0.39	21.906	12.76	138.808	11.00	335.37	15	4.54	0.27	2	4.48
18	16. 6.80	18 26 58.56	0.13	21.864	3.70	138.904	3.91	64.73	80	5.29	0.13	14	5.27
19	6. 7.80	17 26 58.96	0.26	21.845	7.03	138.861	6.52	209.93	17	4.67	0.20	4	4.65
20	19. 7.80	23 46 58.51	0.10	21.855	2.83	138.949	2.87	35.63	184	5.71	0.11	29	5.67
21	3.12.80	17 32 58.48	0.11	21.874	3.48	138.945	3.50	50.09	146	5.58	0.12	21	5.57
22	28. 3.81	17 22 59.17	0.20	21.780	5.91	138.674	6.40	195.42	35	4.80	0.20	4	4.77
23	10. 4.81	17 56 59.03	0.27	21.775	9.34	138.969	10.61	323.49	27	4.83	0.18	5	4.77

• Epicentre Restrained

TABLE 1 (Continued)

	Date	Origin Time	± secs	Latitude ^{o}S	± km	Longitude ^{o}W	± km	Area of Confidence Region sq km	n	$m_b^{(1)}$	±95% CL	n	$m_b^{(2)}$
24	8. 7.81	22 22 58.81	0.16	21.781	4.66	139.049	4.98	95.53	70	5.14	0.16	7	5.10
25	3. 8.81	18 32 58.58	0.14	21.833	3.97	138.900	4.64	79.42	88	5.15	0.13	12	5.06
26	11.11.81	17 06 58.65	0.19	21.833	6.30	138.991	6.10	158.48	25	4.69	0.20	4	4.66
27	5.12.81	16 57 59.00	0.35	21.848	11.69	138.774	11.68	387.61	17	4.73	0.23	3	4.71
28	8.12.81	16 46 58.70	0.17	21.808	4.94	138.896	4.94	92.08	73	5.04	0.15	8	5.09

$m_b^{(1)}$ Iteration 0

$m_b^{(2)}$ Iteration 3. errors reduced using Jeffreys (1961) method of uniform reduction.

TABLE 2(a)

Station Terms for Explosions at Mururoa

ITERATION 0

STATION	COMPUTED* VALUE	95 PERCENT CONFIDENCE LIMITS	NUMBER
ALQ	-0.234	+/- 0.112	16
ARE	-0.217	+/- 0.280	2
ASP	-0.323	+/- 0.229	3
BCT	0.098	+/- 0.288	2
BDW	-0.342	+/- 0.158	7
BFD	-0.032	+/- 0.200	4
BKS	0.214	+/- 0.129	10
BLA	-0.407	+/- 0.229	3
BMN	-0.140	+/- 0.107	18
BNH	-0.097	+/- 0.280	2
COL	0.040	+/- 0.121	12
CTA	0.197	+/- 0.206	4
DUG	-0.166	+/- 0.234	3
EDM	0.644	+/- 0.144	8
EMM	0.352	+/- 0.181	5
EUR	-0.483	+/- 0.127	11
FBA	0.021	+/- 0.157	7
FFC	-0.500	+/- 0.229	3
FVM	0.630	+/- 0.233	3
GIL	0.091	+/- 0.215	4
GLS	-0.073	+/- 0.285	2
GCL	-0.451	+/- 0.176	9
HDM	0.326	+/- 0.233	3
HNH	0.079	+/- 0.282	2
JCT	-0.094	+/- 0.190	5
LD3	-0.094	+/- 0.183	5
LON	-0.086	+/- 0.200	4
LPB	-0.208	+/- 0.163	6
LPS	0.063	+/- 0.207	4
MAW	0.252	+/- 0.199	4
MSO	0.169	+/- 0.105	16
NEW	0.034	+/- 0.201	4
NNA	-0.447	+/- 0.280	2
PMG	-0.024	+/- 0.178	5
PMR	0.230	+/- 0.097	19
PNT	0.028	+/- 0.180	5
SDV	0.348	+/- 0.200	4
SES	0.392	+/- 0.199	4
SPA	-0.581	+/- 0.200	4
STK	0.048	+/- 0.231	3
TOO	0.457	+/- 0.229	3
TCV	-0.025	+/- 0.230	3
TUC	-0.030	+/- 0.237	3
TUL	0.126	+/- 0.119	12
UAV	0.245	+/- 0.230	3
UCT	0.270	+/- 0.281	2
WRA	-0.487	+/- 0.104	19
YKC	0.296	+/- 0.116	14

* To use as station corrections the sign of the station term must be reversed (see equation (2)).

