

Indian explosions of 11 May 1998: An analysis of global seismic bodywave magnitude estimates

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Seismic waves generated by the Indian explosions of 11 May 1998, showed large variations in the globally estimated body wave magnitudes (m_b). The estimated m_b values were in general smaller at the stations in east and west directions with respect to these sources than in the north direction. Synthetic seismograms demonstrate that such pattern is due to the cancellation and superposition of signals from these explosions separated in space by about 1 km. In view of this, the average m_b estimates of the International Data Center (IDC) at Arlington, USA ($m_b = 5.0$) and the US Geological Survey ($m_b = 5.2$) are smaller than the true m_b value. After taking into account the necessary corrections, a value of $m_b = 5.39$ is obtained as the global average. Gauribidanur array (GBA) seismogram showed anomalous PP/P amplitude ratio. After correcting for this anomaly, an estimate of $m_b = 5.4$ is obtained at GBA. The revised m_b estimate gives an average combined yield of 58 ± 5 kt.

At the Pokhran test site in Rajasthan, three nuclear explosions were detonated by India on 11 May 1998 at 1543 hours IST. These explosions were triggered simultaneously and comprised a thermonuclear device, a fission device and a subkiloton device emplaced in spatially separated shafts¹. These explosions (hereafter referred as POK-2) were fully contained from radioactive point of view and the seismic body waves and surface waves generated by these explosions were recorded by several regional and international seismic stations. A closer examination of these seismic observations revealed the following interesting facts:

A plot of body wave magnitude (m_b) estimates of POK-2 from 51 global stations, as reported by the International Data Center (IDC), Arlington, USA, as a function of epicentral distance (Figure 1) together with that of the Gauribidanur array, India (GBA) shows large variations in the measured m_b values (4.1 to 5.8). It can be easily deduced from Figure 1 that the maximum to minimum P wave amplitude ratio for POK-2 at a given distance is about 30, which is thrice as large compared to that for other underground explosions².

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When the above global magnitude estimates are plotted as a function of event azimuth (Figure 2), it is seen that the stations between 340° and 20° azimuth (distance ranging from 28.51° to 94.62°) with respect to the POK-2 site in general showed higher m_b values than the stations located in the eastern or western directions. Adequate data from southern direction were not available as this region happened to be oceanic. This observed magnitude pattern is shown, below, to be consistent with the source geometry of POK-2.

The average m_b value reported by the IDC is 5.0, while the US Geological Survey (USGS) reported the m_b as 5.2 and the surface wave magnitude (M_s) as 3.6. This M_s value is the same as that measured from the Bhabha Atomic Research Centre's stand alone seismic station at Jodhpur¹. Figure 3 shows a plot of M_s versus m_b for two population of events, viz. earthquakes and explosions together with those of POK-2 in order to have a comparison of these estimates. It is seen that the USGS estimate falls close to the explosion population on this plot whereas the IDC estimate lies in between the two populations, indicating that the estimated average m_b may be lower than the true value.

On Gauribidanur array (GBA) seismogram (Figure 4), it is seen that the amplitude to period ratio of the PP phase for POK-2 is about 1.5 times that of the P phase.

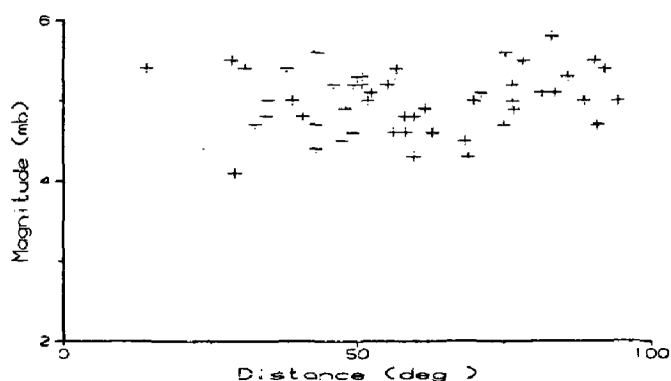


Figure 1. A plot of the epicentral distance versus m_b values corresponding to 51 global stations as reported by the IDC for POK-2. Gauribidanur array estimate is also included.

