The yields of the Indian nuclear tests of 1998 and their relevance to Test Ban verification

A. Douglas*, P. D. Marshall, D. Bowers, J. B. Young, D. Porter and N. J. Wallis

AWE, Blacknest, Brimpton, Reading, RG7 4RS, UK

Indian scientists estimate the yield of the 11 May 1998 nuclear test at Pokhran as around 60 kt. Some of the assumptions made in making this estimate appear unjustified: for example, the assumption that interference between P waves from the two largest explosions in the test reduces the observed body-wave magnitude and that the NEIS estimate of surface wave magnitude is reliable. We show from a comparison of P amplitude observations at twelve common stations for the 11 May 1998 and 18 May 1974 tests that the maximum yield of the 1998 test is around 40 kt with the assumption that the yield of the 1974 test is 13 kt. However, one Indian estimate of the yield of the 1974 test is 8 kt, implying that the 1998 test has a maximum yield of around 25 kt. Our estimate of yield from surface waves is 15–20 kt. The evidence is then that the yield of the 1998 test is closer to 20 kt than the 60 kt obtained by Indian scientists. Even assuming however that the Indian yield estimate is correct the capacity of the International Monitoring System being set up to verify the Comprehensive Test Ban, should be sufficient for the System to act as a strong deterrent to any nation on the Indian Sub-continent and adjacent areas attempting to carry out a clandestine test.

FOLLOWING its nuclear tests of 11 and 13 May 1998 (referred to here as 980511 and 980513 respectively) at the Pokhran test site, India announced that 980511 comprised three explosions of 0.2, 12 and 43 kilotonne (kt), a total yield of 55.2 kt, and that 980513 was two explosions of 0.3 and 0.5 kt The explosions in each test were fired simultaneously. In a series of papers, Indian scientists (from the Bhabha Atomic Research Centre, BARC, which carried out the tests) estimate the total yield of 980511 as around 60 kt (Sikka et al.[1–3] and Roy et al.[4]). Some seismologists outside India estimate a yield of around 12 kt (Barker et al.[5] give 9–16 kt, Wallace[6] 10–15 kt). There are no reports of seismic waves being recorded from 980513 outside India. Here we re-examine the seismological observations from 980511 to see if the yield could be as large as India claims and consider the implications for test ban verification of these disagreements on yield and the failure of 980513 to be detected.

Seismological estimates of yield are most commonly derived from the body-wave magnitude, m_b (see footnote

to Table 1). The relationship between m_b and yield (Y kt) is assumed to be of the form:

$$m_b = a + b \log_{10} Y, \tag{1}$$

where a and b are constants. For most hard rock sites such as eastern Kazakhstan and Pokhran, b is usually assumed to be ~ 0.75. (Wallace[6] uses this value, Sikka et al.[1] use 0.77.) The principal difference in the yield estimate of Sikka et al.[1] and others is in the value of a: Sikka et al.[1] use 4.04 on the assumption that the yield of the first Indian test (18 May 1974 referred to below as 740518) was 13 kt, Wallace[6] uses 4.45 on the assumption that a for Pokhran is the same as that of eastern Kazakhstan. Barker et al.[5] use a different method which relies on matching of observed and theoretical spectra of the P waves.

Both Wallace[6] and Sikka et al.[1] take m_b for 980511 to be 5.2, the value published by the National Earthquake Information Service (NEIS). This gives 10 kt on the Wallace[6] formula and 32 kt on that of Sikka et al.[1]. Sikka et al.[1] however, argue that for 980511 the NEIS m_b is an underestimate because of interference between the P waves from the 43 kt and 12 kt explosions and that the unbiased estimate of m_b is 5.4, giving their yield of 58 kt.