TABLE 2(b)

Station Corrections

ITERATION 3

STATION	COMPUTED VALUE	95 PERCENT CONFIDENCE LIMITS	NUMBER
ALQ	-0.155	+/- 0.061	16
ARE	-0.212	+/- 0.146	2
ASP	-0.343	+/- 0.127	3
BCI	0.022	+/- 0.150	2
BDW	-0.296	+/- 0.085	7
BFD	-0.084	+/- 0.104	4
BKS	0.195	+/- 0.068	10
BLA	0.191	+/- 0.146	3
BMN	-0.113	+/- 0.056	18
BNH	-0.119	+/- 0.146	2
COL	0.043	+/- 0.063	12
CTA	0.149	+/- 0.108	4
DUG	-0.177	+/- 0.122	3
EDM	0.[illegible]	+/- 0.075	8
EMM	0.350	+/- 0.094	5
EUR	-0.522	+/- 0.080	11
FBA	0.045	+/- 0.082	7
FFC	-0.[illegible]42	+/- 0.119	3
FVM	0.[illegible]55	+/- 0.121	3
GIL	0.055	+/- 0.112	4
GLS	-0.154	+/- 0.148	2
GOL	-0.230	+/- 0.081	9
HDM	0.2[illegible]9	+/- 0.121	3
HNH	0.102	+/- 0.147	2
JCT	-0.043	+/- 0.112	5
LDS	-0.071	+/- 0.095	5
LON	-0.088	+/- 0.104	4
LPB	-0.234	+/- 0.086	6
LPS	0.0[illegible]4	+/- 0.108	4
MAW	0.214	+/- 0.104	4
MSO	0.169	+/- 0.05[illegible]	1[illegible]
NEW	0.009	+/- 0.106	4
NNA	-0.469	+/- 0.14[illegible]	2
PMG	-0.055	+/- 0.093	5
PMR	0.231	+/- 0.051	19
PNT	0.040	+/- 0.094	5
SDV	0.3[illegible]4	+/- 0.10[illegible]	4
SES	0.39[illegible]	+/- 0.104	4
SPA	-0.[illegible]02	+/- 0.104	4
STN	-0.012	+/- 0.121	3
TOC	0.115	+/- 0.14[illegible]	3
TOV	-0.019	+/- 0.120	3
TUC	-0.073	+/- 0.124	3
TUL	0.121	+/- 0.062	12
UAV	0.251	+/- 0.120	3
UCT	0.159	+/- 0.147	2
WRA	-0.4[illegible]4	+/- 0.055	19
YKC	0.314	+/- 0.0[illegible]1	14

TABLE 3

Statistical and Other Variables Used - French Test Site

Iteration 0

Number of Readings = 296
Number of Unknowns = 76

Sum of Squares of Residuals = 8.923898
Mean Square of Residuals = 0.040563
Number of Degrees of Freedom = 220
Students T = 1.97
Sum of Residuals = 0.36E-12

Sum of Squares Due to Stations = 23.121092
Mean Square Due to Stations = 0.491938
Number of Effective Stations = 47

Sum of Squares Due to Events = 33.634553
Mean Square Due to Events = 1.201234
Number of Effective Events = 28

Mean Station-Event Effect = 5.112 ± 0.04483
Sum of Dummy Variables = 0.32E-14
Squares Due to Dummy Variables = 0.84E-45

TABLE 3 (continued)