This anomalous behaviour, which was also observed for the Indian explosion of 1974 (hereafter referred as POK-1), indicates that the P phase from Pokhran region undergoes much more attenuation compared to PP phase while traveling to GBA.

The first three of these observations may be attributed to the modification of the body-waves due to the time

delays introduced by the physical separation of the two large explosions of POK-2 (their shafts were located 1 km apart in east-west direction) which varied from 0.0 s to about 0.125 s. Thus, minimum time delay would be in the north and south directions with respect to POK-2 while maximum delay would be in the east and west directions. With the help of synthetic seismograms it will be demonstrated in the next section that the resultant amplitude of two explosions reduces from a maximum true value to a minimum value as the delay is varied from 0.0 s to 0.125 s. However, time delays of this order do not effect the Rayleigh wave amplitudes as they have much larger periods in comparison to these delays³. With the help of the observed global data and synthetic seismograms, this paper aims to (i) highlight the effect of multiple explosions on global seismic magnitude estimates and (ii) obtain a realistic estimate of combined yield of these explosions.

Synthesis of teleseismic signals corresponding to POK-2

The synthesized explosion waveform, $O(\omega)$, in the frequency domain is obtained as

$$O(\omega) = S(\omega)D(\omega)M(\omega)R(\omega)I(\omega), \quad (1)$$

where ω is the angular frequency, $S(\omega)$ is the source function⁴, $D(\omega)$ is the source crust function, $M(\omega)$ is the mantle transfer function⁵, $R(\omega)$ is the receiver crust function and $I(\omega)$ is the broad band seismograph response function. Fourier inverse transform of $O(\omega)$ gives the synthetic explosion seismogram $Y(t)$. Composite seismo-

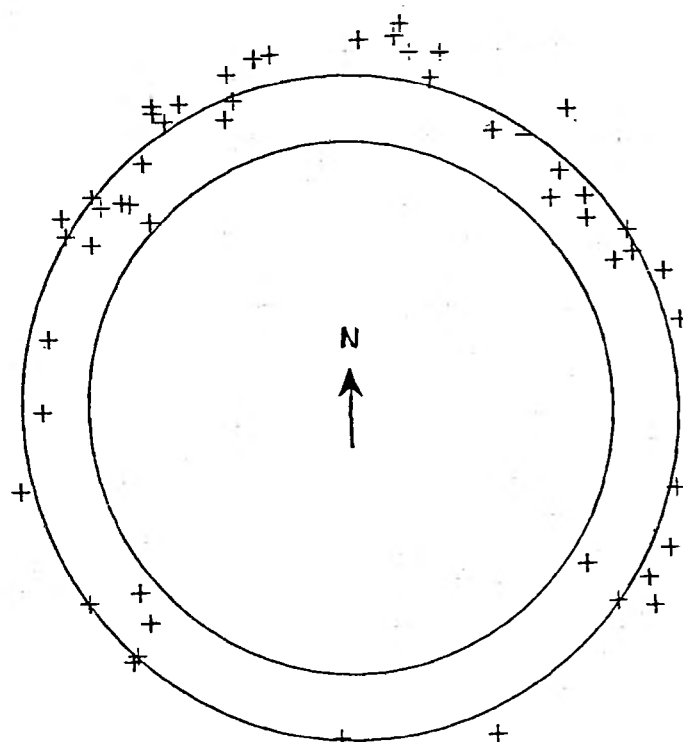


Figure 2. Azimuthal plot of m_b values of Figure 1. Outer circle has radius $m_b = 5.0$ whereas inner circle corresponds to $m_b = 4.0$.