According to Sikka et al.[1], the 43 kt and 12 kt explosions were fired simultaneously in separate boreholes 1 km apart; the line joining the holes being oriented roughly E–W. For stations to the north (or south) of the test site

Table 1. Log A/T for the 18 May 1974 and 11 May 1998 Indian tests

Station	Distance (°)	Azimuth (°)	Log A/T 18 May 1974	Log A/T 11 May 1998
HYB	11.4	145	1.7	2.0
NUR	46.2	330	1.1	1.3
KEV	49.9	341	1.4	1.8
GRF	51.1	313	1.1	1.5
HFS	51.2	327	1.3	1.6*
NBO/NB2	52.8	328	1.0	1.4
BNG/BGCA	55.5	256	1.6	1.8*
LOR	56.0	310	0.9	1.1
EKA	59.7	321	0.7*	0.9*
COL/COLA	83.4	16	1.1	1.7
PMR	85.8	18	1.0	1.5
YKA	90.7	3	0.8*	1.5*
		Average	1.14	1.51
		Difference		0.37

Station $m_b = \log_{10} A/T + B(\Delta, h)$, where $B(\Delta, h)$ is a correction for distance Δ, of the station and depth h of the source. A is half the maximum peak-to-trough ground displacement in the first few seconds of the short-period (~ 1 Hz) P seismogram, and T is the corresponding period.
*Log A/T measured as part of this study. The remaining observations for the 1974 explosion are from the ISC Bulletin and those for the 1998 explosion are from the NEIS.
MOX reports log A/T from the 1974 and 1998 explosions as 0.0 and 1.4 respectively. This large difference suggests that one of these observations is incorrect so the observations from the station have been omitted from the calculation of the average differences in magnitude.
The log A/T reported to the NEIS for YKA is 1.2, whereas the value measured in this study is 1.5. Note that for the 1974 explosion the log A/T reported for YKC, which is very close to YKA, is 1.3.

*For correspondence. (e-mail: alan@blacknest.gov.uk)

the P signals from the two explosions arrive simultaneously and sum constructively, whereas on E–W azimuths the signals are separated by some short-time interval and thus sum destructively. This, they argue, biases the average m_b low by 0.2 magnitude units. However, at long range, the maximum time-separation of the two signals is less than 0.1s, so the frequency for optimum destructive interference is > 5 Hz, well above the dominant frequency (1–2 Hz) of the P waves at most stations. Thus any effects of destructive interference in the frequency band where m_b is measured are negligible.

Nevertheless it could be argued that m_b for explosions at Pokhran is biased low relative to those of explosions of the same yield at test sites of the Former Soviet Union (FSU) because of differences in path effects. For example, there is evidence that P waves from earthquakes and explosions in the south of the FSU, that follow paths that pass under the mountain ranges and adjacent sedimentary basins that lie to the north of India, are more strongly attenuated than on average paths (see for example ref. 7). Presumably then, P waves travelling from Pokhran to stations that lie on azimuths ranging from northwest through north to northeast will be similarly attenuated and so m_b might be biased low. However, assuming that stations that lie on other azimuths, that is those in southern Africa and Australia, are not biased gives an estimate for m_b for 980511 of 5.2, the same as the NEIS estimate.

The yield estimate obtained by Sikka et al.[1] is made on the assumption that the estimate of m_b for 740518 published in the *Bulletin of the International Seismological Centre*, and the NEIS estimate for 980511 have the same baseline, even though they are determined using widely different networks of stations. These differences in the networks can be minimized by considering only observations from stations that recorded both explosions as is done in Sikka et al.[2]. Using eight stations that recorded 740518 and 980511, Sikka et al.[2] obtain a difference in m_b of 0.45 m.u. (implying a yield for the 1998 test of about 48 kt) or 0.5 m.u. (implying a yield for the 1998 test of 53 kt) when allowance is made for the assumed interference effects. We have repeated the exercise using magnitudes from twelve stations (and assuming no interference effects) and obtain a magnitude difference (Table 1) of 0.37 m.u. implying a yield for 980511 of ~ 40 kt.

