$$D = M_0/\mu A. \quad (5)$$

According to Keilis Borok[5], the stress drop $\Delta\sigma$ is expressed in Pascal with the relationship

$$\Delta\sigma = 7M_0/(16R^3). \quad (6)$$

Therefore the estimated parameters are

Seismic moment $M_0 = 4.97 \times 10^{15}$ Nm; length of the rupture plane $R = 190$ m; area of the circular rupture plane $A = 1.14 \times 10^5$ m^2; source dislocation $D = 1.339408$ m; stress drop $\Delta\sigma = 31.27$ MPa.

The rupture plane and the source dislocation are estimated using the kinetic rupture model of Brune[6]. The static stress drop $\Delta\sigma$ describes the difference in shear stress on the fault plane before and after the slip.

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Yield estimation of Indian nuclear tests of 1998

We explain below why we consider the arguments put forward by Douglas *et al.*[1], while commenting on the papers by Sikka *et al.*[2–4] and Roy *et al.*[5] regarding yield estimation of Indian nuclear tests of 11 and 13 May 1998, as inappropriate. The data used in their calculations comprise log (*A*/*T*) values of *P*-waves available from some non-Indian stations and Hyderabad station in India, corresponding to Indian explosions of 1974 (POK1) and 11 May 1998 (POK2). Of these, some estimates are made by Douglas *et al.* and the remaining estimates are accepted as such from the NEIC and ISC bulletins. *It may be noted that Douglas et al. have observed that some of the reported values to NEIC and ISC were incorrect.* An independent surface wave magnitude estimate using data from XAN (China, 32.6 deg) and NIL (Pakistan, 6.6 deg) has also been reported by the authors without mentioning any details of the signals and the *relation used* for the *Ms* estimation at NIL, which showed highly attenuated Rayleigh and *Lg* waves. On the other hand, the seismogram of Bhopal, India at a distance similar (6.3 deg) to that of NIL, showed strong surface waves (see figure 2 of Roy *et al.*[5]). One possible reason for the low estimate of Douglas *et al.* is that proper path effects are not taken into account by them for *Ms* estimation. The *Ms* estimate of Douglas *et al.* from the two stations differs from the NEIC reported estimate (four observations) and the estimate made by us (six regional observations). Douglas *et al.* have further reported that the maximum yield of POK2 is ~ 40 kt, whereas this value according to their calculations corresponds to the average value of the yield. *The maximum value of the yield according to the calculations of Douglas et al. is in fact ~ 110 kt.*

The seismic yield of POK2 has been estimated by Sikka *et al.*[2–4] and Roy *et al.*[5] by using close-in, regional and teleseismic data. The scaling of close-in acceleration data gave the combined yield of POK2 around 58 kt (ref. 3). Additional seismic observations of global *P* waves and regional *P* and *Lg* waves gave the estimate of yield in the range of 54–63 kt (refs 4, 5). It may be emphasized here that the potential of seismic *Lg* waves as a stable source-size estimator is now well established[6,7]. Nevertheless, various estimates obtained by Roy *et al.*[5] and Sikka *et al.*[4] from regional *Lg* waves are *conveniently ignored* by Douglas *et al.* The regional surface wave estimate, *Ms* = 3.56, using a calibrated formula for the Indian region, and *not the conventional magnitude scale* as mentioned by Douglas *et al.*, gave the yield in the range of 49–52 kt (refs 4, 5). All these estimates together gave the yield of POK2 in the range of 49–63 kt. The yield of POK2 using radio-chemical methods was estimated as 13 ± 3 kt for fission device[8] and 50 ± 10 kt for the thermonuclear device[9], giving the range of combined yield as 50–76 kt. Further, the ratios of neutron activation products to fission products for the thermonuclear and fission test of 11 May 1998 were also found to be in quantitative agreement with that expected from their radiochemical yields. BARC has also performed simulation studies of the close-in acceleration values and surface features by finite difference and finite element codes (unpublished). These studies also corroborate the estimated yield of POK2. The seismic yield estimates by Sikka *et al.*[2–4] and Roy *et al.*[5] are found to be consistent with the radiochemically estimated yield of POK2. We have carried out various seismic estimations to bring to scientific literature, the efficacy of different seismic techniques and the need to appropriately use the regional data and methods for obtaining reliable results. Relying on the use of arbitrary formulae or methods may only lead to erroneous results.

