Seismic magnitude and yield for the Indian nuclear test of 11 May 1998

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Indian scientists estimate the yield of the 11 May 1998 nuclear test at Pokhran as around 60 kt. As an earlier paper from our group points out, two of the assumptions made in arriving at this estimate appear unjustified. These are that: (i) interference between P-waves from the two largest explosions in the test significantly reduces the observed body-wave magnitude; and (ii) National Earthquake Information Center, USA estimate of surface-wave magnitude is reliable. Here we give a fuller discussion of the effects of interference on body-wave magnitude and estimate that the maximum effect is to reduce magnitude by only 0.02 magnitude units. We also demonstrate that none of the M_s observations reported in bulletins have been measured on signals from the test: all the observations are from signals from earthquakes, that were mistakenly attributed to the test. However, we have found 17 surface-wave signals which do seem to be from the 11 May test. The estimated M_s from the ten stations with the highest-quality signals is 3.32, which on the magnitude–yield relationship used by Indian scientists gives 25 kt. These results support the view that the yield of the 11 May test is significantly less than 60 kt.

THE seismic magnitude of the Indian nuclear test of 11 May 1998 (referred to here as 980511) is a matter of debate: in general Indian scientists (from the Bhabha Atomic Research Centre (BARC) which carried out the test) claim that the magnitude and hence the total yield of the test is higher than the estimate of non-Indian scientists. Here we examine two main points of disagreement. The first point is that Sikka *et al.*[1,2] claim that the effect on body-wave magnitude (m_b) of interference between P-waves from the two largest yield explosions in the test (announced as three explosions with yields of 0.2, 12, and 43 kt) significantly reduces m_b, whereas Douglas *et al.*[3] argue such effects are negligible. The second point of disagreement is on the value of the surface-wave magnitude (M_s). Sikka *et al.*[2] make use of M_s published by the National Earthquake Information Center (NEIC), USA. Douglas *et al.*[3] claim that the NEIC readings come from earthquake seismograms, the source of which is mistakenly attributed to the explosion. In this paper we look in more detail at the effects of interference of P on m_b and give a revised estimate of M_s using only surface-wave seismograms that are unambiguously from 980511.

The maximum interference effect will be on azimuths in-line with the two explosions. For explosions separated by distance d, the time separation of P for explosions fired simultaneously is d/v, where v is the apparent surface speed at the recording station. In the distance range 30–90°, v ranges from 12.5 to 25.0 km s^{-1}, so that as d is 1 km the time separation is 0.08–0.04 s. For maximum destructive interference, signals must be separated by half the period, so the maximum effect will be for periods 0.16–0.08 s, i.e. 6.25–12.5 Hz. The effects at 1–2 Hz, the predominant frequency of most P signals recorded at long range, will then be small. Sikka *et al.*[1] attempt to demonstrate interference effects using synthetic seismograms. However, the predominant period of these signals is ~ 3 Hz which is above the predominant period of almost all signals recorded at long range. (There is an added puzzle to the synthetic seismograms: they are described as broad band, but appear to be short period.)

In trying to model the seismograms at long range, there are too many unknowns to obtain useful results. Here we use an approach similar to that used by Stewart and Marshall[4]. The epicentres of the two largest of the three explosions that made up 980511 lie on a roughly E–W line so that, as the explosions were fired simultaneously, the signals from the explosions should add constructively at stations to the north and south. Then the P signals, $f(t)$, at stations to the north (and south) can be taken to be P from the combined yields. No doubt, there will be differences between the signals from the 12 and 43 kt explo-

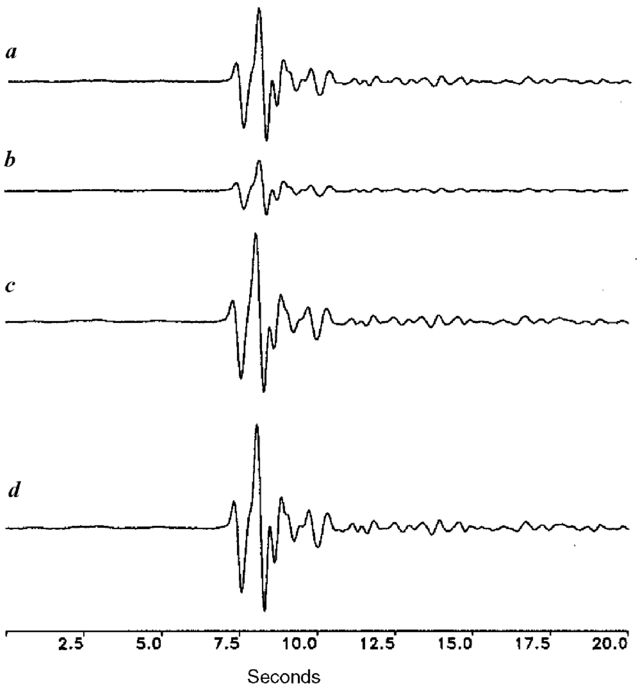

Figure 1. Effect of interference of P estimated using the short-period siesmogram recorded at Yellowknife, Canada ($\phi = 3°$) from 980511. ***a***, Seismogram scaled by 0.72 to represent the P signal from the 43 kt explosion; ***b***, Seismogram scaled by 0.28 to represent P from the 12 kt explosion; ***c***, Sum of ***a*** and ***b***, with ***b*** delayed by 0.1 s; ***d***, Sum of ***a*** and ***b***, with no delay.

