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

S. K. Sikka*, Falguni Roy and T. K. Basu

Seismology Division, Bhabha Atomic Research Centre,
Mumbai 400 085, India

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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*For correspondence. (e-mail: sksikka@magnum.barc.ernet.in)

event by the National Earthquake Information Center (NEIC), International Seismological Centre (ISC), etc. is the average of the magnitudes determined at many seismic stations around the world.

The seismic yield of a nuclear explosion is calculated from an empirical relation:

$$m = C_1 + C_2 \log Y,$$

where C_1 and C_2 are constants, m is the event magnitude and Y is the yield in kt. For m_b vs Y relationship it is well known that C_1 is a test site-dependent constant, while C_2 varies in a narrow range around 0.8. For example, for explosions in former Soviet Union, the m_b–Y relation is[1]

$$m_b = 4.45 + 0.75 \log Y, \tag{1}$$

and for the Nevada test site (NTS) in USA[2] it is

$$m_b = 3.92 + 0.81 \log Y. \tag{2}$$

The variation in C_1 values from region to region has been attributed to geological differences between test sites which include explosion-site geology, source-region crust, upper-mantle composition, etc. These differences can introduce changes in m_b by several tenths of a magnitude unit. An explosion in Shagan River test site (SRTS), eastern Kazakh for which the eq. (1) is valid will record a magnitude of about ~ 0.5 higher than an explosion of same yield in the NTS (eq. (2)). This difference in the m_b values is the so-called m_b-bias between the nuclear testing sites[3]. Lack of attention to this fact led to the overestimation of the yields of Soviet tests, and to incorrect conclusions of the Soviet exceeding the threshold test-ban treaty limit of 150 kt (ref. 3). Large-scale regional variations in the properties of the earth's crust and upper mantle are the primary cause of such body-wave magnitude bias.

The wavelengths of surface waves, on the other hand, are considerably larger than those of the *P*-waves, and therefore they are less influenced by small-scale heterogeneities at the test site and also along the wave path. Many M_s–Y relations available in the literature give almost the same yield for a given M_s value. For example, for explosions in hard rock anywhere, Evernden and Marsh[3] gave a relation

$$\log Y = 0.762\, M_s - 1, \tag{3}$$

and Murphy[4] provided the same for tuff rock medium at NTS as

$$\log Y = 1.19\, M_s - 2.55, \tag{4}$$

and

$$\log Y = 0.75\, M_s - 0.90, \tag{5}$$

for explosions with yields less than 100 kt and greater than 100 kt respectively.

Till now, at the Pokhran test site in Rajasthan, India, six underground nuclear tests have been carried out, one on 18 May 1974 (POK1) and five during 11–13 May 1998. Three of the latter five explosions were detonated simultaneously on 11 May (POK2) and the remaining two on 13 May 1998. Regional stations in India and many stations around the globe recorded the seismic signals from both POK1 and POK2. Some seismologists[5–7] have used the parameters of SRTS (eq. (1)) as representative for Pokhran site and estimated the yield of POK2 as 10–15 kt while Sikka *et al.*[8,9] used Δm_b values for POK2 and POK1 from 13 common stations with a small interference correction for simultaneous explosions, and arrived at a yield of ~ 60 kt. The latter estimate has been confirmed by radio-chemical methods[10]. Further, the average M_s value of 3.56 for POK2, determined from signals recorded at regional stations[11], provided the yield values of 49 and 52 kt using eqs (3) and (4) respectively. This implies that there is a significant magnitude bias between events in Pokhran site and SRTS. In this communication, we have determined the magnitude bias by a procedure similar to the one used by Evernden and Marsh[3] for the Soviet and US test sites.