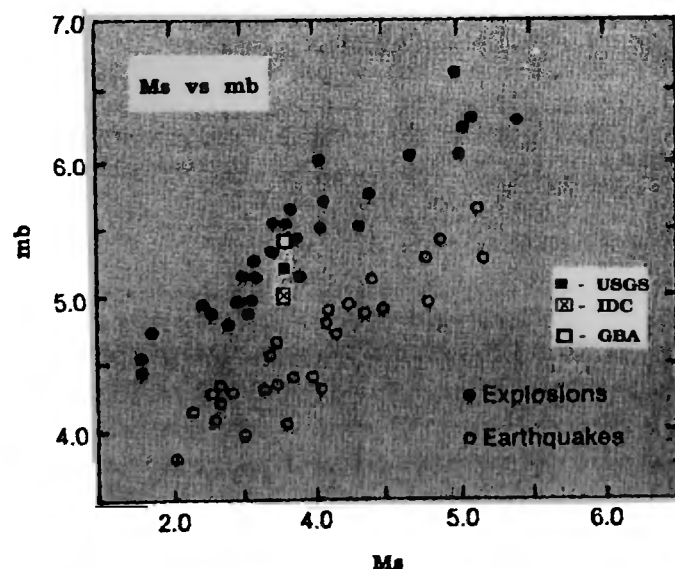


Figure 3. The magnitude estimates of IDC, USGS and GBA on M_s - m_b plot of some earthquakes and explosions¹⁷.

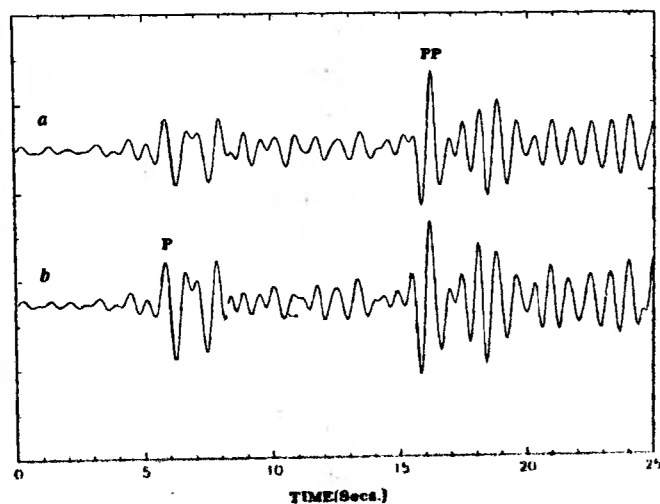


Figure 4. Beamed waveforms of GBA filtered data (0.6-2.0 Hz) corresponding to PP (trace a) and P (trace b) phases. It is seen that the amplitude ratio of PP/P phase in trace a is larger than that in trace b.

gram, $Z(t)$, corresponding to two explosions with amplitude ratio r is obtained as

$$Z(t) = rH(t - tp)Y(t - tp) + H(t - tp - \tau_1)Y(t - tp - \tau_1), \quad (2)$$

where $H(t)$ is the Heaviside function, tp is the travel time of the P wave at a given epicentral distance and τ_1 is the time delay between the two P arrivals which depends primarily on the azimuth of the recording station and apparent phase velocity of the P wave. For the two large explosions of POK-2 with yield ratio 3:1 (determined by close-in ground shock measurements), the value of r is 2.33 (see eq. (3)).

The effect of anelastic attenuation for a signal frequency f is given by $\exp(-\pi f t^*)$ where t^* is the ratio of the travel time to the average Q on the path from source to receiver. For paths from Nevada Test Site, USA, which lies in an orogenic belt to stations in high Q regions t^* is estimated⁶ to be 0.35 s–0.45 s. Further, beneath stable aseismic regions attenuation is expected to be lower than the orogenic regions⁷. In view of the above as well as to match the observed signal periods at various stations, we have used t^* values of 0.4 s and 0.5 s for synthesizing the broad band seismograms at teleseismic distances (3000–10000 km). Figures 5 and 6 show the synthesized waveforms corresponding to $t^* = 0.4$ s and 0.5 s respectively for various time delays τ_1 . For the minimum delay, i.e. $\tau_1 = 0.0$ s, the waveforms

interfere constructively (this is expected in the north and the south directions) while for the maximum delay, $\tau_1 = 0.125$ s (obtained by taking an average value of 12 km/s for apparent phase velocity and accounting for some scatter in the delays due to anisotropy and heterogeneities in the source region), they show cancellation effect. The ratio of A/T (where A and T are signal amplitude and period respectively) for maximum and minimum time delays for t^* value of 0.4 s is obtained as 1:2 (see Figure 5) whereas the same for $t^* = 0.5$ s is 1:1.76 (see Figure 6). These reductions in the values of A/T correspond to deviations of -0.30 and -0.25 respectively from the true m_b value. Deviation in m_b corresponding to a t^* value of 0.3 s is found as -0.46 . Thus some of the worldwide m_b values may be underestimated up to these amounts.