The estimates of yield of POK1 were obtained as 12–13 kt from close-in data, rock mechanics phenomenology calculations and surface wave measurements[10–12]. One of the co-authors of the paper by Douglas *et al.*[1], viz. Marshall, had also obtained the yield of POK1 as 12 kt in an earlier study[13]. There are several papers by other authors as well citing the correctness of this estimated yield. However, Douglas *et al.*, in a transparent attempt to bring down the yield of POK1, seem to repose more faith in a personal opinion (expressed in a lecture, with lack of scientific evidence) in preference to the above scientific facts. Wallace[14] obtained the yield ratio between POK1 and POK2 as 2.4 using m_b values from different network estimates, which is indeed not an accurate method and Douglas *et al.* agree with it. The inadequacy of data and interpretation of Wallace[14] in using m_b-yield relation of former Soviet Union for the Pokhran region is described by Sikka *et al.*[3] and Douglas *et al.*[1]. Nevertheless, Douglas *et al.*, having used a much superior method of yield estimation compared to Wallace[14] and Barker *et al.*[15], are for some reason inclined to believe that the latter estimates are more authentic than theirs. It is interesting to note that Wallace himself, in an IRIS Consortium report to the US Senate in 1994, along with co-authors[16] give the yield of POK1 as 10–15 kt, while in 1998 (ref. 14) he brought it down to 5 kt, which helped Douglas *et al.* in their attempt to underestimate the yield of POK2.

Douglas *et al.* emphasize the efficacy of controlled path for the estimation of relative yield of POK2 and use one of the methods followed by Sikka *et al.*[2]. However, they have not incorporated necessary correction terms in their calculations to account for the interference effect and without any quantitative proof, claim that the corrections are negligible. We have introduced few more columns in Table 1 of Douglas *et al.* to show the yield estimates of POK2 at individual stations corresponding to POK1 yields of 12 kt and 13 kt, respectively (see Table 1). *It may be seen that the maximum yield of POK2 according to measurements by Douglas et al. is ~ 110 kt* (the * symbol in the column for log (A/T) may be noted) and not 40 kt as stated by them. In fact, 40 kt is the average yield estimate obtained by Douglas *et al.* from average $\Delta m_b = 0.37$.

Douglas *et al.* have used data from twelve stations compared to eight stations by Sikka *et al.*[3]. However, the reliability of some of these estimates should be assessed in the light of the observations made by Douglas *et al.*, that some reported values to NEIC and ISC, e.g. MOX, YKA, etc. were incorrect (see footnote below Table 1 of Douglas *et al.*). Among the twelve sets of measurements, Douglas *et al.* have made only two sets of measurements that may be termed as *complete*. By the word *complete* we mean that the authors themselves have analysed both POK1 as well as POK2 *P*-wave data for these stations. These two are the array stations, viz. EKA and YKA. However, it may be noted that log A/T value (0.9) computed by Douglas *et al.* for POK2 using EKA data differs from that of pIDC estimate (1.0). Nevertheless, if we consider these two array station estimates only, the average m_b difference is obtained as 0.45. Further, if we include the estimate of another *complete* analysis from Sikka *et al.*[3] (ignored by Douglas *et al.*) corresponding to GBA array data ($\Delta m_b = 0.5$), then the average m_b difference from three array stations turns out as 0.47. This m_b difference corresponds to a yield of 55 kt for POK2. It may be emphasized here that the array stations have the capability of enhancing signal-to-noise ratio considerably and therefore the Δm_b estimates from array data are, in general, more reliable than those obtained from single stations. Further, it may be noted that *these are the only three complete sets of estimates which were analysed by Douglas et al. and Sikka et al.*[3] *prior to this note*. Incidentally, now we have estimated Δm_b value at Hyderabad, India also. The estimate is 0.46 *and not 0.3* as reported by Douglas *et al.* Three array stations and Hyderabad data give the same average Δm_b value of 0.47, which corresponds to the yield of 55 kt.