For a given site, it is expected that the m_b vs Y and M_s vs Y relation should give similar yield estimates. Thus, by equating log Y values in (m_b, Y) and (M_s, Y) relations, one should get a self-consistent m_b–M_s relation for a given site (see e.g. Fisk *et al.*[12]). One can also fit m_b–M_s observations from explosions at a given site. By a least squares fit to data given by Stevens and Murphy[13], we obtained the following m_b–M_s relations for SRTS and NTS respectively.

$$m_b = 0.5\, M_s + 3.89, \tag{6}$$

$$m_b = 0.58\, M_s + 3.23. \tag{7}$$

These relations are very close to those obtained from eqs (1) and (3), and eqs (2) and (3) respectively, after eliminating log Y. In Figure 1, we have drawn these lines for SRTS and NTS along with the m_b–M_s data. For a given M_s value, the difference between SRTS and NTS m_b values is ~ 0.45, which is identical to the m_b-bias value between the two sites determined earlier by Evernden and Marsh[3]. Before proceeding to find out the bias between Pokhran and SRTS sites, we first present a brief account of the m_b and M_s estimates of POK1 and POK2 explosions.

For POK1, NEIC has listed the $<m_b>$ value of 5.0 based on data from 11 stations, and ISC has given $<m_b>$ of 4.9 from 14 observations. Nair[14] determined $M_s = 3.19$ from the data of Quetta station ($\Delta = 5.2°$) in Pakistan, whereas Marshall *et al.*[15] gave $<M_s> = 3.2$ from three observations. This value was accepted by Bache[16] in his analysis of M_s vs Y for explosions in different parts of the world. So, we adopt $m_b = 5.0$ and $M_s = 3.2$ for our analy-

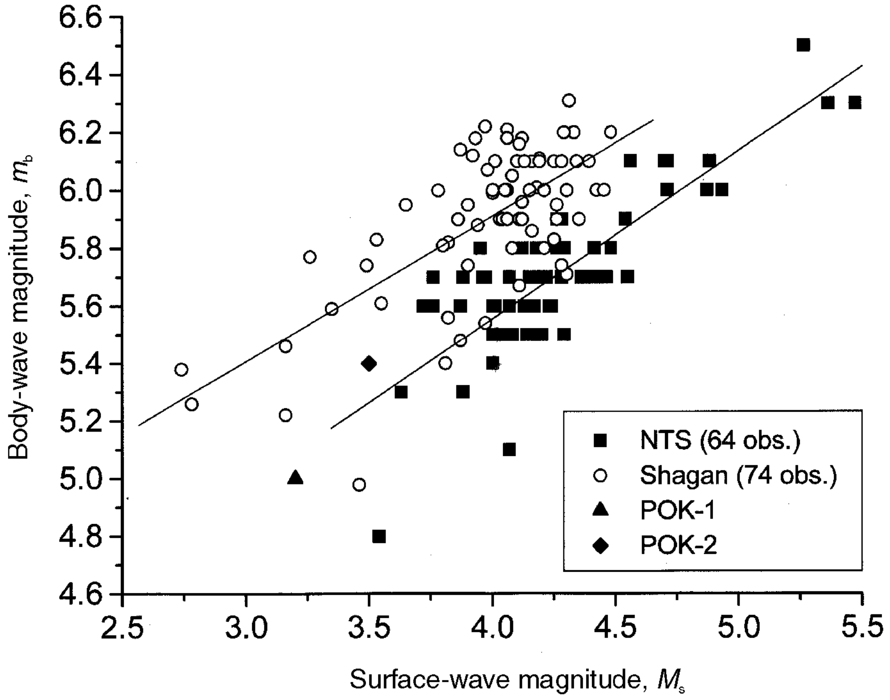

Figure 1. Plot of M_s vs m_b estimates for the nuclear explosions in NTS and SRTS. Data are taken from Stevens and Murphy[13].

Table 1. m_b values for POK2 given by different seismic data centres

Centre	m_b	Station
NEIC	5.2	99
MOS	5.4	36
EIDC	5.0	51
ISC	5.1	149

sis. This pair of m_b–M_s values for POK1 is also plotted in Figure 1.

Table 1 shows the $<m_b>$ values for POK2 as given by different seismic data centres around the world.