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Table 1. Surface-wave magnitudes (M_s^{BULL}) attributed to 980511 in the ISC and NEIC bulletins. M_s^{RP} is our estimate of surface-wave magnitude using the curve of Rezapour and Pearce[10] to correct for the effects of epicentral distance. Station LOR is not included by the NEIC in the mean magnitude. The M_s at station NJ2 is measured from the horizontal components

Bulletin	Station	Δ(°)	A (nm)	T (s)	M_s^{BULL}	M_s^{RP}
ISC	NJ2	41.01	780(N), 1605(E)	30.0	4.8	–
ISC	KEV	49.84	80(Z)	18.0	3.8	3.75
ISC	HAU	54.22	50(Z)	22.0	3.5	3.51
ISC	LOR	55.94	30(Z)	23.0	3.3	3.28
ISC	FLN	58.70	30(Z)	19.0	3.4	3.40
NEIC	KEV	49.83	80(Z)	18.1	3.8	3.75
NEIC	KONO	53.02	50(Z)	20.6	3.5	3.53
NEIC	HAU	54.23	50(Z)	22.0	3.5	3.51
NEIC	LOR	55.95	30(Z)	23.3	3.3	3.28
NEIC	FLN	58.71	30(Z)	19.0	3.4	3.40

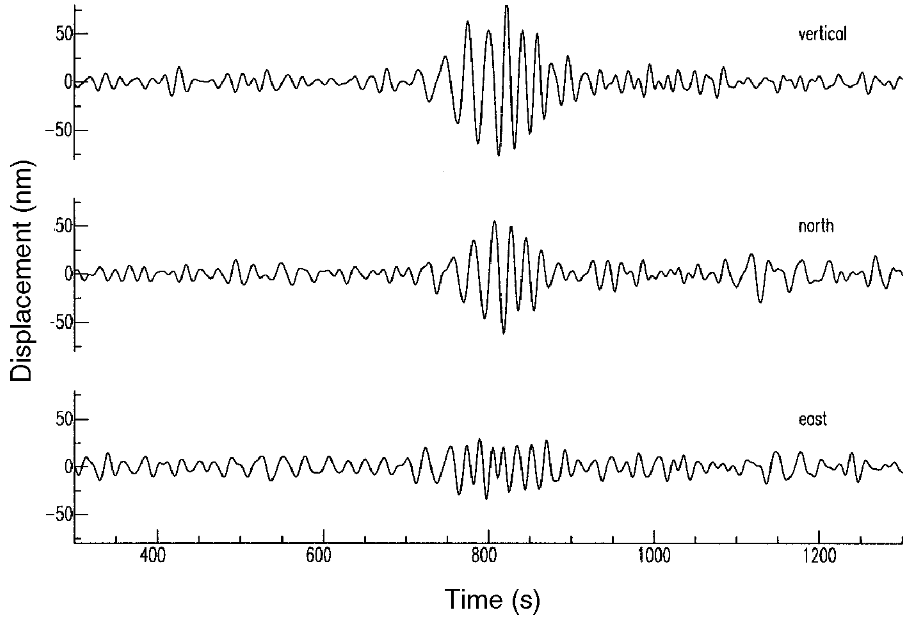

Figure 2. Three-component, long-period seismogram recorded at station KEV. Retrieved waveforms are converted to the long-period response of the KS36000 seismometer and the ordinate gives displacement in nm at 25 s period. Waveforms are band-pass filtered with corners at 0.03 Hz and 0.1 Hz. Origin time of the abscissa is 10:21:44 UT.

sions, but this is presumably much less than the differences between the true signals and any signal generated by modelling. Assuming then that the signals from each of the two explosions have identical shape, the effect of destructive interference can be investigated by forming:

$$g(t) = a_1 f(t) + a_2 f(t + \delta t),$$

where $a_1 f(t)$ is the signal at a station to the north scaled to have the amplitude expected from the 43 kt explosion, assuming $f(t)$ is from 55 kt; $a_2 f(t + \delta t)$ being the signal scaled for the 12 kt explosion and time shifted by δt. As amplitude depends on $Y^{0.75}$, where Y is yield, a_1 and a_2 are 0.72 and 0.28 respectively. Figure 1 shows an example of forming $g(t)$ with a delay of 0.1 s using P recorded at Yellowknife, Canada (YKA). Interference reduces the magnitude by 0.08 magnitude units (m.u.). This however, only applies to stations on azimuths in-line with the epicentres of the two explosions at distances of 25°. The only station on an E–W azimuth used by Sikka *et al.*[1] (and by us) is BCAO at 55°, where v is 15.4 km s^{-1};

hence δt is 0.06 s. The effect of this is to reduce the amplitude by 0.03 m.u.

