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Body-Wave Magnitudes and Locations of Explosions at the Chinese Test Site, 1967-1989

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SUMMARY

Estimates are given of the magnitudes, epicentres and origin times of 17 explosions fired by China at the test site in Xinjiang Province between 1967 and 1989, for which time and amplitude data are published in the bulletins of the International Seismological Centre (ISC). The epicentres and origin times are estimated using the joint epicentre method. The epicentres are estimated relative to those of the explosions of the 6 October 1983 and 3 October 1984 for which some information on the true epicentres is available.

The magnitudes are determined using a joint maximum-likelihood method. With this method allowance is made for the detection threshold of the stations reporting P amplitudes. If such allowance is not made the estimates will usually be biased high with the bias increasing as magnitude decreases. Thus at a body-wave magnitude (m_b) of around 4.5 the systematic differences between the maximum-likelihood estimates of magnitude and the ISC estimates, is found to be about 0.25 magnitude units whereas above m_b 5.5 the difference is negligible.

The joint methods of epicentre and magnitude estimation also produce estimates of station time and magnitude effects. These effects are listed for up to 319 stations.

1. INTRODUCTION

Since 1964 China has carried out nuclear tests in Xinjiang Province. In this report we give estimates of body-wave magnitudes (m_b), epicentres and origin times of 17 presumed explosions carried out by China in the period 1967-1989 for which P onset times and amplitudes are published in the bulletin of the International Seismological Centre (ISC). Between 1967 and 1980 there were 11 tests, 7 of them in the atmosphere; the other four tests being underground. Since 1981 all tests have been underground. The site for the atmospheric tests is near Lop Nor lake and that for the underground explosions near the village of Singer; Singer being about 100 km from Lop Nor.

In computing the epicentres and origin times we use the method of Joint Epicentre Determination (JED) of Douglas [1]. To estimate the magnitude, the joint maximum-likelihood method of Lilwall [2] and Lilwall & Neary [3] is used. The method has an advantage over the least squares method usually used, in that allowance is made for the detection (or reporting) thresholds of the stations. If such allowance is not made the estimates are biased high with the bias increasing as magnitude decreases.

2. EPICENTRE RELOCATIONS

The JED method was used to relocate the explosions using P & PKP arrival times taken from ISC bulletins. Arrival time readings were weighted to allow for gross errors and for variation between stations in the quality of the arrival time measurements. The effect of gross errors is reduced using the method of uniform reduction (Jeffreys [4]). The method assumes that the errors in the observations are essentially normally distributed but that this is modified by the addition of a small uniform distribution due to gross errors. This modification to the distribution results in weights that progressively reduce the contribution of residuals as their deviation from the mode increases.

For stations that report sufficient explosions (here set at 10) the standard deviation of the residuals is calculated and used to weight the arrival times for the station. This technique permits the incorporation of a large body of PKP data which would normally be given zero weight because its variance is significantly greater than that of most P observations.

The overall location of groups of epicentres is best determined by restraining one or more epicentres to the true values if these are available. For the Singer site "two Chinese-supplied test locations" are shown on a map published by Matzko [5]. The dates of the two tests were not given by the Chinese but Matzko [5] argues that they are the explosions of the 6 October 1983 and 3 October 1984. Here these two tests have been restrained to the epicentres read from the published map (Matzko [5]). The origin time of the 6 October 1983 explosion is restrained to the nearest exact minute. All depths are restrained to zero. The number of stations used is 265.

Figure 1(a) shows the ISC epicentres for the 17 explosions and figure 1(b) the JED results. Both sets of epicentres clearly separate into two groups corresponding to the Singer and Lop Nor sites. However, the JED results show that the Singer epicentres are concentrated into three groups, which is not clear from the ISC results. Within each of the three groups the spread of epicentres is only a few kilometres.

Figure 2 shows the JED epicentres for the Singer explosions on a topographic map of the area. The three groups are marked A, B & C. Group A which contains the two explosions with the restrained epicentres lies in an area of low relief. The explosions in this group appear to have been fired at the bottom of vertical shafts (Matzko [5]). Groups B & C lie in or close to steep-sided hills so the explosions may have been fired in tunnels driven into the hillsides.

At the Lop Nor site the JED results (figure 1b) suggest that 6 of the 7 explosions have true epicentres that are spread over an area of less than 10 km radius: 5 of the 6 explosions are spread in an E-W direction over about 15 km at a latitude of around 40.7°N. The uncertainties on the sixth epicentre which lies about 20 km to the north of the group of 5 is so large that the true epicentre could be close to the other 5. The uncertainties on the JED estimate of the remaining epicentre which is the most northerly of the Lop Nor estimates are less than 10 km and so on the evidence of this analysis it is unlikely that this explosion has an epicentre close to the others at Lop Nor.

Table 1 gives the relocated epicentres, origin times and 95% confidence limits. In addition to the epicentres, the JED method gives estimates of the station time-terms. These are listed in table 2. Positive values, show that the signal was late relative to the time predicted from travel-time tables (here Jeffreys-Bullen) and conversely a negative value shows that the onset is early relative to the predicted time. If the time terms are to be used as corrections which when added to the observed time corrects for deviations from predicted times, then all the time terms should have their sign reversed.

3. <u>MAGNITUDES</u>

Given n explosions recorded at some or all of q stations, then it is usually assumed that m_{ij}, the magnitude at the ith explosion recorded at the jth station can be written:

$$m_{ij} = b_i + s_j + \varepsilon_{ij}$$

where b_i is the magnitude of explosion i, s_j is a station term and ε_{ij} is an error term. Following Gutenberg and Richter [6] the body-wave magnitude at station j for explosion i is:

$$m_{ij} = \log A_{ij}/T_{ij} + B\,(\Delta_{ij})$$

where A_{ij} is the amplitude of the P wave, T_{ij} its predominant period, and $B(\Delta_{ij})$ the correction factor for the distance Δ_{ij} between explosion i and station j. Usually b_i and s_j are estimated by least squares (see for example Douglas [7]) with the assumption that:

$$\sum_{j=1}^{j=q} s_j = 0. \tag{1}$$

Such estimates are unbiased if the observed m_{ij} are sampled randomly from a normal distribution. In practice however, the distribution of m_{ij} will not be normal. Below average amplitudes will tend to be under-reported because at some stations the amplitude will be so small it will not be detected or if detected will not be measured and reported to data centres. Magnitudes estimated by least squares will thus tend to be biased high.

Lilwall [2] and Lilwall and Neary [3] following Christoffersson [8] shows that unbiased estimates of magnitude (and station effects) can be obtained (given estimates of station threshold and the variance of the threshold) by using maximum-likelihood methods, again with the assumption given in (1). Using Lilwall's method, maximum-likelihood estimates of body wave magnitude $\left(m_b^{ML}\right)$ have been determined for all the 17 explosions considered here.

From Christoffersson et al [8] the distribution of <u>observed</u> station magnitudes m_{ij} can be written as:

$$P\left(\begin{matrix} m_{ij} \\ \text{obs} \end{matrix} \middle| b_i,\ s_j,\ \sigma\ ..\right) = \frac{\phi\left(\dfrac{m_{ij}-G_j}{\gamma_j}\right)\theta\left(\dfrac{m_{ij}-s_j-b_i}{\sigma}\right)}{\phi\left(\dfrac{s_j+b_i-G_j}{\sqrt{(\sigma^2+\gamma_j^2)}}\right)} \tag{2}$$

$$\text{where } G_j = g_j + B(\Delta_{ij}). \tag{3}$$

θ is the normal density function of variance σ^2 representing the distribution of "uncensored" values of m_{ij}; ϕ the cumulative normal distribution; g_j the mean (50%) amplitude measurement threshold in terms of logA/T for station j; γ_j^2 the variance of the threshold assumed normally distributed about g_j. If the sources are close together equation 3 enables the main logA/T thresholds g_j to be expressed in terms of magnitude thresholds G_j.