Douglas *et al.*[17] have argued that the estimate of $m_b = 5.2$ is more appropriate as there is an attenuating path between the Pokhran site and stations to the north of India. Similarly, Evernden[18] also obtained $m_b = 5.2$ by considering data from stations at low elevations. However, Sikka *et al.*[9] pointed out that a correction to the above m_b value is required to account for the interference effect, as the POK2 explosions were carried out simultaneously. A revised value of $m_b = 5.4$ was subsequently assigned to POK2 based on the following additional observations:

(1) The average Δm_b difference between POK2 and POK1 has been determined by Douglas *et al.*[17] as 0.37 using data from 12 stations. Sikka *et al.*[9] applied a small correction of 0.07 to it, in order to account for the interference effects. This makes the estimate of $m_b(\text{POK2}) = m_b(\text{POK1}) + 0.37$ or $0.44 \sim 5.4$.

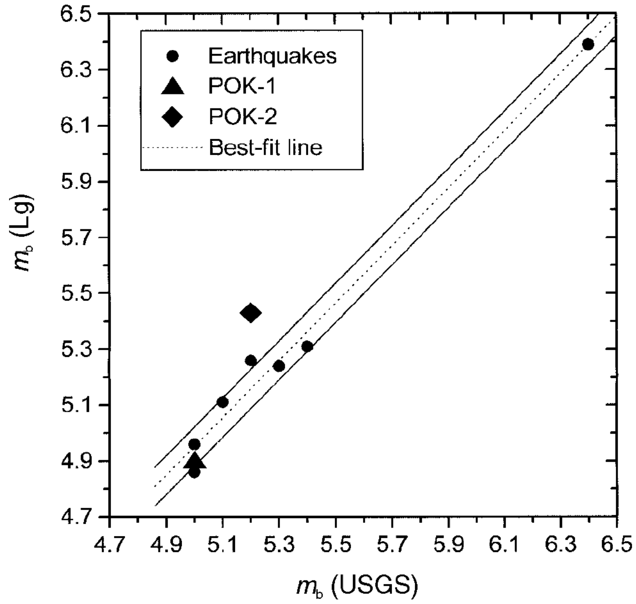

Figure 2. Comparison of m_b(USGS) and m_b(Lg) estimates of Indian earthquakes having magnitude ≥ 5.0. Estimates of POK1 and POK2 are superimposed. The best-fit line and ± 1 standard deviation lines are also shown. POK2 estimate is the only one that shows large deviation from the best-fit line, indicating that m_b(USGS) estimate of POK2 is an underestimate.

(2) Roy *et al.*[11] estimated m_b(Lg) of POK2 from regional data as 5.47, which is in excellent agreement with the RMS-based m_b(Lg) estimate of 5.43 obtained by Bhadauria and Roy[19], using a relation