Anomalous amplitude ratio of P and PP phases at GBA

The medium aperture seismic array at Gauribidanur, GBA, has 20 short period seismometers arranged along two perpendicular arms. The digital data at GBA are sampled at a rate of 20 per second for each sensor. More details and design characteristics of GBA are available elsewhere⁸. Short period seismograms at GBA pertaining to POK-2 show PP/P amplitude ratio close to 1.5. Similar feature was observed for POK-1 also.

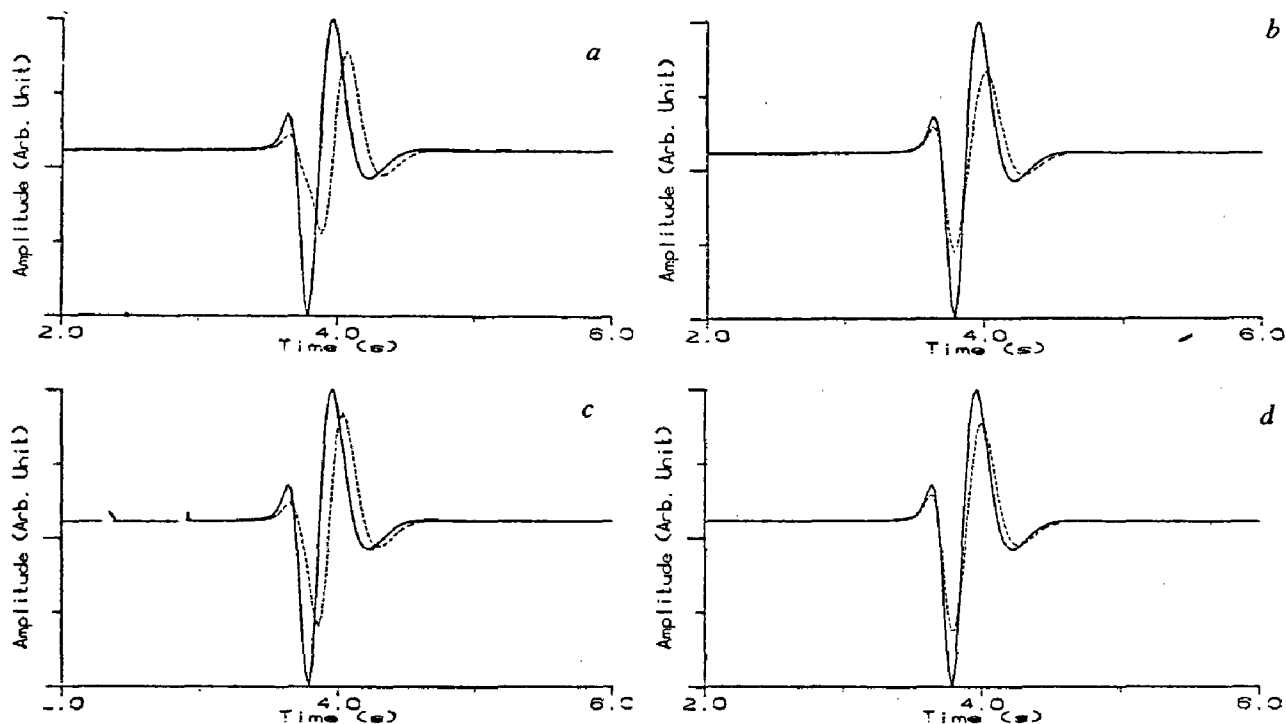


Figure 5. Synthetic broad band seismograms for $t^* = 0.4$ s. Waveforms with continuous line represent zero time delay superposed signals. In (a), broken line corresponds to synthesized signal for the eastern direction with respect to POK-2 for a time delay $\tau_1 = 0.125$ s whereas in (b) it is for the western direction. c is same as (a) for $\tau_1 = 0.1$ s and (d) is same as (b) for $\tau_1 = 0.1$ s.

Figure 4 shows two array beams corresponding to POK-2 data at GBA, one tuned for the P phase with slowness 13.1 s/deg (trace b) and the other one for the PP phase with a slowness of 14.0 s/deg (trace a) for an azimuth of 332° with respect to GBA. A comparison of P/PP amplitude ratio in trace a with that in trace b reveals that P amplitude has reduced in comparison to the PP amplitude in trace a, thus confirming the second prominent phase as PP which is also in agreement with the arrival time of PP at GBA from POK-2.