For a station on azimuth ϕ (measured clockwise from north), the effective separation of the epicentres is $d\sin\phi$. Forming $g(t)$ for each station used by us with time shift $\delta t(= d\sin\phi/v)$ gives an average amplitude reduction of 0.02 m.u., which is negligible given all the other greater uncertainties in the estimation of yield from m_b.

Surface-wave magnitudes for 980511 are reported in the bulletins of the International Seismological Centre (ISC), UK and the National Earthquake Information Center (NEIC) of the United States Geological Survey. The individual station measurements of M_s reported in the bulletins are given in Table 1. The ISC average is 3.8 (on five readings) and that of the NEIC is 3.5 (on four readings). Now, it would be expected that the most likely stations to report M_s would be the closest stations where amplitudes should be well above noise, but none of the bulletin reports are for stations closer than 41° to 980511, which suggests that the signals on which M_s is measured are not from the explosion. Consequently, attempts were made to obtain the surface-wave seismograms for which M_s is reported to see if their azimuth of approach to the station (back-azimuth) and dispersion (variation of group arrival time with frequency) is compatible with the source being 980511. Unfortunately, only the recordings from KEV and KONO could be obtained. However, we have obtained the seismograms for the station SSB in France and used these in place of the seismograms from the French stations HAU, LOR, and FLN.

Figure 2 shows the long-period seismograms recorded at KEV between 10:26:44UT and 10:42:28UT on 11 May 1998. The clear surface-waves shown are presumably those reported in the ISC and NEIC bulletins. Measurement of the back-azimuth of the Rayleigh waves (using the method of Selby[5]) gives 352°. This is compatible with an earthquake which occurred near Svalbard (84.8N, 9.1E) at 10:26:08UT, but not with the back-azimuth of 124° to 980511. Figure 3 shows a frequency–time (dispersion) plot (using the method of Dziewonski *et al.*[6]) for the vertical component at KEV. The peak amplitude marks the group arrival time of the signal at each frequency. The group arrival times predicted from the epicentre and origin time of the Svalbard earthquake and 980511, using the earth model of Stevens and McLaughlin[7], are also shown. The dispersion of the Rayleigh wave is obviously compatible with that of the Svalbard earthquake – allowing for uncertainties in the earth model – but not with 980511. It seems clear then that the Rayleigh wave at KEV has been misassociated in the NEIC and ISC bulletins. Similar analysis shows that the signals at KONO and SSB are also Rayleigh waves from the Svalbard earthquake.

We were unable to obtain waveforms from station NJ2 in southeast China. However, observations listed later in the article from other Chinese stations suggest it is highly unlikely that the report listed in the ISC bulletin is correct. We therefore conclude that none of the M_s reports in the NEIC or ISC bulletins are related to 980511.