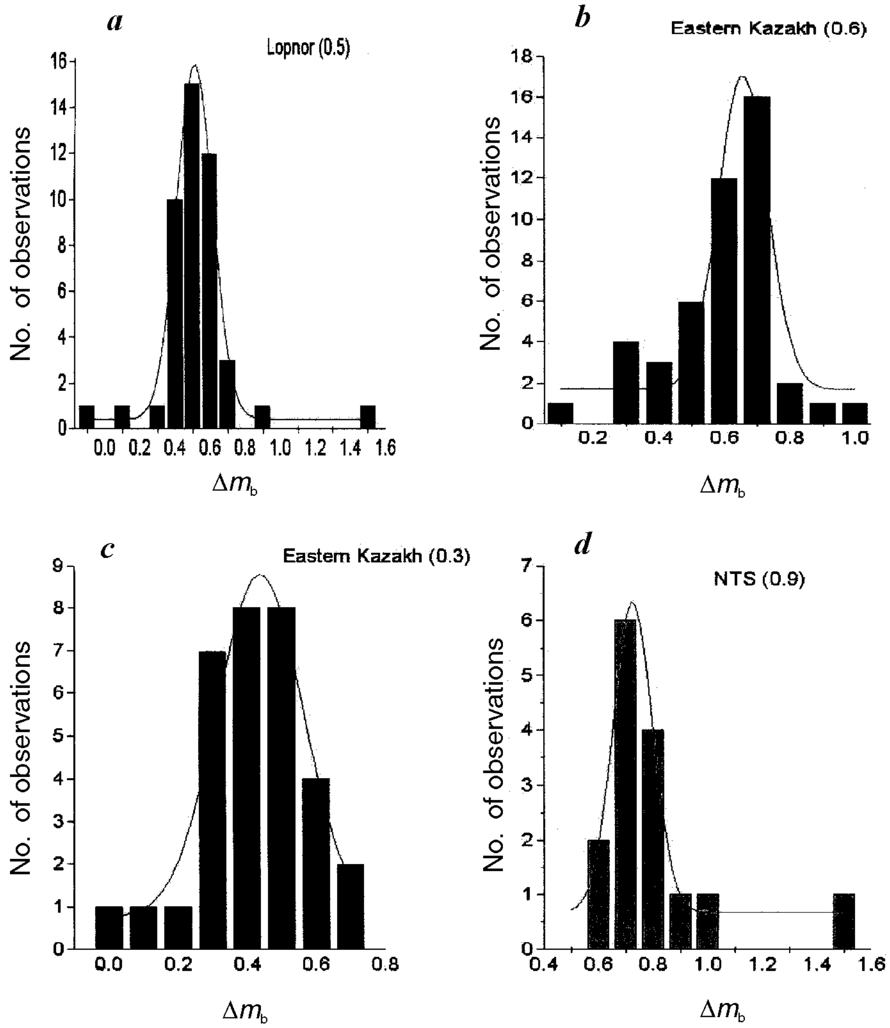

Figure 3. Plot of Δm_b values (at all available common stations) with number of observations corresponding to a pair of explosions at a given site. The USGS estimated Δm_b values for each pair of events are given in parentheses. Plots are generated from the body-wave magnitude data of (***a***) Lopnor events of 5 October 1993 and 26 May 1990; (***b***) Eastern Kazakh events of 8 July 1989 and 2 September 1989; (***c***) Eastern Kazakh events of 8 July 1989 and 29 June 1977, and (***d***) NTS events of 25 July 1990 and 31 August 1978.

based on RMS value of Lg waves. For seven Indian earthquakes with m_b(NEIC) ≥ 5.0, a linear fit between NEIC m_b values and m_b(Lg) estimates using RMS values gave a relation $m_b(\text{Lg}) = m_b\ (\text{NEIC}) \pm 0.07$ (ref. 19). Considering the excellent match between m_b(NEIC) and m_b(Lg) for eight events, including POK1 (see Figure 2), it is concluded that $m_b = 5.2$ for POK2, which is the only value showing relatively larger deviation from the mean, is an underestimate. Further, the Lg amplitude ratio of 3.7 between POK2 and POK1 gave a Δm_b(Lg) value of 0.57 between the two events[11], which is consistent with the Δm_b value between POK2 and POK1.

(3) In order to highlight the interference phenomenon, we have carried out another exercise as follows. We have selected several explosions randomly from SRTS, Lopnor and NTS sites. For a pair of explosions from a given site, we have estimated Δm_b values at all available common stations. Figure 3 shows four such plots between Δm_b values and the number of observations (we have shown only a few cases, but have studied several). It has been observed that these Δm_b values and the number of observations followed a Gaussian distribution with maximum number of observations around the mean, which is the most likely Δm_b value between the two events. Ideally, one should get identical estimates of Δm_b at all the common stations, since all the relevant parameters between the source and the receiver remain more or less constant. However, in practice there could be some random errors associated with the actual estimates, which will make the distribution a