Estimates of b_i,s_j and σ can be determined by maximising the likelihood function resulting from the product over the observed values of m_{ij} of terms given by equation 2.

$$L(b_i,s_j,\sigma) = \prod_{\substack{\text{observed} \\ m_{ij}}} P(m_{ij}\,|\,b_i,s_j\ ...) \tag{4}$$

Maximisation being subject to the constraint equation 1.

Ideally station thresholds and the variance of the thresholds would be determined once for each station and then used for all time. However, station thresholds do change with time. Possible reasons for this might be increased noise levels due to the growth of industry in the vicinity of the station and changes in reporting procedures with some stations deciding to measure amplitudes on smaller signals than they had in the past. Estimates of station thresholds and variance covering the period 1982-1989 have been combined with those of Lilwall and Neary [3] to cover the whole period 1964-1989. The threshold and variances are estimated from the overall distribution of log A/T submitted to the ISC for each station, using the method of Kelly and Lacoss [9]. As with the travel times the effects of gross errors in the amplitudes are reduced using weighting based on the method of uniform reduction (Jeffreys [4]). Examination of the distributions of observed amplitudes away from the mode suggests that the frequency of gross errors is 0.01 times the peak frequency.

The amplitude data for the two test sites, Lop Nor and Singer, have been analysed separately. This is done to allow for possible differences in the near source effects. Now, the station network for each of the analyses is not constant and it is possible that this will result in systematic biases in the magnitudes estimated. There is no sure way of correcting for these possible biases. Here, we have simply assumed that the average station effect for the analysis that uses the largest number of stations (that for the 10 underground explosions with 185 stations) sets the baseline. Then for the atmospheric explosions the average s_j^A - s_j^U is computed; where s_j^A is the magnitude term for station j obtained from the analysis of the observations from the atmospheric explosions and s_j^U the equivalent terms obtained from the analysis of the observations from the underground explosions; the average being formed from only those stations common to both the atmospheric and underground analyses. The average (-0.13 magnitude units) is then subtracted from s_j^A and added to the magnitudes of the atmospheric explosions.

The data used for each analysis are: (i) Singer (underground) explosions - 397 readings from 10 explosions and 185 stations; and (ii) Lop Nor (atmospheric) explosions - 32 readings from 7 explosions at 23 stations. The estimated magnitudes and station magnitude terms, corrected to a common baseline as described above, are given in tables 1 and 2 respectively. For the station magnitude terms positive values indicate above average amplitudes and negative values below average amplitudes.

Comparisons of station terms from the two analyses are displayed in figure 3. Figure 3(a) shows a comparison of the station magnitude terms with the time terms. Assuming that P wave speeds in the earth are negatively correlated with attenuation - the lower the wave speed the greater the attenuation - then this would be expected to show up as a negative correlation between the station magnitude and time terms. As figure 3(a) shows, if there is such a correlation it is very weak. Figures 3(b) shows the station magnitude term for the atmospheric explosions against the terms for the underground explosions. It is clear that there is little correlation between the station magnitude terms which justifies the decision to analyse the two data sets separately.

The magnitude analyses described above were made using the distance-correction curve ($B(\Delta)$) of Lilwall [10] which covers the range 20-180°. The advantage of using this curve, is that observations from many more stations can be included than with the standard Gutenberg curve which ends at 100°. However, comparison of magnitudes (m_b^{ML}) estimated using the data from 20-180° range with those estimated using data in the 20-100° range (and the Lilwall curve) shows that with the larger range the magnitudes are 0.04 magnitude units smaller than those obtained with stations only out to 100° (figure 4(a)). (Similar results are obtained using the Gutenberg curve to estimate the magnitudes for data in the 20-100° range.) Conversely the station magnitude terms obtained using data at distances of 20-180° are 0.04 magnitude units larger than those obtained using data only out to 100° (figure 3(c)). This result may indicate that the $B(\Delta)$ curve of Lilwall is systematically too low at distances beyond 100°. However, a similar analysis of French explosions in the South Pacific suggests that if anything the $B(\Delta)$ curve of Lilwall [10] is biased high. These differences between magnitudes estimated using different distance ranges are perhaps to be expected because for analyses of the explosions at one test site (and other closely-spaced groups of sources) the distance from each explosion to a given station is almost constant. The station effect will thus include any systematic effect that is peculiar to the particular station-test site paths. Presumably for widely distributed sources the results using $B(\Delta)$ curves with different distance ranges would on average be equal. The disadvantage of carrying out joint analyses of widely spaced data is that station effects are averages of a wide range of paths and thus will not correct as well for individual paths as is possible with closely- spaced sources. The absolute estimates of magnitude for analyses of data from closely-spaced sources then becomes a matter of definition. Here we assume that the best estimates of m_b^{ML} are obtained using data from as many stations as possible, that is data that covers the whole range 20-180°.

Figure 4(b) shows a comparison of the m_b^{ML} obtained here and those published by the ISC (which uses the Gutenberg curve). The figure shows that there are systematic differences between the two sets of magnitudes. As expected the difference is greatest ($\approx$0.25 magnitude units) at the lowest magnitudes and decreases as magnitude increases. Above about m_b5.5 the differences are negligible.

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TABLES

Table 1: Epicentres, origin times and magnitudes for the Chinese explosions.

Table 2: Station time and amplitude terms with 95% confidence limits.

FIGURE CAPTIONS

Figure 1: Estimated Epicentres for the Chinese Explosions.

(a) ISC epicentres.
(b) JED epicentres.

Figure 2: Topographic map of the Singer test site showing the JED epicentres.

Figure 3: Comparisons of Station Terms

(a) Station magnitude terms against station time-terms for the Singer (underground) explosions.

(b) Station magnitude terms for the Lop Nor (atmospheric) explosions against the magnitude terms for the Singer explosions.

(c) Station magnitude terms for the Singer explosions derived using only data in the range 20-100° against those derived using data out to 180°.

Figure 4: (a) Maximum-likelihood magnitudes derived for the Singer underground explosions using only data in the range 20-100° against the magnitudes derived using data in the range 20-180°.

(b) ISC magnitudes against maximum-likelihood magnitudes. Also shown is the line m_b^{ISC} - m_b^{ML} and the least squares line through the data.

TABLE 1.

Epicentres, Origin Times and Magnitudes of the Chinese Explosions

Date	Origin time	Latitude*	Longitude*	Area(km^2)	m_b^{ML}	$N_A^†$
Epicentres estimated relative to those of the explosions of the 6 October 1983 and the 3 October 1984						
670617A	0:19:10.19±0.27	40.714N± 3.7	89.717E± 3.9	67.7	4.28±0.20	3
690922	16:15: 1.15±0.14	41.353N± 2.5	88.297E± 2.2	25.4	5.10±0.08	16
690929A	8:40:23.86±0.42	40.681N± 6.2	89.617E± 4.4	132.5	4.37±0.24	2
701014A	7:30: 1.62±0.39	41.012N± 5.3	89.535E± 5.8	143.9	4.49±0.23	2
730627A	3:59:48.23±0.37	40.699N± 6.4	89.715E± 5.0	152.7	4.52±0.28	13
740617A	5:59:56.65±1.25	40.827N±14.4	89.554E±11.0	557.4	4.31±0.17	4
751027	1: 0: 0.19±0.22	41.372N± 3.4	88.311E± 4.0	55.4	4.80±0.07	27
761017	5: 0: 0.83±0.15	41.712N± 2.5	88.360E± 2.4	28.9	4.72±0.11	17
761117A	6: 0:14.80±0.28	40.642N± 8.8	89.529E± 9.1	169.4	4.41±0.14	7
781014	0:59:59.89±0.19	41.511N± 2.8	88.734E± 2.8	36.8	4.53±0.06	40
801016A	4:30:31.85±0.37	40.660N± 8.5	89.558E± 9.5	208.9	4.44±0.32	1
830504	5: 0: 0.16±0.33	41.741N± 5.5	88.379E± 3.8	102.1	4.05±0.20	3
831006	10: 0: 0.00±0.00	41.540N± 0.0	88.720E± 0.0	0.0	5.47±0.04	70
841003	5:59:59.98±0.08	41.570N± 0.0	88.730E± 0.0	0.0	5.20±0.04	69
841219	6: 0: 0.34±0.13	41.724N± 2.2	88.396E± 1.6	17.6	4.32±0.11	11
870605	5: 0: 0.26±0.09	41.511N± 1.7	88.704E± 1.3	10.1	6.23±0.03	137
880929	6:59:59.91±0.18	41.759N± 3.3	88.400E± 1.9	31.4	4.26±0.13	7

* Confidence limits in kilometres

† Number of stations used in computing m_b^{ML}

A Atmospheric explosions (Lop Nor)

TABLE 2.