Iteration 3

Number of Readings = 296
Number of Unknowns = 76

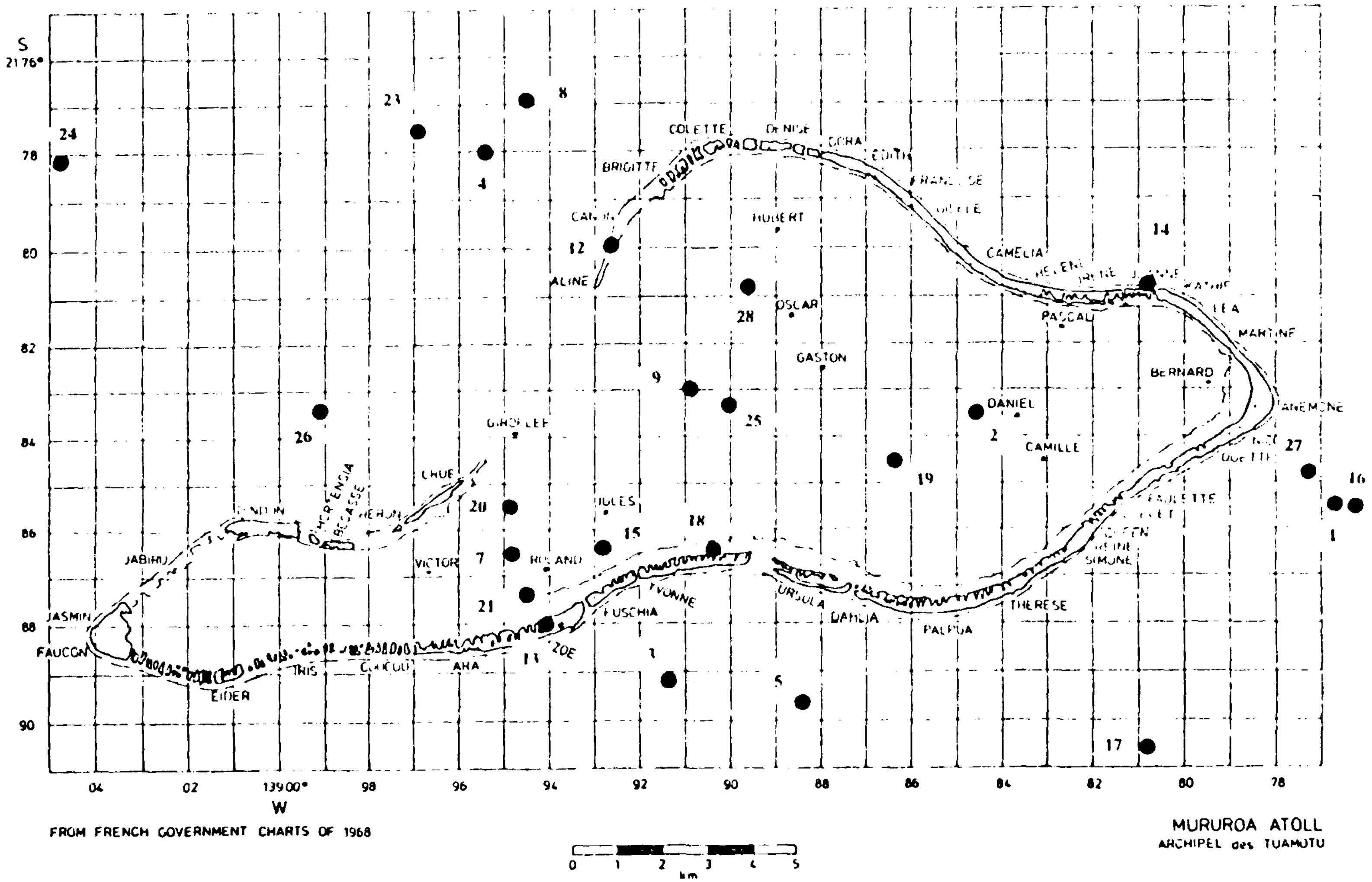
Sum of Squares of Residuals = 2.392113
Mean Square of Residuals = 0.010873
Number of Degrees of Freedom = 220
Students T = 1.97
Sum of Residuals = -0.80E-03

Sum of Squares due to Stations = 19.978145
Mean Square due to Stations = 0.425067
Number of Effective Stations = 47

Sum of Squares due to Events = 33.954501
Mean Square due to Events = 1.212661
Number of Effective Events = 28

Mean Station-Event Effect = 5.100 ± 0.02369
Sum of Dummy Variables = -0.32E-04
Squares due to Dummy Variables = 0.22E-15

FIGURE 1. PLOT OF COMPUTED EPICENTRES ON A MAP OF THE MURUROA ATOLL. (NOTE THAT EVENTS NUMBERED 6, 10, 11 AND 22 IN TABLE 1 ARE LOCATED OUTSIDE AREA OF MAP).