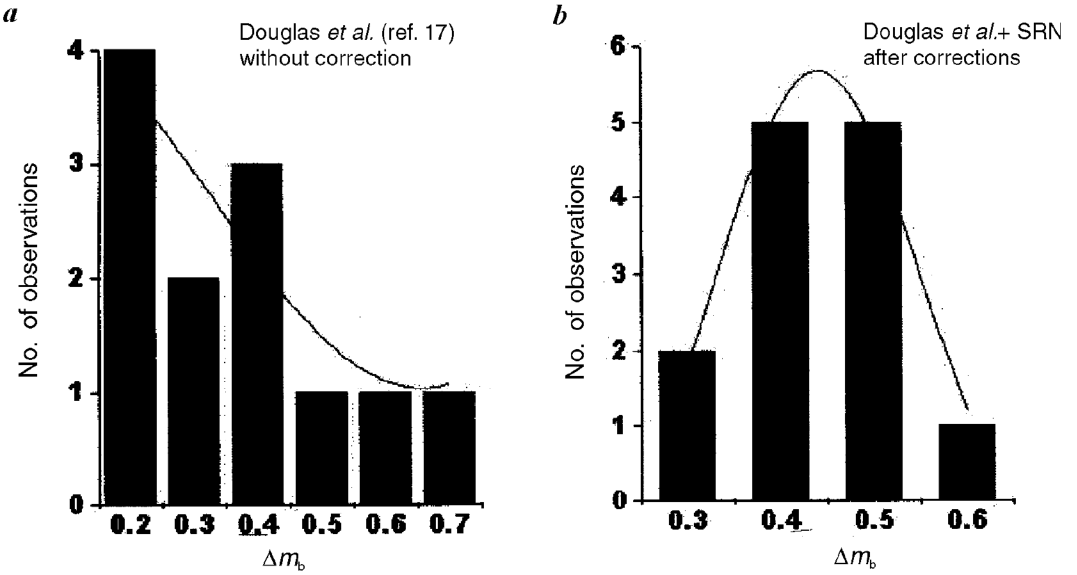

Figure 4. Common station Δm_b estimates of (*a*) Douglas *et al.*[17] corresponding to POK2 and POK1 showing one-sided distribution; and (*b*) Between POK2 and POK1 showing a Gaussian distribution after incorporating appropriate corrections to the data of Douglas *et al.*[17] (see Sikka *et al.*[9], SRN).

Table 2. Surface-wave magnitude estimates of POK2 from IRIS data

Station	Distance (°)	Azimuth (°)	Log$(A/T)_{max}$	M_s^{RP}
AAK	15.65	7.38	0.95	3.51
WMQ	21.05	33.49	0.77	3.46
KURK	24.15	10.63	0.74	3.49
BRVK	25.95	357.90	0.82	3.60
XAN	32.57	68.59	0.53	3.42
TLY	34.30	35.66	0.62	3.53
			Average →	3.50

$M_s^{RP} = \log(A/T)_{max} + 1/3\ \log(\Delta) + 1/2\ \log(\sin\ \Delta) + 0.0046\ \Delta + 2.370$, where $(A/T)_{max}$ is in nm/s.
RP, Rezapour and Pearce[22].

Gaussian one. This is evident from Figure 3 as well. When we subjected the POK2 data of Douglas *et al.*[17] to similar analysis (see Figure 4*a*), it showed one-sided distribution. Since the data of Douglas *et al.*[17] comprised only 12 observations, we picked up a pair of explosions from NTS region comprising only fifteen observations primarily to see the behaviour of these observations *vis-à-vis* data of Douglas *et al.*[17]. Unlike data of Douglas *et al.*[17], observations from the NTS explosions duly showed a Gaussian distribution (see Figure 3*d*). These observations prompted us to conclude that the data set of Douglas *et al.*[17] was not proper and required correction. After incorporating appropriate corrections to the data of Douglas *et al.*[17] (see Sikka *et al.*[9]), we found that the observations followed a Gaussian distribution (see Figure 4*b*), with a mean Δm_b of 0.44.

It is evident from the above observations that $m_b = 5.4$ for POK2 is a reasonable estimate.