Station Times and Magnitude Efects with 95% Confidence Limits

Station	Time term(s)	N_T^*	Singer mag. term	N_1^*	Lop Nor mag. term	N_2^*	Δ°	φ°
ABU	0.00±0.00	0	-0.77±0.40	1	0.00±0.00	0	37	84
ADE	0.00±0.00	0	0.59±0.31	1	0.00±0.00	0	88	141
AKL	-6.49±0.48	2	0.00±0.00	0	0.00±0.00	0	23	208
AKU	0.00±0.00	0	-0.52±0.32	1	0.00±0.00	0	60	333
ALE	-3.23±0.35	4	-0.60±0.24	3	0.00±0.00	0	55	356
ALQ	-1.76±0.39	3	-0.11±0.27	2	0.00±0.00	0	103	13
ANP	5.54±2.16	2	0.00±0.00	0	0.00±0.00	0	32	111
AQU	-1.14±0.47	2	0.00±0.00	0	0.00±0.00	0	54	298
ARE	4.85±0.77	6	-0.65±0.34	1	0.00±0.00	0	150	320
ASPA	-1.55±0.39	3	0.02±0.31	1	0.00±0.00	0	77	138
ATH	-1.57±0.49	2	0.00±0.00	0	0.00±0.00	0	49	288
AVE	-1.37±0.50	2	0.00±0.00	0	0.00±0.00	0	73	299
AVF	-2.63±0.33	4	0.22±0.16	4	0.00±0.00	0	59	307
BAL	-2.07±0.47	2	-0.08±0.31	1	0.00±0.00	0	76	155
BAO	0.00±0.00	0	-1.66±0.33	1	0.00±0.00	0	135	292
BDT	-1.29±0.36	5	-0.25±0.23	2	0.00±0.00	0	26	157
BDW	-1.86±0.47	2	0.00±0.00	0	0.00±0.00	0	94	13
BFD	0.00±0.00	0	-0.15±0.34	1	0.00±0.00	0	92	140
BGF	0.00±0.00	0	0.11±0.31	1	0.00±0.00	0	59	307
BHA	-1.10±0.52	2	0.20±0.21	2	0.00±0.00	0	78	239
BHG	-1.11±0.47	2	0.03±0.34	1	0.00±0.00	0	52	304
BHJ	0.28±0.45	3	0.00±0.00	0	0.00±0.00	0	24	227
BJI	-1.88±0.31	6	-0.24±0.31	1	0.00±0.00	0	21	85
BKS	0.00±0.00	0	0.12±0.33	1	0.00±0.00	0	96	24
BLF	-1.12±0.47	2	0.00±0.00	0	0.00±0.00	0	91	231
BMA	0.12±1.14	2	0.00±0.00	0	0.00±0.00	0	136	281
BMO	-2.77±0.45	4	-0.39±0.30	1	-0.05±0.13	3	91	19
BNG	-3.05±0.25	9	0.49±0.17	4	0.00±0.00	0	72	260
BPI	-1.11±0.47	3	0.00±0.00	0	0.00±0.00	0	88	232
BRG	-1.90±0.31	5	-0.33±0.18	3	0.12±0.26	1	51	308
BRS	-1.49±0.41	3	-0.16±0.31	1	0.00±0.00	0	91	127
BRT	-1.59±0.47	2	0.00±0.00	0	0.00±0.00	0	52	295
BSF	-2.29±0.34	4	-0.06±0.17	4	0.00±0.00	0	56	306
BTO	-3.99±0.47	2	0.00±0.00	0	0.00±0.00	0	16	86
BUL	-1.58±0.28	7	0.15±0.12	7	0.00±0.00	0	83	235
CAF	-1.90±0.33	4	-0.08±0.18	3	0.00±0.00	0	60	305
CCH	1.63±1.61	2	0.00±0.00	0	0.00±0.00	0	148	311
CDF	-2.07±0.24	8	-0.09±0.16	4	0.00±0.00	0	55	307
CEP	-5.95±0.38	4	0.00±0.00	0	0.00±0.00	0	15	244
CEY	-2.17±0.47	2	0.00±0.00	0	0.00±0.00	0	52	301
CHCP	-4.89±0.45	3	0.00±0.00	0	0.00±0.00	0	14	241
CHG	-0.46±0.21	12	0.04±0.29	1	-0.27±0.31	1	24	156
CHTO	-0.16±0.41	3	0.01±0.30	1	0.00±0.00	0	25	155
CIN	-1.74±0.58	2	0.00±0.00	0	0.00±0.00	0	46	286
CIR	-1.75±0.48	2	-0.22±0.31	1	0.00±0.00	0	82	232
CLE	0.00±0.00	0	-0.68±0.52	1	0.00±0.00	0	97	353
CLK	0.00±0.00	0	-0.16±0.43	1	0.00±0.00	0	75	234
CLL	-2.16±0.23	9	0.08±0.17	4	0.23±0.27	2	51	308
CLO	-1.33±0.47	2	0.00±0.00	0	0.00±0.00	0	47	298
CNCB	1.06±1.24	2	0.00±0.00	0	0.00±0.00	0	148	314
COL	-2.61±0.28	7	0.28±0.19	3	0.00±0.00	0	65	23
COP	0.00±0.00	0	0.22±0.31	1	0.00±0.00	0	50	314
COZ	-1.06±0.47	2	0.00±0.00	0	0.00±0.00	0	46	297
CPA	-5.27±0.45	3	0.00±0.00	0	0.00±0.00	0	16	242
CTA	-1.48±0.29	7	-0.05±0.18	3	0.00±0.00	0	81	127
CTAO	-1.51±0.47	2	-0.07±0.33	1	0.00±0.00	0	81	127
CTI	-2.66±0.47	2	0.00±0.00	0	0.00±0.00	0	54	303
CVF	-2.02±0.38	3	0.26±0.18	3	0.00±0.00	0	57	300
CVP	0.00±0.00	0	-0.07±0.31	1	0.00±0.00	0	37	120
CYP	-1.88±0.49	2	0.30±0.31	1	0.00±0.00	0	45	306
DAG	-2.99±0.26	7	0.38±0.13	7	0.00±0.00	0	54	344
DCN	-2.45±0.38	3	0.28±0.24	2	0.00±0.00	0	61	317
DDI	-3.85±0.47	2	0.00±0.00	0	0.00±0.00	0	14	221
DDK	0.00±0.00	0	-0.16±0.37	1	0.00±0.00	0	61	17
DIM	-0.23±0.48	2	0.00±0.00	0	0.00±0.00	0	46	293
DIX	-1.90±0.34	4	0.36±0.28	2	0.00±0.00	0	56	304
DLE	-2.73±0.38	3	0.02±0.19	3	0.00±0.00	0	61	317
DMN	-3.31±0.39	3	0.00±0.00	0	0.00±0.00	0	14	193
DMU	-2.44±0.38	3	0.24±0.24	2	0.00±0.00	0	61	318
DOU	-2.39±0.34	4	0.15±0.31	1	0.00±0.00	0	56	310
DRP	-4.67±0.41	3	0.00±0.00	0	0.00±0.00	0	18	243
DUI	-1.64±0.47	2	0.00±0.00	0	0.00±0.00	0	54	297
EAB	0.00±0.00	0	-0.43±0.33	1	0.00±0.00	0	59	319
EAU	-2.92±0.47	2	0.10±0.23	2	0.00±0.00	0	58	318
EBL	-2.86±0.47	2	0.10±0.23	2	0.00±0.00	0	58	318
EBR	-2.09±2.09	2	0.00±0.00	0	0.00±0.00	0	63	302
ECP	0.00±0.00	0	0.27±0.31	1	0.00±0.00	0	62	316
EDC	-1.01±0.47	2	0.00±0.00	0	0.00±0.00	0	45	290

TABLE 2. cont.

