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 $M_{sp}$ is calculated using the curve of Rezoupor and Pearce to correct for the effect of epicentral distance.

<table>
<thead>
<tr>
<th>Station</th>
<th>$\Delta$ (s)</th>
<th>Quality</th>
<th>$A$ (nm)</th>
<th>$T$ (s)</th>
<th>$M_{sp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHM</td>
<td>15.28</td>
<td>A</td>
<td>88.33</td>
<td>17.2</td>
<td>3.26</td>
</tr>
<tr>
<td>AAK</td>
<td>15.65</td>
<td>A</td>
<td>116.27</td>
<td>16.0</td>
<td>3.42</td>
</tr>
<tr>
<td>TKM2</td>
<td>16.08</td>
<td>A</td>
<td>71.72</td>
<td>18.3</td>
<td>3.16</td>
</tr>
<tr>
<td>TLG</td>
<td>16.68</td>
<td>A</td>
<td>156.70</td>
<td>23.1</td>
<td>3.51</td>
</tr>
<tr>
<td>WMQ</td>
<td>21.05</td>
<td>B</td>
<td>95.78</td>
<td>17.6</td>
<td>3.52</td>
</tr>
<tr>
<td>VOS</td>
<td>25.65</td>
<td>A</td>
<td>70.77</td>
<td>21.8</td>
<td>3.29</td>
</tr>
<tr>
<td>ZRN</td>
<td>25.90</td>
<td>B</td>
<td>34.88</td>
<td>23.1</td>
<td>2.96</td>
</tr>
<tr>
<td>BRVK</td>
<td>25.95</td>
<td>A</td>
<td>84.27</td>
<td>22.5</td>
<td>3.35</td>
</tr>
<tr>
<td>CHTO</td>
<td>26.28</td>
<td>B</td>
<td>50.18</td>
<td>18.1</td>
<td>3.23</td>
</tr>
<tr>
<td>CHK</td>
<td>26.56</td>
<td>A</td>
<td>65.23</td>
<td>21.9</td>
<td>3.27</td>
</tr>
<tr>
<td>LZH</td>
<td>28.62</td>
<td>B</td>
<td>29.35</td>
<td>25.6</td>
<td>2.89</td>
</tr>
<tr>
<td>XAN</td>
<td>32.57</td>
<td>A</td>
<td>41.52</td>
<td>23.6</td>
<td>3.14</td>
</tr>
<tr>
<td>TLY</td>
<td>34.30</td>
<td>A</td>
<td>63.11</td>
<td>18.1</td>
<td>3.46</td>
</tr>
<tr>
<td>ULN</td>
<td>34.39</td>
<td>A</td>
<td>42.23</td>
<td>20.5</td>
<td>3.23</td>
</tr>
<tr>
<td>MIV</td>
<td>37.22</td>
<td>B</td>
<td>41.50</td>
<td>25.8</td>
<td>3.17</td>
</tr>
<tr>
<td>OBN</td>
<td>37.90</td>
<td>A</td>
<td>59.67</td>
<td>27.0</td>
<td>3.31</td>
</tr>
<tr>
<td>BJT</td>
<td>38.77</td>
<td>A</td>
<td>51.31</td>
<td>23.1</td>
<td>3.32</td>
</tr>
</tbody>
</table>

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. 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. (2006) ($M_s = 0.49 + 0.84\log Y$), 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 $M_s$ for 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 $m_s$ 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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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 \( \sim 0.5 \) 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 \( M_b-Y \) relations available in the literature give almost the same yield for a given \( M_b \) value. For example, for explosions in hard rock anywhere, Evernden and Marsh \(^4\) gave a relation

\[ \log Y = 0.762 M_b-1, \tag{3} \]

and Murphy \(^5\) provided the same for tuff rock medium at NTS as

\[ \log Y = 1.19 M_b-2.55, \tag{4} \]

and

\[ \log Y = 0.75 M_b-0.90, \tag{5} \]

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 \(^6\)–\(^8\) 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. \(^9\) used \( \Delta m_b \) values for POK2 and POK1 from 13 common stations with a small interference correction for simultaneous explosions, and arrived at a yield of \( \sim 60 \) kt. The latter estimate has been confirmed by radio-chemical methods \(^10\). Further, the average \( M_e \) value of 3.56 for POK2, determined from signals recorded at regional stations \(^1\), 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 \(^7\) for the Soviet and US test sites.