For POK2, NEIC reported four teleseismic M_s observations with an average of 3.5, whereas ISC reported an average M_s of 3.8 based on five observations. At the regional distances ($\Delta < 2000$ km), Rayleigh waves in the period range of 3.5–7 s with high SNR were observed at several Indian stations. Nuttli's relation[20] gave an average M_s of 3.56 based on the data of six stations. Recently, Douglas *et al.*[17] argued that teleseismic M_s observations reported to NEIC were surface-waves from an earthquake north of Svalbard and not from POK2. Since we do not have access to the digital data from these stations, we cannot comment on the same. However, we have now analysed the data from some stations of the Incorporated Research Institutions for Seismology (IRIS). Using the Rayleigh waves with SNR > 3, we have obtained average M_s of POK2 as 3.5 (Table 2), which is the same as reported by the NEIC. From travel-time considerations, we find that at none of the stations listed in Table 2, the surface waves are due to Svalbard earthquake. We would like to point out here that data of NIL station gave $M_s = 3.53$ ($T = 8.0$ s), when Nuttli's relation was used. Interestingly, this is close to the M_s estimate of 3.56 from the data of six regional stations[11].

Thus, the m_b and M_s estimates of POK2 based on teleseismic data are obtained as 5.4 and 3.5 respectively. These values are also plotted in Figure 1 along with SRTS and NTS data.

Figure 1 shows that the (m_b, M_s) data for Pokhran explosions are nowhere near the Shagan River curve, but are closer to the Nevada test site curve; thus the use of Shagan River (m_b vs Y) relation for Pokhran site is not appropriate. For a given M_s, the m_b for SRTS event is ~ 0.4 magnitude units more than the m_b for Pokhran event. Although there are only two observations from the Pokhran site, the trend is easily seen.

It may also be pointed out that Sikka *et al.*[21] had earlier determined the value of $C_1 = 4.04$ for Pokhran and $C_2 = 0.77$, which is close to the C_2 value of eq. (1). This, together with the present analysis confirms that m_b-bias between SRTS and Pokhran sites is about 0.4 magnitude units.

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High-temperature studies on Mo–Si multilayers using transmission electron microscope

A. K. Srivastava*, P. Tripathi, M. Nayak,
G. S. Lodha and R. V. Nandedkar

Centre for Advanced Technology, Indore 452 013, India

In the present investigation we have carried out studies on thermally-induced phase transformations in Mo–Si multilayer. The microstructural characterizations were carried out on samples deposited on copper grids and heated *in situ*, using a transmission electron microscope. We have found that at temperatures above 400°C, the sample starts transforming to crystalline phase. Almost complete transformation of Mo–Si multilayer takes place at around 750°C to the Mo_5Si_3 phase.

SYNTHETICALLY produced multilayer structures made it possible to reflect energies in soft X-ray regions. The mirrors are fabricated using a high atomic number material and a low atomic number material alternately in a stack[1]. Molybdenum (Mo) and silicon (Si) are the most widely used materials for fabrication of mirrors for soft X-rays in the wavelength range of 13 to 30 nm, due to their high reflection efficiencies. The normal incidence reflectivity of a Mo–Si multilayer mirror is around 60% (refs 2–4). High brilliance soft X-rays incident on the multilayer produce high heat load, if not cooled, and may deteriorate the performance of these mirrors[5–8]. The rise in temperature sometimes may be as high as 900°C (ref. 7), so the multilayer structure must be highly heat-resistant in order to have good X-ray reflectance over the whole temperature range. The loss of reflectivity is related to the structural change in the multilayer structure. In the present investigation we have studied the effect of temperature (up to 750°C) on the structural changes in the multilayer fabricated using electron beam evaporation technique. The microstructural characterization was carried out using a transmission electron microscope (TEM). We have found that the formation of crystalline phase (Mo_5Si_3) starts at around 450°C and nearly complete transformation of phase takes place at 750°C, where Mo_5Si_3 and $MoSi_2$ phases form. The formation of Mo_5Si_3 phase was confirmed by high-resolution electron microscopy coupled with selected area diffraction pattern.

Mo–Si multilayer was deposited using an electron beam evaporation system[9] in ultra high vacuum environment at a base pressure of 2×10^{-9} mbar. The vacuum chamber was pumped using a turbomolecular pump and sputter ion pump combination, which contained three

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*For correspondence. (e-mail: sarvind@cat.ernet.in)