Station	Time term(s)	N_T^*	Singer mag. term	N_1^*	Lop Nor mag. term	N_2^*	Δ°	φ°
EDM	-1.92±0.29	6	0.00±0.00	0	0.00±0.00	0	84	13
EDU	-2.80±0.47	2	0.34±0.23	2	0.00±0.00	0	58	319
EGL	0.00±0.00	0	0.05±0.34	1	0.00±0.00	0	58	318
EIL	-0.77±0.49	2	0.00±0.00	0	0.00±0.00	0	45	272
EKA	-2.59±0.26	7	-0.05±0.16	4	0.00±0.00	0	58	318
ELL	-1.55±0.40	3	0.00±0.00	0	0.00±0.00	0	45	284
ELO	-2.47±2.09	2	0.00±0.00	0	0.00±0.00	0	58	319
EMS	-2.16±0.47	2	0.58±0.31	1	0.00±0.00	0	57	304
ENN	-1.93±0.38	3	0.09±0.18	3	0.00±0.00	0	55	310
EPF	-2.78±0.34	4	0.38±0.18	3	0.00±0.00	0	62	304
ESK	-2.67±0.48	2	-0.07±0.32	1	0.00±0.00	0	58	318
EUR	-1.09±0.48	2	0.55±0.22	2	0.00±0.00	0	96	19
EVA	-0.51±0.43	3	0.00±0.00	0	0.00±0.00	0	87	231
EZN	-1.50±0.47	2	0.00±0.00	0	0.00±0.00	0	46	290
FBA	-2.65±0.47	2	0.33±0.31	1	0.00±0.00	0	65	23
FEN	-0.54±0.47	2	0.00±0.00	0	0.00±0.00	0	26	78
FFC	-2.23±0.29	6	0.53±0.14	5	0.00±0.00	0	83	6
FLN	-2.68±0.28	7	0.15±0.15	5	0.00±0.00	0	60	310
FRB	-3.53±0.47	2	-0.25±0.31	1	0.00±0.00	0	74	350
FRF	-2.43±0.38	3	0.08±0.18	3	0.00±0.00	0	58	302
FUR	-1.06±0.34	4	0.16±0.23	2	0.51±0.19	1	53	305
FVM	0.00±0.00	0	0.28±0.31	1	0.00±0.00	0	101	360
GBA	-3.09±0.36	6	-0.01±0.23	3	0.00±0.00	0	29	203
GOL	0.00±0.00	0	-0.15±0.31	1	0.00±0.00	0	98	11
GRC	-2.58±0.39	3	0.00±0.00	0	0.00±0.00	0	58	307
GRF	-1.11±0.26	7	0.34±0.23	2	0.32±0.26	1	53	307
GRR	-2.63±0.24	8	0.44±0.16	4	0.28±0.33	1	60	310
GTA	-2.81±0.41	3	0.00±0.00	0	0.00±0.00	0	9	101
GWF	-2.00±0.48	2	0.00±0.00	0	0.00±0.00	0	55	307
GYA	-2.01±0.40	3	0.00±0.00	0	0.00±0.00	0	21	130
HAU	-2.24±0.28	6	-0.25±0.15	5	-0.31±0.37	1	56	307
HFS	-2.47±0.14	14	0.34±0.12	7	0.09±0.17	2	48	319
HHC	-1.95±0.40	4	0.00±0.00	0	0.00±0.00	0	17	85
HOF	0.00±0.00	0	-0.26±0.31	1	0.00±0.00	0	52	308
HRI	0.37±0.47	2	0.00±0.00	0	0.00±0.00	0	42	277
HYB	-2.05±0.28	8	0.09±0.13	7	0.00±0.00	0	26	203
IMA	-2.60±0.47	2	0.00±0.00	0	0.00±0.00	0	63	24
INK	-2.86±0.27	7	0.09±0.20	3	0.00±0.00	0	66	16
IPM	-1.36±0.39	3	-0.15±0.21	3	0.00±0.00	0	38	160
IR5	0.29±0.47	2	0.00±0.00	0	0.00±0.00	0	30	271
ISK	-1.11±0.48	2	0.00±0.00	0	0.00±0.00	0	44	290
ISO	-2.85±0.49	2	0.00±0.00	0	0.00±0.00	0	59	303
ISQ	-1.67±0.39	3	0.42±0.31	1	0.00±0.00	0	78	132
IST	-1.10±0.48	3	0.00±0.00	0	0.00±0.00	0	44	290
ITB	-0.81±1.14	2	0.00±0.00	0	0.00±0.00	0	145	287
ITB7	-0.31±0.93	3	0.00±0.00	0	0.00±0.00	0	145	286
ITR	-0.15±1.14	3	0.00±0.00	0	0.00±0.00	0	123	290
JAY	-1.81±0.48	2	0.08±0.32	1	0.00±0.00	0	64	119
JMB	-0.80±0.47	2	0.00±0.00	0	0.00±0.00	0	45	293
JOS	0.00±0.00	0	-0.56±0.36	1	0.00±0.00	0	48	303
KAD	-8.35±0.47	3	0.00±0.00	0	0.00±0.00	0	27	212
KAS	-0.32±0.51	2	0.00±0.00	0	0.00±0.00	0	41	289
KBA	-2.04±0.47	2	-0.28±0.23	2	0.00±0.00	0	52	303
KBL	-4.22±0.46	7	0.00±0.00	0	0.00±0.00	0	17	252
KDC	-2.96±0.40	3	0.00±0.00	0	0.00±0.00	0	69	30
KDZ	-0.56±0.47	2	0.00±0.00	0	0.00±0.00	0	46	292
KEV	-1.65±0.28	6	0.05±0.16	4	0.00±0.00	0	42	333
KHC	-1.52±0.31	5	-0.41±0.31	1	0.00±0.00	0	51	306
KHI	0.45±0.50	2	0.00±0.00	0	0.00±0.00	0	25	263
KIC	-2.01±0.24	8	0.00±0.00	0	0.00±0.00	0	88	277
KIR	-2.16±0.27	8	0.41±0.19	3	0.00±0.00	0	44	330
KJF	-2.19±0.30	11	0.01±0.20	4	-0.74±4.23	1	41	324
KJN	-2.35±0.50	2	0.00±0.00	0	0.00±0.00	0	41	324
KKM	0.00±0.00	0	-0.10±0.31	1	0.00±0.00	0	43	38
KKN	-2.74±2.09	4	0.00±0.00	0	0.00±0.00	0	14	193
KLB	0.00±0.00	0	-0.10±0.31	1	0.00±0.00	0	77	155
KLG	0.00±0.00	0	0.31±0.31	1	0.00±0.00	0	78	152
KMI	-2.87±0.32	5	0.00±0.00	0	0.00±0.00	0	20	140
KNA	0.00±0.00	0	-0.01±0.32	1	0.00±0.00	0	68	138
KOD	-2.52±2.09	3	0.00±0.00	0	0.00±0.00	0	33	201
KRA	-1.43±0.45	3	-0.12±0.21	3	0.00±0.00	0	47	305
KRI	-2.26±0.47	3	0.23±0.22	2	0.00±0.00	0	80	237
KRR	-1.48±0.41	3	0.46±0.17	3	0.00±0.00	0	80	236
KSH	-2.08±2.09	2	0.00±0.00	0	0.00±0.00	0	10	262
KSP	0.00±0.00	0	-0.11±0.31	1	0.00±0.00	0	49	307
LAO	-2.92±0.59	4	0.00±0.00	0	0.29±0.14	3	92	11
LBF	-2.79±0.26	7	-0.20±0.15	5	0.00±0.00	0	58	307
LDF	-2.70±0.38	3	0.32±0.18	3	0.00±0.00	0	60	310

TABLE 2. cont.