Now, if one wants to include all the reported data, then it calls for a systematic statistical analysis after duly incorporating necessary correction terms, primarily to ensure the reliability of the reported values. It needs to be emphasized here that seismic waves are not pure sinusoids of a given frequency. They comprise significant amplitudes in the frequency band 0.5–10.0 Hz and hence it is necessary that correction terms be estimated from synthetic seismograms as presented earlier by Sikka *et al.*[2]. The conclusion of Douglas *et al.* that corrections for frequencies ≥ 5 Hz are only significant, cannot be accepted without proof. Further, it may be stressed that the destructive interference is not required to be *optimum* for the small magnitude corrections relevant to this study. We have incorporated necessary correction terms for the additional data of Douglas *et al.* and shown the corrected Δm_b values in Table 2. It is observed that for thirteen stations, the average Δm_b value is 0.44 and shows less scatter (standard deviation, SD = 0.09) than the uncorrected values of Douglas *et al.* (SD = 0.17). By confining to the data within one standard

Table 1. Log A/T and yield estimates of POK2 (modified table of Douglas *et al.*)

Station	Log(A/T) POK1	Log(A/T) POK2	Diff. of m_b Δm_b	Yield of POK2 (kt) for POK1 : 12–13 kt
HYB	1.7	2.0	0.3	30–33
NUR	1.1	1.3	0.2	22–24
KEV	1.4	1.8	0.4	41–44
GRF	1.1	1.5	0.4	41–44
HFS	1.3	1.6*	0.3	30–33
NBO/NB2	1.0	1.4	0.4	41–44
BNG/BGCA	1.6	1.8*	0.2	22–24
LOR	0.9	1.1	0.2	22–24
EKA	0.7*	0.9*	0.2	22–24
COL/COLA	1.1	1.7	0.6	76–82
PMR	1.0	1.5	0.5	56–60
YKA	0.8*	1.5*	0.7	103–112

Table 2. Δm_b values for thirteen stations used by Douglas *et al.*[1] and Sikka *et al.*[3].

Station	Distance (deg)	Azimuth (deg)	Δm_b of Douglas *et al.*	Δm_b with correction for Douglas *et al.*$	Δm_b of Sikka *et al.*	Δm_b + correction of Sikka *et al.*	Δm_b of Sikka *et al.* and Douglas *et al.*+
HYB	11.4	145	0.3	0.46@			0.46
NUR	46.2	330	0.2	0.40	0.2	0.4	0.40
KEV	49.9	341	0.4	0.40	0.4	0.4	0.40
GRF	51.1	313	0.4	0.40			0.40
HFS*	51.2	327	0.3	0.40			0.40
NBO/NB2	52.8	328	0.4	0.50	0.4	0.5	0.50
BNG/BGCA*	55.5	256	0.2	0.40			0.40
LOR	56.0	310	0.2	0.30			0.30
EKA*,&	59.7	321	0.2	0.20	0.3	0.3#	0.30
COL/COLA	83.4	16	0.6	0.60	0.6	0.6	0.60
PMR	85.8	18	0.5	0.50	0.5	0.5	0.50
YKA*,&	90.7	3	0.7	0.70	0.5	0.5	0.50
GBA	14.4	158			0.5	0.5	0.50
Average/SD			0.37 ± 0.17	0.44 ± 0.13	0.43 ± 0.13	0.46 ± 0.09	0.44 ± 0.09

Confining to the data within one standard deviation, the average Δm_b value is obtained as 0.45 ± 0.05 from the data of Sikka *et al.* and Douglas *et al.* (see column 8).