A comparison of amplitude correction term $B(\Delta, h)$ (where Δ is the epicentral distance and h is the depth of the source) developed by Gutenberg⁹ for P waves with that for PP for various distance ranges¹⁰ reveals that the reduction in amplitudes of P and PP phases at a given distance due to the geometrical spreading is comparable. However, the PP phase undergoes an additional attenuation due to the reflection at the free surface. The epicentral distance of GBA from the POK-2 site is 14.4°. The PP phase should get attenuated by a factor of 2 as the reflection coefficient¹¹ for this distance is around 0.5. Thus, after accounting for the reflection coefficient, the net PP to P ratio should be around 0.5. However, the observed PP/P amplitude ratio is about 1.5. From this observation, it is inferred that the P wave from POK-2 has undergone much more attenuation than what is accounted by $B(14.4, 0.0)$ value. In view of this, it becomes essential to include a correction term in the body wave magnitude relation to account for the

additional attenuation of P wave amplitude by a factor of 3 (obtained by comparing observed and theoretical values of P/PP amplitude ratio) for this path. With the inclusion of this term, the m_b estimate at GBA is obtained as 5.4. It may be noted that GBA is situated at an azimuth of 157° with respect to the test site, therefore the signals from POK-2 interfere constructively giving the true m_b value of 5.4.

Revised magnitude estimate from global data

As pointed out earlier, the IDC through its reviewed event bulletin announced the average m_b for POK-2 as 5.0 whereas the m_b estimate of USGS was 5.2. As shown above, with the help of synthetic seismograms we have demonstrated that the m_b of POK-2 as seen globally will vary between a true value, when observed from the perpendicular direction with respect to the line joining the two large explosions, and a minimum value when observations are made parallel to this line. However, there could be some effect on this value due to anisotropy. Signals from two explosive sources when superposed give the true m_b as the maximum value whereas any time delay between them will result in partial cancellation of the amplitudes leading to lower m_b values. Due to this a large number of global stations could have underestimated the true m_b .

In view of the above, to obtain a true estimate of m_b from global data it will be reasonable to consider