Station	Time term(s)	N_T^*	Singer mag. term	N_1^*	Lop Nor mag. term	N_2^*	Δ°	φ°
LFF	-1.61±0.24	8	0.56±0.14	6	0.11±0.35	1	61	306
LF4	0.00±0.00	0	0.00±0.00	0	0.42±0.25	1	91	11
LJU	-1.72±0.48	2	0.00±0.00	0	0.29±0.24	1	52	302
LLS	-2.48±0.38	3	0.26±0.24	2	0.00±0.00	0	55	305
LMR	-2.28±0.28	6	0.04±0.14	5	0.00±0.00	0	58	302
LOR	-3.02±0.14	10	0.16±0.17	5	-0.04±0.17	1	58	307
LPB	1.31±0.82	5	-0.47±0.25	2	0.00±0.00	0	148	314
LPF	-2.70±0.30	5	0.01±0.15	5	0.00±0.00	0	61	310
LPO	-1.79±0.24	8	0.50±0.19	6	0.00±0.00	0	61	305
LRG	-2.30±0.28	6	0.04±0.15	5	0.00±0.00	0	58	302
LRM	-1.67±0.38	3	0.00±0.00	0	0.00±0.00	0	91	15
LRR	-0.90±0.47	2	0.00±0.00	0	0.00±0.00	0	45	297
LSF	-2.90±0.28	6	-0.11±0.15	5	0.00±0.00	0	60	307
LZH	-3.37±0.41	3	0.00±0.00	0	0.00±0.00	0	13	110
MAF	0.00±0.00	0	0.50±0.31	1	0.00±0.00	0	60	307
MAIO	0.21±0.61	4	0.00±0.00	0	0.00±0.00	0	23	266
MAL	-3.11±0.47	2	0.00±0.00	0	0.00±0.00	0	69	301
MAT	-3.42±0.48	2	-0.64±0.37	1	0.00±0.00	0	38	81
MBC	-2.50±0.26	8	0.45±0.13	7	0.00±0.00	0	61	7
MBL	0.00±0.00	0	-0.08±0.31	1	0.00±0.00	0	68	149
MEK	-2.45±0.48	2	-0.34±0.34	1	0.00±0.00	0	73	152
MEM	-1.96±0.47	2	0.00±0.00	0	0.00±0.00	0	55	310
MFF	-2.55±0.33	4	-0.01±0.16	4	0.00±0.00	0	61	308
MHI	-0.23±0.34	4	-0.32±0.39	2	0.00±0.00	0	23	267
MLR	-0.72±0.38	4	0.00±0.00	0	0.00±0.00	0	45	297
MLS	-2.52±0.47	3	0.00±0.00	0	0.00±0.00	0	62	304
MMB	-1.48±0.48	2	0.00±0.00	0	0.00±0.00	0	48	293
MMK	-2.32±0.38	3	0.49±0.22	2	0.00±0.00	0	56	304
MNL	-3.64±0.56	2	0.00±0.00	0	0.00±0.00	0	14	238
MNS	-2.22±0.38	3	0.00±0.00	0	0.00±0.00	0	55	298
MNT	0.00±0.00	0	-0.34±0.33	1	0.00±0.00	0	92	348
MOX	-1.79±0.18	11	-0.24±0.20	3	0.22±0.24	2	52	308
MRWA	0.00±0.00	0	-0.71±0.32	1	0.00±0.00	0	74	156
MSH	0.92±0.64	2	0.00±0.00	0	0.00±0.00	0	23	267
MSL	-1.10±0.47	2	0.00±0.00	0	0.00±0.00	0	35	277
MTD	-2.17±0.33	5	0.26±0.15	4	0.00±0.00	0	78	235
MUD	-1.61±0.47	2	0.00±0.00	0	0.00±0.00	0	51	316
MUN	-2.38±0.40	3	0.05±0.24	2	0.00±0.00	0	77	156
MZF	-2.12±0.38	3	0.59±0.32	1	0.00±0.00	0	59	306
NAI	0.44±2.09	2	-0.14±0.23	2	0.00±0.00	0	63	242
NAO	-3.45±0.36	4	-0.36±0.31	1	-0.04±0.14	2	49	321
NBO	0.00±0.00	0	0.00±0.00	0	0.08±0.14	1	50	321
NB2	-2.66±0.30	7	0.01±0.12	6	0.00±0.00	0	49	321
NDI	-3.67±0.38	12	0.00±0.00	0	0.00±0.00	0	16	218
NEW	-1.41±0.31	5	-0.06±0.34	2	0.00±0.00	0	88	17
NIE	-1.01±0.35	4	0.13±0.31	1	0.45±0.20	1	47	304
NIL	-4.39±0.56	2	0.00±0.00	0	0.00±0.00	0	15	242
NJ2	-1.05±0.47	2	0.00±0.00	0	0.00±0.00	0	26	102
NOR	0.00±0.00	0	0.00±0.00	0	0.47±0.29	1	52	350
NP-	0.00±0.00	0	0.42±0.30	1	0.00±0.00	0	61	7
NPA	0.00±0.00	0	-0.33±0.33	1	0.00±0.00	0	72	231
NUR	-1.84±0.17	11	0.02±0.19	3	0.37±0.21	2	43	319
NWAO	-2.14±0.47	2	-0.08±0.31	1	0.00±0.00	0	79	156
OGA	-2.24±0.47	2	0.02±0.33	1	0.00±0.00	0	54	304
OHR	-2.76±0.47	2	0.00±0.00	0	0.00±0.00	0	50	293
OIS	0.00±0.00	0	-0.58±0.32	1	0.00±0.00	0	37	86
ORI	-1.08±0.47	2	0.00±0.00	0	0.00±0.00	0	53	294
ORV	3.96±2.12	2	0.00±0.00	0	0.00±0.00	0	95	23
OSS	-1.97±0.38	3	0.00±0.00	0	0.00±0.00	0	54	304
OTT	-1.91±0.47	2	0.31±0.23	2	0.00±0.00	0	92	349
PAE	0.00±0.00	0	-0.39±0.35	1	0.00±0.00	0	125	83
PCT	-0.51±0.47	2	-0.56±0.33	1	0.00±0.00	0	29	154
PGC	-1.26±0.39	3	0.04±0.31	1	0.00±0.00	0	86	21
PHC	-1.82±0.47	2	-0.01±0.40	1	0.00±0.00	0	83	22
PKI	-2.90±0.41	4	0.00±0.00	0	0.00±0.00	0	14	192
PME	0.00±0.00	0	-0.65±0.33	1	0.00±0.00	0	67	26
PMG	-1.25±0.49	2	0.17±0.31	1	0.00±0.00	0	74	119
PMO	0.00±0.00	0	-0.48±0.34	1	0.00±0.00	0	125	79
PMR	-3.23±0.49	2	-0.10±0.23	2	0.00±0.00	0	67	26
PNT	-1.77±0.47	2	-0.22±0.24	2	0.00±0.00	0	86	18
POO	-1.98±0.40	5	0.14±0.36	1	0.00±0.00	0	26	213
PPN	0.00±0.00	0	-0.68±0.36	1	0.00±0.00	0	125	83
PPT	0.00±0.00	0	-0.04±0.35	1	0.00±0.00	0	125	83
PRA	-1.70±2.09	2	-0.32±0.31	1	0.00±0.00	0	50	307
PRK	-0.90±0.50	2	0.00±0.00	0	0.00±0.00	0	46	289
PRU	-1.66±0.34	4	-0.32±0.31	1	0.00±0.00	0	50	306
PSH	-4.83±0.56	2	0.00±0.00	0	0.00±0.00	0	16	247
PSI	-3.93±0.48	2	-0.70±0.25	2	0.00±0.00	0	40	164

TABLE 2. cont.