$Correction due to interference, wherever necessary. Correction terms for HFS and BGCA have been estimated using pIDC reported periods.

*Log(*A*/*T*) measured for POK2 as part of this study by Douglas *et al.* (see Table 1).

&Log(*A*/*T*) measured for POK1 as part of this study by Douglas *et al.* (see Table 1).

#Revised, using pIDC data. No correction is required for 1s period signal.

@For Hyderabad, India, Δm_b value between POK2 and POK1 is 0.46. It does not include any correction term.

+This includes Δm_b values as obtained from the data of HYB (present authors), eight stations of Sikka *et al.*[3] and remaining four stations, viz. GRF, HFS, BNG/BGCA and LOR of Douglas *et al.*[1].

deviation, the average Δm_b estimate is obtained as 0.45 (SD = 0.05) from ten stations, which is close to the earlier estimate of 0.46 by Sikka *et al.*[3]. The yield estimate from $\Delta m_b = 0.45$ is 52 kt and it is still consistent with the radiochemical yield estimate of POK2.

Douglas *et al.* make elaborate imaginary assumptions regarding geology, depth of burial, seismic coupling and position of water table and come out with several subjective conclusions regarding the yield of POK2. As they have no such data available to them, these conjectures have no relevance to the present analysis. Moreover, why should anybody expect such data to be declassified by India alone? We also fail to understand what do Douglas *et al.* mean by 'non-Indian yield estimates of ~ 12 kt'. The yield estimate of 46 kt obtained earlier by Evernden[17] was certainly not an Indian estimate. Finally, to conclude, we observe that whereas the seismic yield estimates of POK2 by Sikka *et al.*[2–4] and Roy *et al.*[5] based on *P*, *Lg* and regional Rayleigh wave data were consistent with the radiochemical estimates of the yield[4,8,9], the yield estimates of Douglas *et al.* obtained from surface and *P*-wave data showed large difference. Further, *the yield estimates of Douglas et al. based on P-wave data of individual stations showed large scatter.* To arrive at a definite conclusion from such data is highly subjective.

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Reply:

It should be clear to the general reader of the papers on the seismological estimation of the yield of the Indian nuclear tests of 1998 that these estimates are subject to large uncertainties – which is one of the purposes of our paper[1]. Despite what Sikka *et al.*[2] seem to believe, we set out to see what seismological evidence there is that the yield of 980511 is above about 20 kt, the upper bound of most non-Indian estimates and we hope we have given a fair assessment of the evidence. We are the only group outside India to make a plausible argument that the yield of 980511 could have been significantly greater than 20 kt. Sikka *et al.*[2] claim we should have pointed out that the range of estimates extends up to 110 kt, they do not however, point out that by the same argument it extends down to 22 kt. We do not wish to comment on the minutiae of the argument of Sikka *et al.*[2] on magnitude differences. If such an involved argument is required to arrive at a seismological estimate of yield, the estimate cannot be regarded as robust.

Sikka *et al.*[2] ask for, amongst other things, fuller explanations of our interpretation of M_s, and of how we reached the conclusion that the effects on m_b of interference between *P* from the two largest explosions of 980511 are negligible. This we are happy to do, but this will take more time and journal space than we have been allowed for this reply. We therefore intend to deal with the request of Sikka *et al.*[2] in a later paper. Perhaps however, we should emphasize that the M_s values reported by the NEIS (and used apparently by Evernden[3]) are measured from earthquake signals which are mistakenly associated with 980511.

One final point in this brief note; we are accused of making 'elaborate imaginary assumptions'. In the absence of any firm information we can only make assumptions based on the evidence we have. We do however, point out that they are assumptions and when drawing conclusions state that these are dependent on the assumptions being correct. We hope the assumptions are reasonable.

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