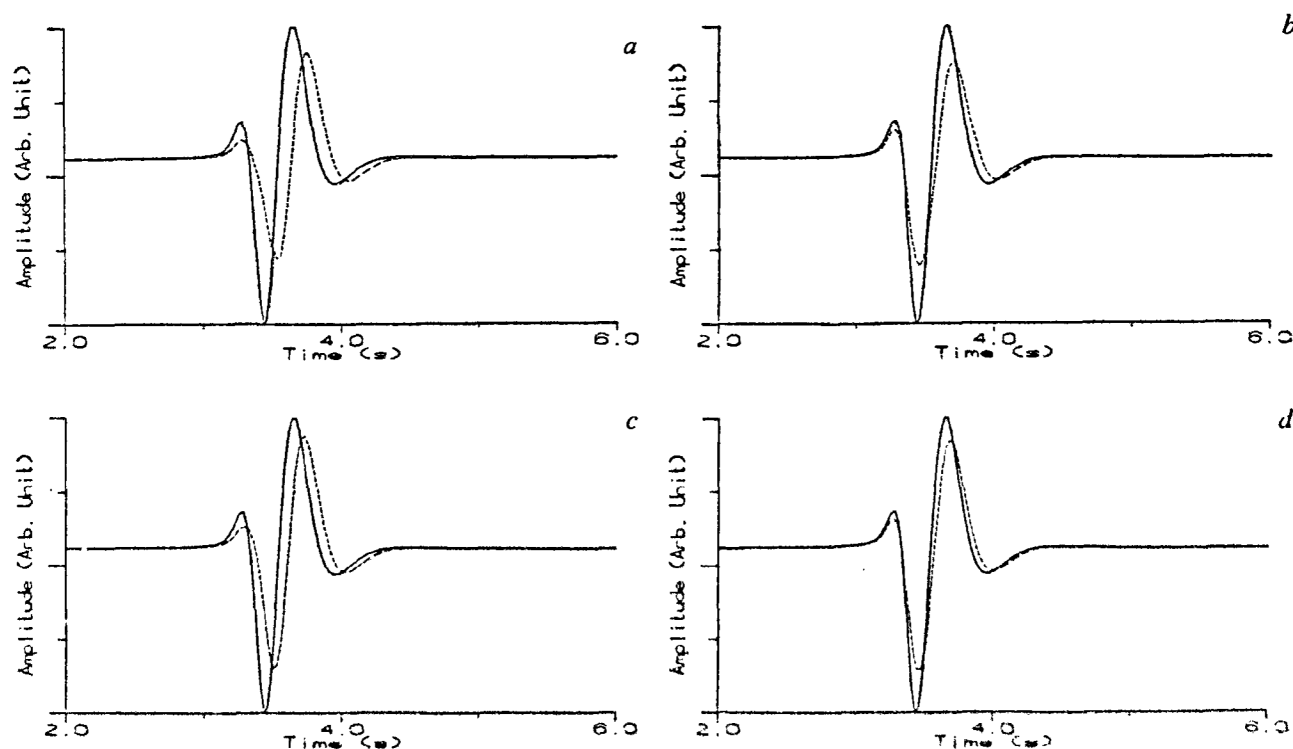


Figure 6. Synthesized broad band seismograms for $t^* = 0.5$ s. Nomenclature is same as in Figure 4

only those data which are available from the perpendicular directions with respect to the line joining the sources because only such data will be composed of superposed signals ($t_1 \sim 0.0$ s). Using data from 12 such stations, 10 in the north between azimuth 340° and 20° and two in the south including GBA (Table 1), the average m_b is obtained as 5.36. However, it may be noted that MAW station showed a very small signal to noise ratio (SNR) for POK-2. At such low SNR values, estimation of true signal amplitudes is likely to be less accurate. An estimate of m_b using eleven stations data after excluding that of MAW gives an average value of m_b as 5.39, which is in good agreement with the m_b estimate of GBA discussed in the previous section. On the (M_s, m_b) plot (Figure 3), the point (3.6, 5.4), corresponding to our estimates, falls well within the explosion population.

It may be interesting to point out here that for the Pakistan nuclear explosion of 30 May 1998, the stations between 340° and 20° azimuth with respect to POK-2 having similar azimuths and epicentral distances for Pakistan test site, gave an average m_b value of 4.46

Table 1. Magnitude estimates from stations between azimuth 340° and 20° for POK-2

Station	Distance ($^\circ$)	Azimuth ($^\circ$)	SNR	m_b
ZAL	28.51	16.2	27.8	5.5
ARU	30.83	345.7	10.6	5.4
NRIS	43.05	8.5	191.1	5.6
ARCES	50.16	340.7	182.6	5.3
SPITS	56.81	348.3	190.0	5.4
SFJ	76.79	340.1	7.7	4.9
INK	83.08	9.2	374.1	5.8
ILAR	83.65	15.6	157.0	5.1
YKA	90.60	3.0	238.0	5.5
DLBC	92.89	11.3	32.5	5.4
MAW	94.62	183.4	2.9	5.0

Table 2. Yield versus M_b for some announced USA PNE tests in hard rocks¹²

Event	Medium	Yield (kt)	m_b
Aardvark	Tuff	38	4.55–4.9
Antler	Tuff	2.6	4.03–4.7
Blanca	Tuff	22	4.8
Chartreuse	Rhyolite	70	5.15–5.22
Discuss thrower	Tuff	21	4.73
Duryea	Rhyolite	65	5.17
Gasbuggy	Shale	29	4.53–4.81
Handear	Dolomite	12	4.19–4.7
Hardhat	Granite	4.8	4.15–4.9
Knickerbucker	Tuff	71	5.14–5.54
Logan	Tuff	5.1	4.4
Piledriver	Granite	56	5.53–5.56
Platte	Tuff	1.85	3.44
Rainer	Tuff	1.08	4.1
Rex	Tuff	16	4.8
Scotch	Tuff	150	5.51
Shoal	Granite	12.2	4.62–4.9

Yields were obtained by radio chemical analysis.

which is less by 0.14 compared to the average global $m_b = 4.6$ reported by the IDC. This confirms that the higher average m_b estimate obtained from these stations for POK-2 was less dependent on the path effects and was mainly due to the source geometry of POK-2.