Station	Time term(s)	N_T^*	Singer mag. term	N_1^*	Lop Nor mag. term	N_2^*	Δ°	φ°
PVL	1.09±0.55	2	0.00±0.00	0	0.00±0.00	0	46	294
PYM	-2.38±0.39	3	0.00±0.00	0	0.00±0.00	0	59	306
QUE	-1.99±0.41	4	0.00±0.00	0	0.00±0.00	0	21	244
RJF	-1.86±0.28	6	0.29±0.14	5	0.00±0.00	0	60	306
RMP	-2.22±0.49	2	0.00±0.00	0	0.00±0.00	0	55	298
RSNT	-1.89±0.40	3	0.00±0.00	0	0.00±0.00	0	75	11
RSNY	-1.20±0.47	2	0.00±0.00	0	0.00±0.00	0	93	348
RSON	-2.65±0.39	3	0.10±0.22	2	0.00±0.00	0	88	2
RSSD	-1.08±0.47	2	0.24±0.35	1	0.00±0.00	0	94	9
RUV	0.00±0.00	0	-0.67±0.36	1	0.00±0.00	0	125	79
SAL	-2.15±0.47	2	0.00±0.00	0	0.00±0.00	0	55	303
SARP	-6.39±0.38	4	0.00±0.00	0	0.00±0.00	0	16	237
SAX	-2.19±0.47	2	-0.16±0.31	1	0.00±0.00	0	55	305
SCH	-2.64±0.39	3	-0.03±0.31	1	0.00±0.00	0	82	346
SCO	-1.44±0.47	2	0.32±0.31	2	0.00±0.00	0	58	338
SEK	-1.15±0.49	2	0.09±0.23	2	0.00±0.00	0	90	231
SES	-2.48±0.39	3	0.00±0.00	0	0.00±0.00	0	87	13
SGO	-1.68±0.47	2	0.00±0.00	0	0.00±0.00	0	54	295
SHK	-2.37±0.51	2	0.00±0.00	0	0.00±0.00	0	35	87
SHL	-2.86±0.38	7	0.00±0.00	0	0.00±0.00	0	16	169
SIT	-1.00±0.47	2	0.00±0.00	0	0.00±0.00	0	75	23
SKO	-1.37±0.39	3	0.07±0.24	2	0.00±0.00	0	49	294
SLE	-2.19±0.38	3	0.44±0.22	2	0.00±0.00	0	55	306
SLL	-2.38±0.35	4	0.00±0.00	0	0.00±0.00	0	48	320
SLR	-0.51±0.47	2	-0.03±0.31	1	0.00±0.00	0	87	232
SMF	-2.56±0.33	4	0.48±0.22	2	0.00±0.00	0	58	306
SMY	0.00±0.00	0	0.20±0.31	1	0.00±0.00	0	56	47
SNY	-1.69±0.47	2	0.00±0.00	0	0.00±0.00	0	26	78
SOB1	-0.72±1.14	2	0.00±0.00	0	0.00±0.00	0	125	291
SOD	-1.75±0.27	7	0.00±0.00	0	0.00±0.00	0	42	329
SPC	-1.10±0.47	2	0.00±0.00	0	0.00±0.00	0	47	304
SPF	-2.37±0.35	4	0.14±0.25	2	0.00±0.00	0	58	302
SSB	-2.32±0.52	2	0.00±0.00	0	0.00±0.00	0	59	305
SSC	-2.54±0.34	4	0.25±0.24	2	-0.02±0.33	1	60	310
SSE	-1.40±0.48	2	-0.09±0.23	2	0.00±0.00	0	28	101
SSF	-2.91±0.24	8	0.05±0.15	6	0.00±0.00	0	58	307
STJ	0.00±0.00	0	0.34±0.33	1	0.00±0.00	0	85	335
STK	-2.02±0.47	2	0.05±0.31	1	0.00±0.00	0	88	137
SUF	-1.77±0.34	4	0.02±0.18	3	0.00±0.00	0	42	322
SVW	-1.82±0.63	2	0.00±0.00	0	0.00±0.00	0	65	29
TCF	-2.18±0.24	8	0.51±0.20	4	0.20±0.33	1	59	307
TET	-1.99±0.47	2	0.00±0.00	0	0.00±0.00	0	77	234
THW	-5.20±0.50	2	0.00±0.00	0	0.00±0.00	0	16	241
TIA	-1.40±0.49	2	0.00±0.00	0	0.00±0.00	0	23	94
TIO	-1.31±0.47	2	0.00±0.00	0	0.00±0.00	0	74	297
TIR	-1.90±2.09	2	0.00±0.00	0	0.00±0.00	0	50	294
TIY	-1.61±0.50	3	0.00±0.00	0	0.00±0.00	0	19	94
TMA	-2.95±0.38	3	0.67±0.31	1	0.00±0.00	0	55	304
TOL	-1.34±0.48	2	0.73±0.22	2	0.00±0.00	0	67	303
TOO	0.00±0.00	0	0.03±0.33	1	0.00±0.00	0	94	138
TPT	0.00±0.00	0	-0.37±0.35	1	0.00±0.00	0	125	79
TRI	-2.70±0.47	2	0.00±0.00	0	0.00±0.00	0	53	302
TRO	-2.15±0.48	2	0.00±0.00	0	0.00±0.00	0	45	332
TRT	0.00±0.00	0	-0.05±0.31	1	0.00±0.00	0	53	150
TSK	0.00±0.00	0	-0.28±0.32	1	0.00±0.00	0	40	80
TUL	0.00±0.00	0	0.18±0.32	1	0.00±0.00	0	103	4
TVO	0.00±0.00	0	0.06±0.34	1	0.00±0.00	0	125	83
UBO	0.00±0.00	0	-0.23±0.33	1	0.00±0.00	0	97	14
UCC	-2.18±0.47	2	0.00±0.00	0	0.00±0.00	0	56	310
UME	-2.12±0.37	5	0.00±0.00	0	0.00±0.00	0	44	324
UPP	-2.26±0.17	12	0.46±0.19	3	0.00±0.00	0	46	319
VAH	0.00±0.00	0	-0.47±0.35	1	0.00±0.00	0	125	79
VAR	-0.72±0.47	3	0.00±0.00	0	0.00±0.00	0	17	198
VDL	-2.12±0.38	3	0.78±0.31	1	0.00±0.00	0	55	304
VKA	0.00±0.00	0	-0.06±0.31	1	0.00±0.00	0	50	304
VRI	-0.71±0.47	2	0.00±0.00	0	0.00±0.00	0	44	297
VTS	-0.77±0.47	2	0.00±0.00	0	0.00±0.00	0	48	294
WBN	-1.28±0.39	3	-0.50±0.32	1	0.00±0.00	0	76	145
WB2	-2.14±0.31	5	0.00±0.00	0	0.00±0.00	0	75	135
WCB	-2.29±0.40	4	0.00±0.00	0	0.00±0.00	0	74	136
WET	-1.60±0.40	3	-0.48±0.20	3	0.00±0.00	0	52	306
WHN	-0.48±0.35	4	0.00±0.00	0	0.00±0.00	0	24	110
WIT	-0.96±2.09	2	0.00±0.00	0	0.00±0.00	0	54	312
WLF	-2.62±0.54	2	0.00±0.00	0	0.00±0.00	0	56	309
WMQ	2.62±0.51	4	0.00±0.00	0	0.00±0.00	0	2	346
WOL	0.00±0.00	0	0.72±0.36	1	0.00±0.00	0	59	313
WRA	-2.11±0.29	7	0.23±0.14	5	0.00±0.00	0	75	135
WRS	-5.04±0.60	2	0.00±0.00	0	0.00±0.00	0	15	246

TABLE 2. cont.