These results illustrate how sensitive the yield estimate of 980511 is to assumptions on interference effects and on the stations used. Further, yield estimates made from comparisons of the 1974 and 1998 explosions depend crucially on 13 kt for 740518 being the true yield. However, 13 kt is itself a seismological estimate based on the surface wave magnitude, M_s, from one station, so the uncertainty is large. (M_s is calculated from the Rayleigh surface waves from a seismic disturbance.) Nevertheless, the estimate is supported by Marshall et al.[8] who obtain an estimate of 12 kt from M_s from three stations. Further, Chidambaram and Ramanna[9] by combining seismological

and close-in observations of ground motion also estimate the yield at 12 kt. However, P. K. Iyengar, BARC gives the yield of 740518 as 8 kt 'exactly as predicted' (lecture at Henry L. Stimson Center, Washington reported in ref. 10). This implies that 980511 has an yield of only ~ 25 kt, much closer to the estimates of Barker et al.[5] and Wallace[6].

Another point to be considered is the depth of the explosions. The 1974 explosion was fired at shallow depths (107 m) above the water table in dry sandstone and shale[9]. As the largest of the 1998 explosions was apparently expected to have a yield of 43 kt, it was presumably fired much deeper than that of 1974 to ensure that the radioactivity is contained. Thus, the 1998 explosion was probably fired in water-saturated rocks. If this is so, then for a given yield, explosions in water-saturated rocks have higher magnitudes than those fired in dry porous rocks, the larger magnitude of 980511 compared to 740518 may be due at least in part to the differences in water content of the rocks in which the nuclear devices were emplaced. The estimate of ~ 25 kt derived above may then still be too high.

Sikka et al.[2] find that as with m_b the yield from M_s, (3.62) is 58 kt; M_s being determined from observations at three stations in India in the distance range 2–17°, and four outside India (reported by the NEIS) in the range 50–59°. If M_s was 3.62 then it would certainly imply that the 980511 yield is much larger than the 12 kt of Barker et al.[5] and Wallace[6]. However, our estimate of M_s from observations at Nilore, Pakistan (NIL) and Xi'an, China (XAN) is 3.2, implying an yield of 15–20 kt, consistent with the non-Indian estimates from m_b. One possible explanation of the high estimate of Sikka et al.[2] is that M_s for stations in India are biased high because their distances are less than 20° and the conventional magnitude scale does not correctly account for the effects of propagation at such distances[11]. Further, it seems unlikely the NEIS estimates of M_s are for the 980511 test. Had M_s been so large, surface waves would have been detected more widely than they were. The observations reported to the NEIS are surface waves from earthquakes and just fortuitously arrived at the recording stations at about the expected time of those from the Indian explosion. Analysis of the surface waves from Kevo, Finland associated in the NEIS report with 980511 shows that the waves are arriving at the station from the north, and are in fact from an earthquake north of Svalbard. Had the waves been from 980511 they should have arrived at Kevo from the south east.

Our conclusion is that there is no significant evidence from body and surface wave magnitudes that the yield of 980511 was nearly 60 kt. A case can be made from m_b for the yield being about 40 kt but only if the true yield of 740518 was close to 13 kt and the coupling between explosion and surrounding rock is the same for both the 1974 and 1998 tests. Roy et al.[4] and Sikka et al.[3] also

make estimates of yield from Lg using seismograms recorded at stations within India. We intend to carry out a similar study once we have been able to obtain digital files of the seismograms from these in-country stations.

Sikka et al.[2] argue that many of the assumptions made by others in estimating the yield of 980511 are incorrect and that without the availability of 'close-in ground motion measurements, radiochemical methods, calibration events and hydrodynamic shock measurements' together with 'knowledge of the surroundings of the device' any estimates other than those by scientists involved in the test 'will be not just highly subjective but erroneous'. If Sikka et al.[1,2] have so little confidence in such methods – and we agree that yields estimated by seismological methods are subject to large uncertainties – it is not clear why they have gone to such lengths to obtain so precise a seismological estimate of yield. The only close-in information that Sikka et al.[1,3] seem to have used in estimating the yield seismologically is the relative positions of the three explosions in the 980511 test and we suggest above that the spatial separation of the explosions has a negligible effect on seismic magnitude. The close-in information that might enable non-Indian scientists to improve their yield estimates is: the depth of firing of the explosions; the firing medium; and the water content of the medium, but none of this information seems to have been released.