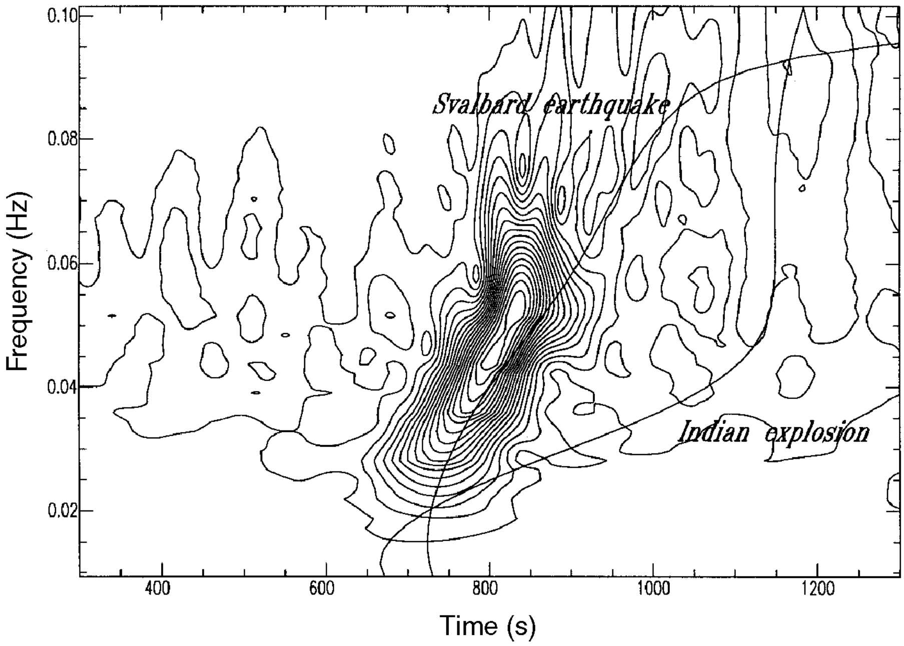

Figure 3. Frequency–time contour plot for the vertical component seismogram recorded at KEV. The two curves show the predicted group arrival times using the model of Stevens and McLaughlin[7]. The observed energy is clearly associated with the Svalbard earthquake.

Table 2. Surface-wave magnitude for 980511 from signals that are associated with the test: Quality A indicates the signals associated using the back-azimuth and dispersion test and quality B signals associated using the dispersion test only. The surface wave magnitude M_s^{RP} is calculated using the curve of Rezapour and Pearce[10] to correct for the effect of epicentral distance

Station	Δ(°)	Quality	A (nm)	T (s)	M_s^{RP}
CHM	15.28	A	88.33	17.2	3.26
AAK	15.65	A	116.27	16.0	3.42
TKM2	16.08	A	71.72	18.3	3.16
TLG	16.68	A	156.70	23.1	3.51
WMQ	21.05	B	95.78	17.6	3.42
VOS	25.65	A	70.77	21.8	3.29
ZRN	25.90	B	34.88	23.1	2.96
BRVK	25.95	A	84.27	22.5	3.35
CHTO	26.28	B	50.18	18.1	3.23
CHK	26.56	A	65.23	21.9	3.27
LZH	28.62	B	29.35	25.6	2.89
XAN	32.57	A	41.52	23.6	3.14
TLY	34.30	A	63.11	18.1	3.46
ULN	34.39	B	42.23	20.5	3.23
MHV	37.22	B	41.50	25.8	3.17
OBN	37.90	B	59.67	27.0	3.31
BJT	38.77	A	51.31	23.1	3.32

No M_s is reported for 980511 in the Reviewed Event Bulletin (REB) published by the International Data Centre (IDC) – which is surprising given that the detection threshold for M_s of the International Monitoring System (IMS) which provides data to the IDC, is about an order of magnitude lower than that of the NEIC bulletins[8]. However, a careful search of the recordings from the IMS and other stations shows that surface waves were recorded at 17 stations outside India (only one of which is an IMS primary station, the remainder are stations operated by the Incorporated Research Institutes for Seismology). For ten of the signals the back-azimuth of the signal can be measured and these turn out to be close to that predicted for the epicentre of 980511. Back-azimuths could not be determined for the other seven signals because the horizontal components are too noisy or not available. However, all 17 signals show dispersion that is compatible with the source being 980511. Using only the ten M_s estimates from the stations for which a back-azimuth could be determined, the average is 3.32. On the M_s/yield relationship of Sikka *et al.*[9] ($M_s = 2.14 + 0.84\log Y$), this gives an yield estimate of 25 kt. (The average for all 17 magnitudes is 3.26, which gives a yield of 21 kt.) Note that the stations in China (WMQ, LZH, XAN and BJT) all have M_s estimates less than 3.5. The M_s of 4.8 reported in the ISC bulletin for the Chinese stations NJ2 is much too large to be from a 980511 signal.

The main conclusions are: (1) There is no justification for assuming that interference between P from the two largest yield explosions of 980511 reduces the average m_b by more than a few hundredths of a magnitude unit. (2) All M_s observations published in bulletins have been measured on earthquake signals that were mistakenly assumed to be from 980511. (3) The M_s of 980511 estimated from ten highest-quality observations is 3.32 ± 0.04, which implies a yield of around 25 kt.

These results support the view that the yield of the 11 May 1998 test is significantly less than 60 kt.

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Body-wave magnitude bias between Pokhran and eastern Kazakh nuclear test sites

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For estimating the yield of the Indian nuclear explosions of 11 May 1998 (POK2), some seismologists have used the parameters of Shagan River test site (SRTS) eastern Kazakh as a representative for Pokhran test site, and have underestimated the yield of POK2. Here, we have shown that there is a body-wave magnitude bias of ~ 0.4 units between the SRTS and the Pokhran site. In view of this, it will be necessary to take this bias into account before estimating the yield of POK2 using a yield–magnitude relation that is applicable to the SRTS alone.

HISTORICALLY, two seismic magnitudes are assigned to underground nuclear explosions. One is the body-wave magnitude, m_b, evaluated from the amplitude of P-waves of ~ 1 s period and the other is the surface wave magnitude, M_s, estimated from the amplitudes of Rayleigh waves of ~ 20 s period. The magnitude assigned to an

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