Station	Time term(s)	N_T^*	Singer mag. term	N_1^*	Lop Nor mag. term	N_2^*	Δ°	φ°
WTS	-1.68±0.35	4	-0.11±0.19	3	0.00±0.00	0	54	311
XAN	-2.45±0.46	3	0.00±0.00	0	0.00±0.00	0	18	109
YKA	-1.83±0.31	7	0.00±0.00	0	0.00±0.00	0	75	11
YKC	-2.36±0.40	3	0.20±0.25	2	0.00±0.00	0	75	11
ZOBO	0.38±1.14	2	-0.98±0.34	1	0.00±0.00	0	148	315
ZST	0.00±0.00	0	-0.50±0.33	1	0.00±0.00	0	50	304
ZUL	0.00±0.00	0	0.40±0.32	1	0.00±0.00	0	56	306

* N_T is the number of arrival times used to estimate the time term.
N_1, N_2 and N_3 are the number of amplitude observations used to estimate the amplitude terms.

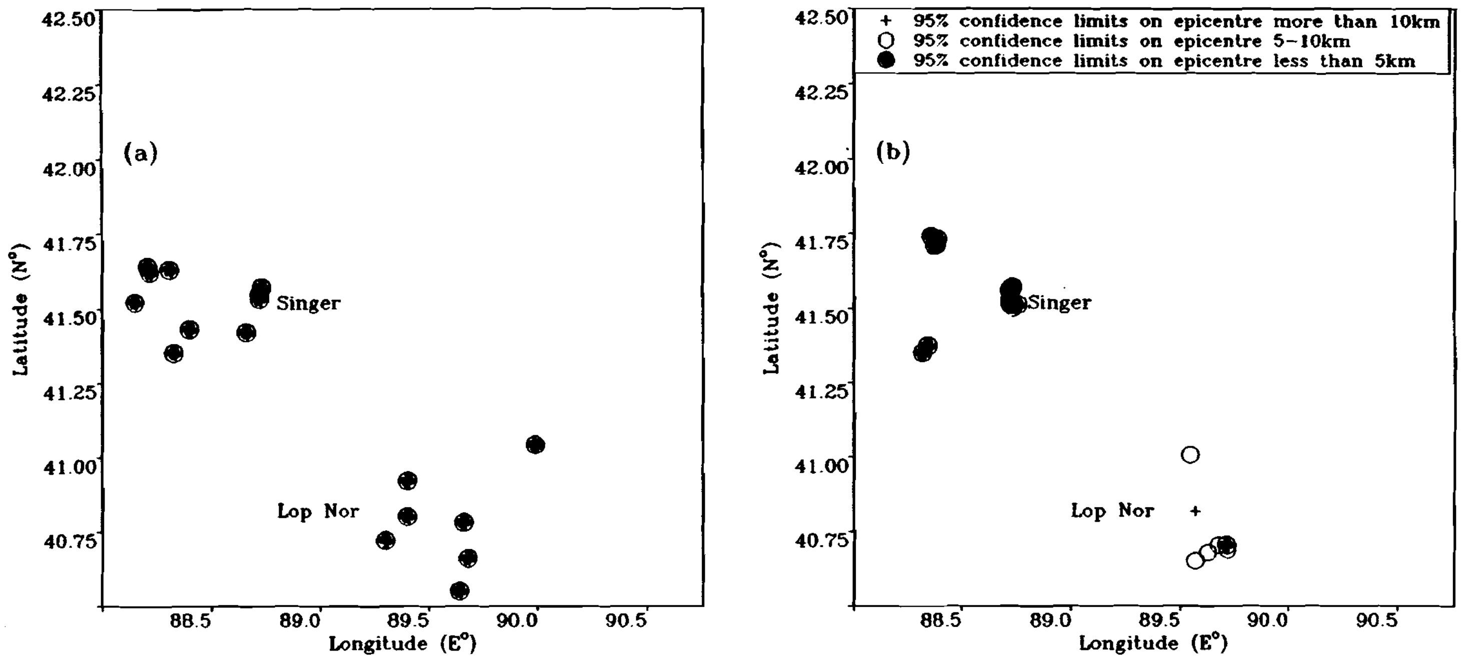
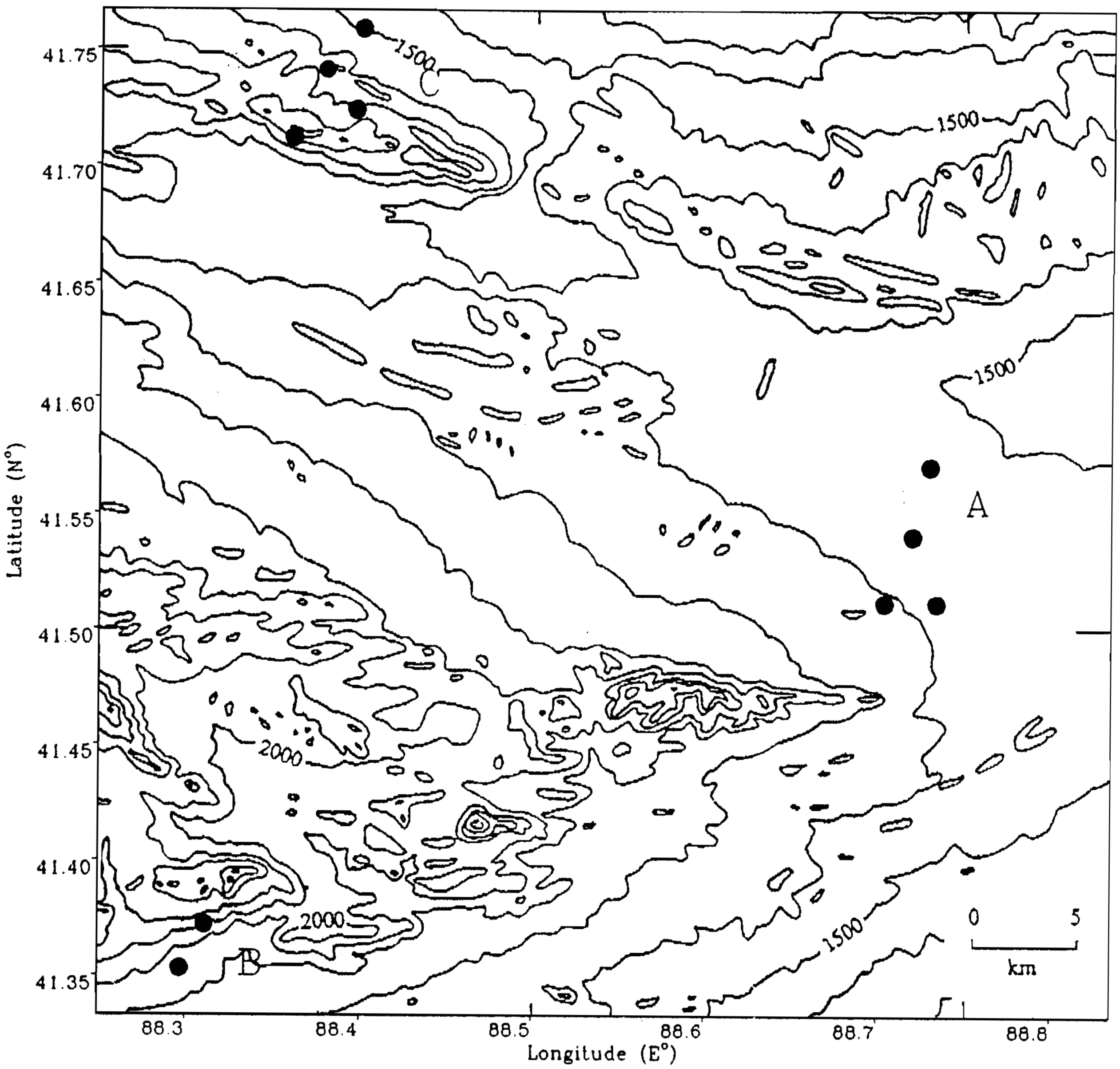


FIGURE 1. ESTIMATED EPICENTRES FOR THE CHINESE EXPLOSIONS.