The failure of Barker et al.[5] and Wallace[6] to obtain a yield estimate close to that of Sikka et al.[1,2] for 980511, or of any stations outside India to detect 980513 leads Sikka et al.[2] to express doubts as to whether the Comprehensive Test Ban (CTB) can be verified effectively. However, even accepting that the yield of 980511 was around 60 kt it still implies that a 1 kt explosion at Pokhran will have a magnitude around m_b 4 and it is expected that the International Monitoring System (IMS) being set up to verify the CTB will, when completed, have a threshold at long range below this magnitude, so that sub-kiloton tests at the site should be detected and recognized as possible explosions. Extrapolating from the amplitudes observed from 980511 supports the view that signals 20 times smaller (equivalent to a yield ratio of 60) would be detected in Canada. (Of course if the true yield of 980511 was close to the non-Indian estimates of ~ 12 kt, very low yield explosions at Pokhran should be detectable at long range.)

The failure of existing stations – particularly the seismological station at Nilore, Pakistan – to detect 980513 which India claims had a total yield of 0.8 kt is then a puzzle. The only possible explanations seem to be that either the yield was much lower than expected or that the explosions were fired in dry, porous material or both. It

would be useful to have some seismograms of signals from the explosion from within India to make an estimate of the range of possible yields assuming best- and worst-case coupling. The failure of the Nilore station to detect the signal leads Barker et al.[5] to assume low coupling, to put an upper bound on yield of 300 tons.

If the reason the seismic signals from 980513 are weak is that the explosions were fired in dry, porous material then the relevance of this test to CTB verification is marginal. Anyone trying to carry out a clandestine test in violation of the treaty has to bury the device much deeper than for simple containment to ensure it produces no surface effects that would be visible from a satellite and that there is no escape of radioactive particulates or noble gases which could be detected by radionuclide sensors. This will usually mean that any such explosion will be in water-saturated, consolidated rock which leads to good coupling between the explosion and the surrounding material, and the efficient generation of seismic waves.

Currently the IMS is incomplete; eventually the System will comprise four networks of sensors (seismic, acoustic, hydroacoustic and radionuclide) a total of 321 stations, and were India to sign the Treaty presumably there would be at least a station of the seismological network within that country. It is also to be hoped that recordings from the seismological stations within India would be made available to organizations verifying compliance with the Treaty. All this should act as a strong deterrent to any nation on the Indian Sub-continent and in adjacent areas, attempting to carry out a clandestine test.

1. Sikka, S. K., Roy, F and Nair, G. J., Curr. Sci., 1998, **74**, 486–491.
2. Sikka, S. K., Roy, F., Nair, G. J., Kolvankar, V. G. and Kakodkar, A., BARC News Lett., 1998, **178**, 1.
3. Sikka, S. K., Nair, G. J., Roy, F., Kakodkar, A. and Chidambaram, R., Curr. Sci., 2000, **79**, 1359–1366.
4. Roy, F., Nair, G. J., Basu, T. K., Sikka, S. K., Kakodkar, A., Chidambaram, R., Bhattacharya, S. N. and Ramamurthy, V. S., Curr. Sci., 1999, **77**, 1669–1673.
5. Barker, B. et al., Science, 1998, **281**, 1967–1968.
6. Wallace, T. C., Seismol. Res. Letts., 1998, **69**, 386–393.
7. Stewart, R. C., Phys. Earth Planet. Int., 1987, **46**, 381–383.
8. Marshall, P. D., Springer, D. L. and Rodean, H. C., Geophys. J. R. Astron. Soc., 1979, **57**, 609–638.
9. Chidambaram, R. and Ramanna, R., Some studies of India's peaceful nuclear explosion experiment, Proc. Tech. Committee on Peaceful Nuclear Explosions IV, IAEA, Vienna, 1975, pp. 421–427.
10. Gupta, V. and Pabian, F., Sci. Global Security, 1996, **6**, 101–189.
11. Marshall, P. D. and Basham, P. W., PAGEOPH, 1973, **103**, 406–414.