For a given site, it is expected that the \( m_b \) vs \( Y \) and \( M_e \) vs \( Y \) relation should give similar yield estimates. Thus, by equating log \( Y \) values in \( (m_b, Y) \) and \( (M_e, Y) \) relations, one should get a self-consistent \( m_b-M_e \) relation for a given site (see e.g. Fisk et al. \(^11\)). One can also fit \( m_b-M_e \) observations from explosions at a given site. By a least squares fit to data given by Stevens and Murphy \(^12\), we obtained the following \( m_b-M_e \) relations for SRTS and NTS respectively.

\[ m_b = 0.5 M_e + 3.89, \tag{6} \]

\[ m_b = 0.58 M_e + 3.23. \tag{7} \]

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 \( m_b-M_e \) data. For a given \( M_e \) value, the difference between SRTS and NTS \( m_b \) values is \( \sim 0.45 \), which is identical to the \( m_b \)-bias value between the two sites determined earlier by Evernden and Marsh \(^7\). Before proceeding to find out the bias between Pokhran and SRTS sites, we first present a brief account of the \( m_b \) and \( M_e \) 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 \(^13\) determined \( M_e \) = 3.19 from the data of Quetta station (\( \Delta = 5.2^{\circ} \)) in Pakistan, whereas Marshall et al. \(^14\) gave \( <M_e> = 3.2 \) from three observations. This value was accepted by Bache \(^15\) in his analysis of \( M_e \) vs \( Y \) for explosions in different parts of the world. So, we adopt \( m_b = 5.0 \) and \( M_e = 3.2 \) for our analy-
sis. This pair of $m_b$–$M_b$ 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.\textsuperscript{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\textsuperscript{16} also obtained $m_b = 5.2$ by considering data from stations at low elevations. However, Sikka et al.\textsuperscript{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 $\Delta m_b$ difference between POK2 and POK1 has been determined by Douglas et al.\textsuperscript{17} as 0.37 using data from 12 stations. Sikka et al.\textsuperscript{9} applied a small correction of 0.07 to it, in order to account for the interference effects. This makes the estimate of $m_b$(POK2) = $m_b$(POK1) + 0.37 or 0.44 ~ 5.4.

2. Roy et al.\textsuperscript{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 Bhaduria and Roy\textsuperscript{12}, using a relation.
based on RMS value of Lg waves. For seven Indian earthquakes with \(m_b(\text{NEIC}) \geq 5.0\), a linear fit between NEIC \(m_b\) values and \(m_b(\text{Lg})\) estimates using RMS values gave a relation \(m_b(\text{Lg}) = m_b(\text{NEIC}) + 0.07\) (ref. 19). Considering the excellent match between \(m_b(\text{NEIC})\) and \(m_b(\text{Lg})\) 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 \(\Delta m_b(\text{Lg})\) value of 0.57 between the two events\(^{11}\), which is consistent with the \(\Delta m_b\) 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 \(\Delta m_b\) values at all available common sites. Figure 3 shows four such plots between \(\Delta m_b\) values and the number of observations (we have shown only a few cases, but have studied several). It has been observed that these \(\Delta m_b\) values and the number of observations followed a Gaussian distribution with maximum number of observations around the mean, which is the most likely \(\Delta m_b\) value between the two events. Ideally, one should get identical estimates of \(\Delta m_b\) 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

<table>
<thead>
<tr>
<th>Station</th>
<th>Distance (°)</th>
<th>Azimuth (°)</th>
<th>Log(A/T)_max</th>
<th>M_i^oo</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAK</td>
<td>15.65</td>
<td>7.38</td>
<td>0.95</td>
<td>3.51</td>
</tr>
<tr>
<td>WMQ</td>
<td>21.05</td>
<td>33.49</td>
<td>0.77</td>
<td>3.46</td>
</tr>
<tr>
<td>KURK</td>
<td>24.15</td>
<td>10.63</td>
<td>0.74</td>
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</tr>
<tr>
<td>BRVK</td>
<td>25.95</td>
<td>350.90</td>
<td>0.82</td>
<td>3.60</td>
</tr>
<tr>
<td>XAN</td>
<td>32.57</td>
<td>68.59</td>
<td>0.53</td>
<td>3.42</td>
</tr>
<tr>
<td>TLY</td>
<td>34.30</td>
<td>35.66</td>
<td>0.62</td>
<td>3.53</td>
</tr>
</tbody>
</table>

Average \( M_{i}^{oo} = \log(A/T)_{max} + 1/3 \log(\Delta) + 1/2 \log(\sin \Delta) + 0.0046 \Delta + 2.370 \), where \( A/T \text{ max is in am/s} \).

RP, Rezapour and Pearce9.

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 the 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 (\( \Delta < 2000 \text{ km} \)), Rayleigh waves in the period range of 3.5–7 s with high SNR were observed at several Indian stations. Nuttli’s relation20 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 \( M_s = 3.53 \) (\( T = 8.0 \text{ s} \)), when Nuttli’s relation was used. Interestingly, this is close to the \( M_s \) estimate of 3.56 from the data of six regional stations11.

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 ($m_s$ vs $Y$) relation for Pokhran site is not appropriate. For a given $M_s$, the $m_s$ for SRTS event is ~ 0.4 magnitude units more than the $m_s$ 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. 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 $m_s$-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

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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 around 750°C to the Mo5Si3 phase.

SYNTHECTICALLY 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. 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 mirrors5–8. 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 (Mo5Si3) starts at around 450°C and nearly complete transformation of phase takes place at 750°C, where Mo5Si3 and MoSi2 phases form. The formation of Mo5Si3 phase was confirmed by high-resolution electron microscopy coupled with selected area diffraction pattern.

Mo–Si multilayer was deposited using an electron beam evaporation system9 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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