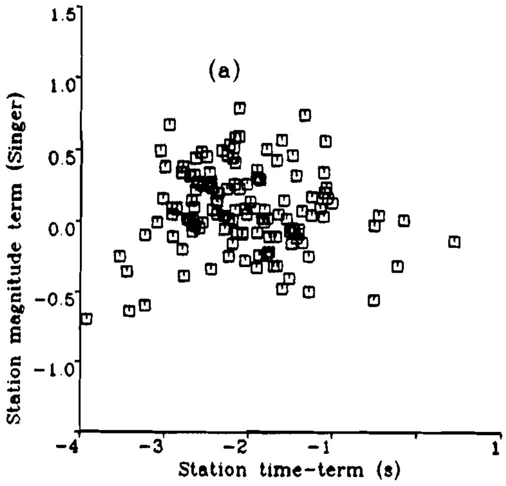
a) ISC epicentres

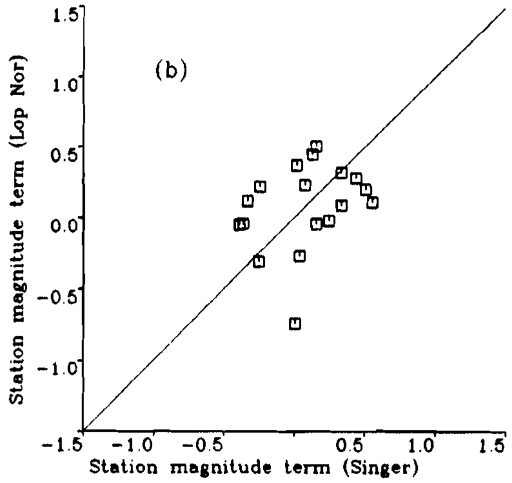
b) JED epicentres

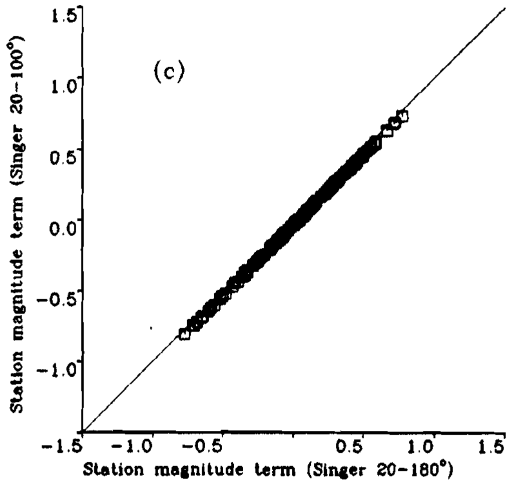


Contour interval 100 metres

<u>FIGURE 2. TOPOGRAPHIC MAP OF THE SINGER TEST SITE SHOWING THE JED EPICENTRES</u>





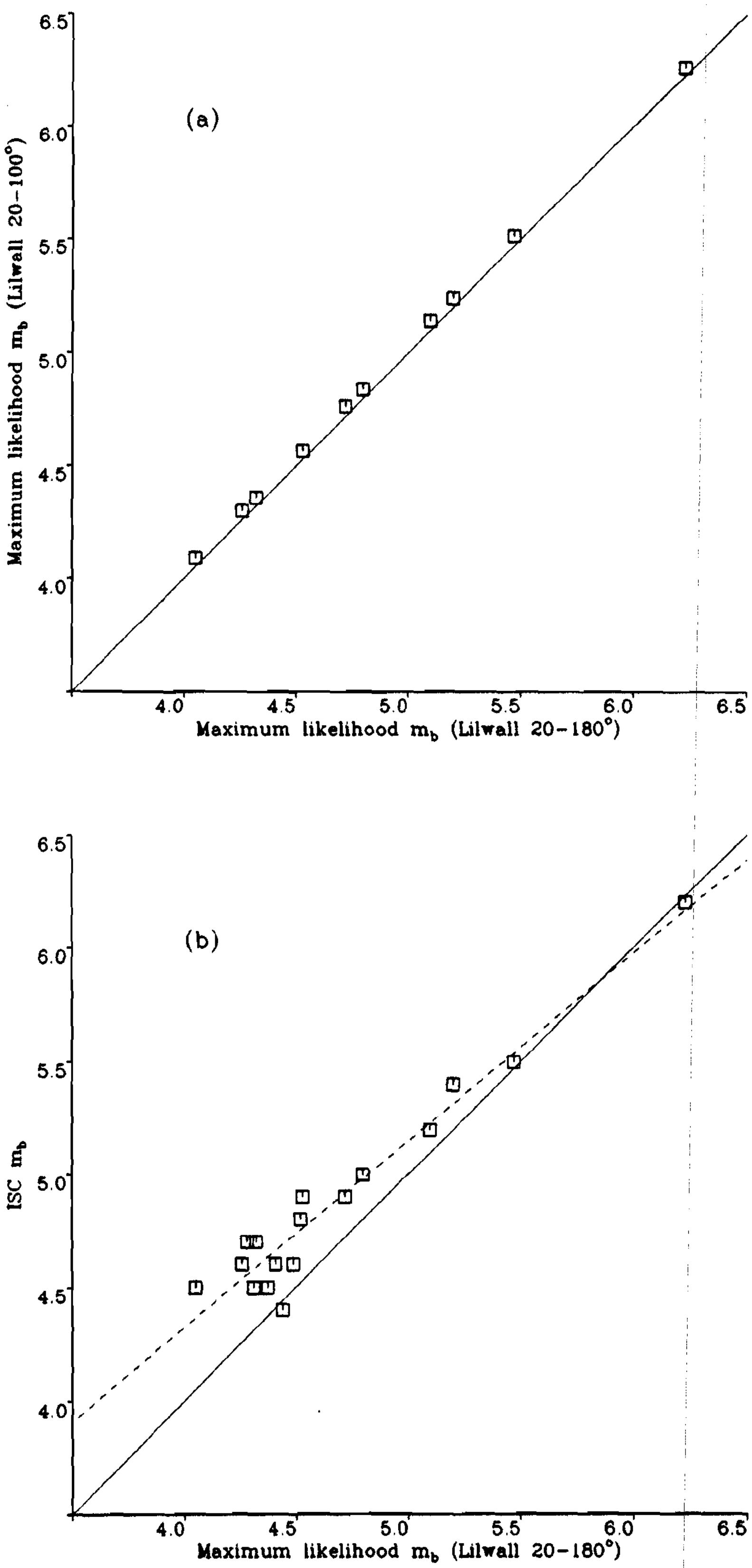


(a) Station magnitude terms against station time-terms for the Singer (underground) explosions.

(b) Station magnitude terms for the Lop Nor (atmospheric) explosions against the magnitude terms for the Singer explosions.

(c) Station magnitude terms for the Singer explosions derived using only data in the range 20-100° against those derived using data out to 180°.

<u>FIGURE 3. COMPARISONS OF STATION TERMS</u>



(a) Maximum-likelihood magnitudes derived for the Singer underground explosions using only data in the range 20-100° against the magnitudes derived using data in the range 20-180°.

(b) ISC magnitudes against maximum-likelihood magnitudes. Also shown is the line $m_b^{ISC} - m_b^{ML}$ and the least squares line through the data.

FIGURE 4.

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