Estimation of the yield using m_b -yield regression relations

The details of the m_b and medium properties of 17 peaceful nuclear explosions conducted at various locations in USA with precisely known yields from radio-chemical estimates are listed¹² in Table 2. Using the well known form of the relation between m_b and yield, viz.

$$m_b = C1 + C2 \log(Y), \quad (3)$$

the data points of Table 2 are fitted to estimate the constants C1 and C2. Y is the yield in kilotons. The regression constants C1 and C2 are estimated for average values of m_b and the spreads in these constants are estimated by fitting maximum and minimum m_b values to the known yields. The values of C1 and C2 obtained by least square fitting this data are 3.8 ± 0.15 and 0.77 ± 0.05 respectively. It is well known that the value of C1 depends on the site geology and its value is ~ 4 for hard rock formations like granite and is ~ 3.3 for alluvial basins¹³. From the literature it is seen that constant C2 varies¹⁴ between 1.0 and 0.6. For Nevada test site and Novaya Zemlya its values are 0.81 and 0.75 respectively¹⁵. In order to estimate the site-specific constant C1 for Pokhran, the known yield of 13 kt for

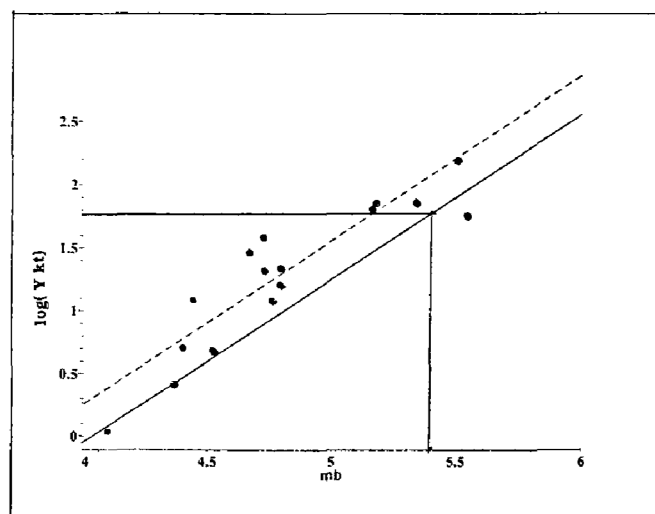


Figure 7. Regression fitting of m_b versus yield for some US explosions¹². The yields of these explosions are estimated by radio chemical methods. The dotted curve gives average fit for the US region and the solid curve gives the fit for the Pokhran region.

POK-1 (estimated from the surface wave data at Quetta¹⁶), an yield exponent $C2 = 0.77 \pm 0.05$ obtained from the above data fit and an average m_b of 4.9 for POK-1 as reported by the International Seismological Centre, UK, are used in eq. (3). The value of $C1$ for Pokhran region found from this analysis is 4.04 ± 0.04 . The estimated yield of POK-2 for an $m_b = 5.4$ using the values of $C1 = 4.04$ and $C2 = 0.77$ turns out as 58 kt (see Figure 7) with a spread of ± 5 kt. This is close to the value of 60 kt, estimated from a preliminary analysis¹. It may be noted that the fitted constants for US tests (see broken line in Figure 7) give an yield of 120 kt for $m_b = 5.4$.

Conclusions

Large variations in the estimated global magnitudes ranging between 4.1 and 5.8 were observed for POK-2. Further, it was seen that the amplitudes recorded at stations having similar distances from the explosion site varied up to a factor of about 30, which was thrice as larger than what is normally expected. Stations located in the eastern and western direction from the POK-2 site, in general, recorded lower magnitudes compared to those situated in the north. With the help of synthetic seismograms it is shown that the observed global m_b pattern was consistent with the source geometry. In view of such a pattern, averaging of the global m_b estimates will result in an underestimation of the true m_b value. Therefore, in order to obtain a realistic value of m_b , estimates from eleven stations comprising ten from the north between azimuth 340° and 20° and GBA m_b value of 5.4 have been used. The average m_b obtained by this process is 5.39. Using the revised m_b value of 5.4, the combined yield of POK-2 is obtained as 58 ± 5 kt, which is very close to the preliminary estimate¹.

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