FROM FRENCH GOVERNMENT CHARTS OF 1968

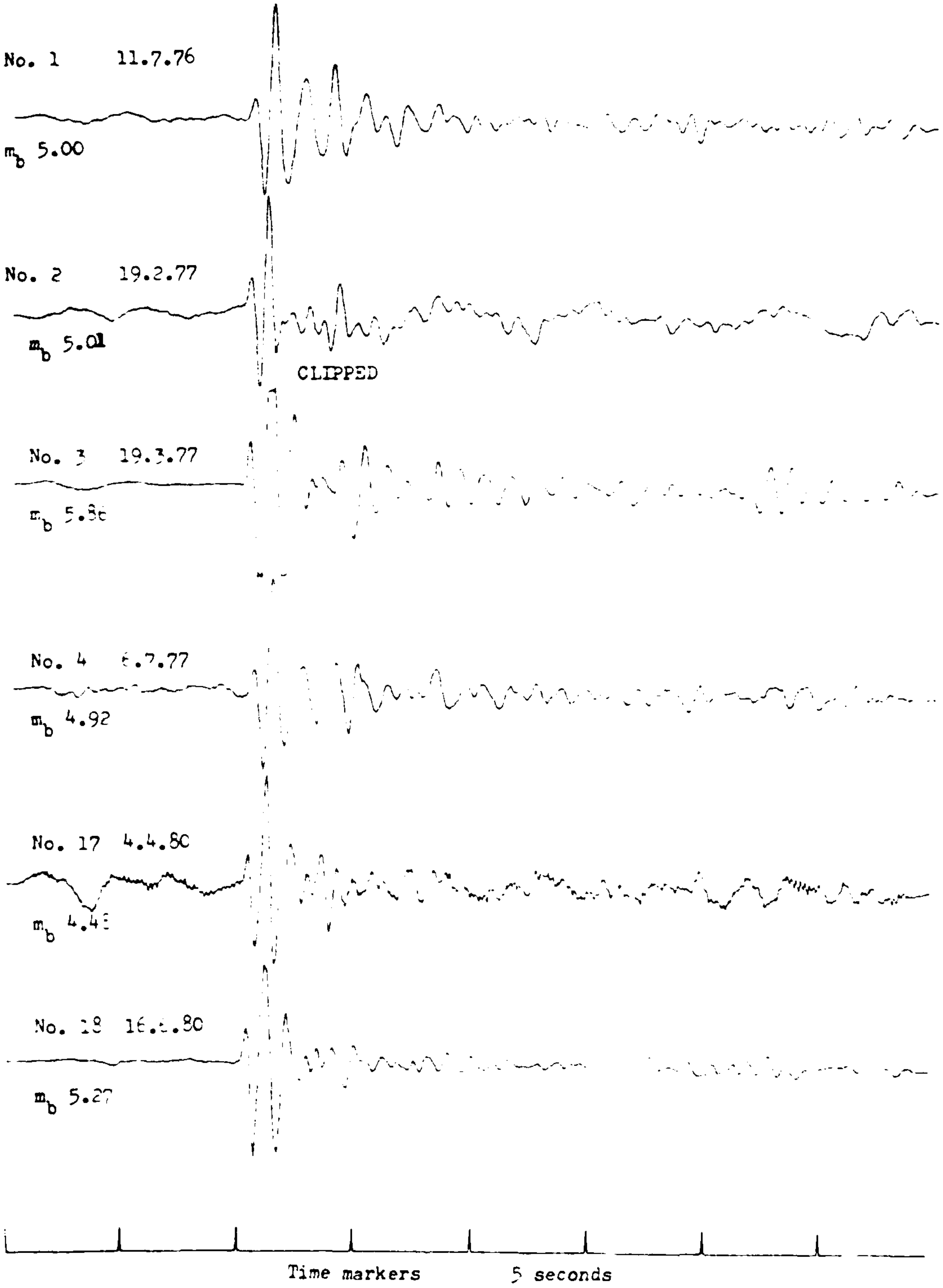
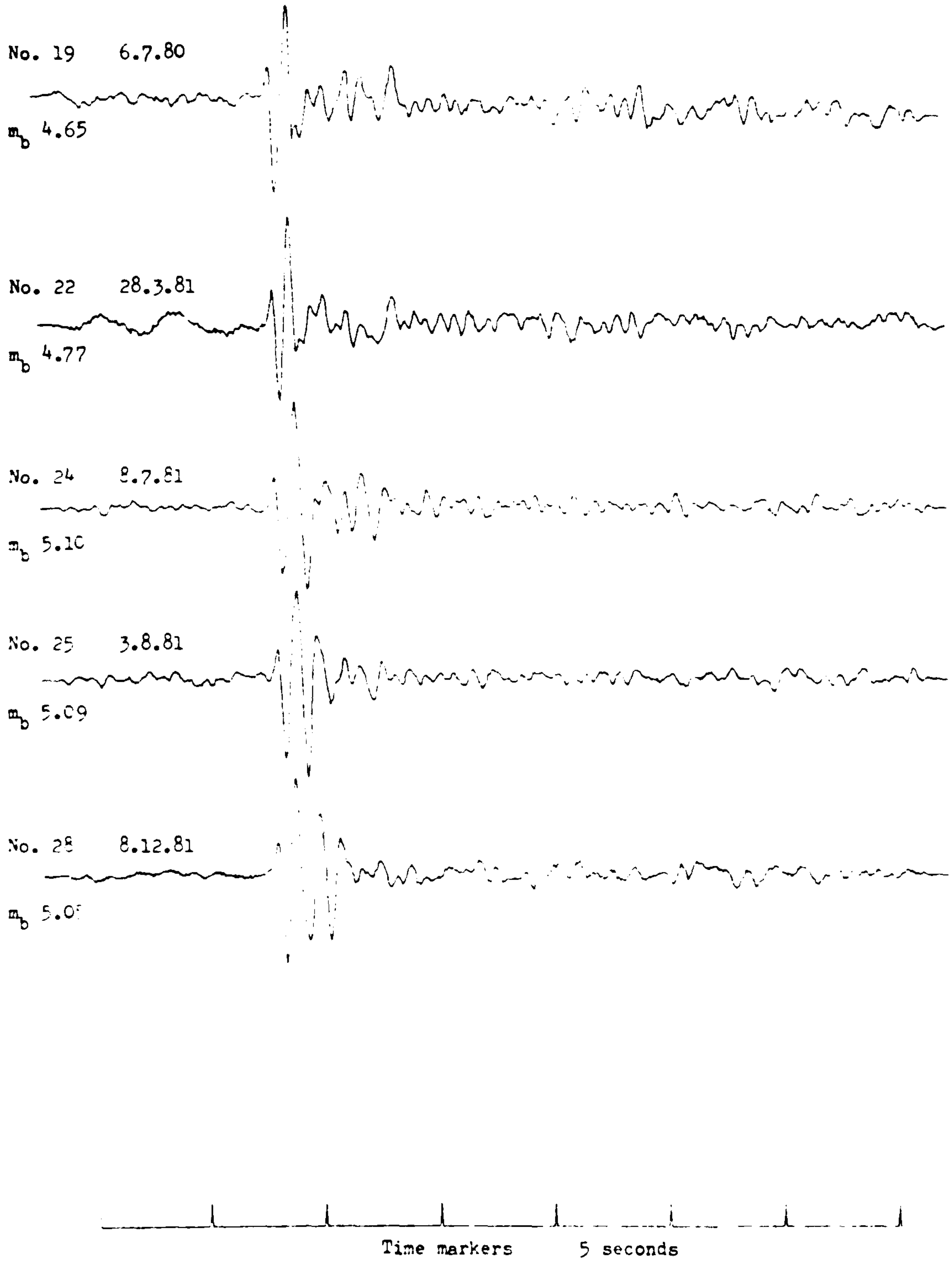


FIGURE 2. EXAMPLES OF THE P-WAVEFORMS RECORDED AT YELLOWKNIFE, CANADA FROM UNDERGROUND EXPLOSIONS AT MURUROA.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m_b 4.65
No. 22 28.3.81
m_b 4.77
No. 24 8.7.81
m_b 5.10
No. 25 3.8.81
m_b 5.09
No. 28 8.12.81
m_b 5.05
Time markers 5 seconds

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Abstract Since 1975 the French have conducted underground nuclear weapon tests beneath the Mururoa atoll in the Tuamotu Archipelago in the Southern Pacific. A least Squares joint estimate of origin time and epicentre together with a least squares joint estimate of magnitude is presented for presumed explosions in this area. These are based on data taken from bulletins of the International Seismological Centre. Some seismograms, recorded in Canada, are included to illustrate the nature of the P waves from these presumed explosions.

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