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

*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]

$$m_b = 4.45 + 0.75 \log Y, \quad (1)$$

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

$$m_b = 3.92 + 0.81 \log Y. \quad (2)$$

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

$$\log Y = 0.762\, M_s - 1, \quad (3)$$

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

$$\log Y = 1.19\, M_s - 2.55, \quad (4)$$

and

$$\log Y = 0.75\, M_s - 0.90, \quad (5)$$

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.

$$m_b = 0.5\, M_s + 3.89, \quad (6)$$

$$m_b = 0.58\, M_s + 3.23. \quad (7)$$

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 $\langle m_b \rangle$ value of 5.0 based on data from 11 stations, and ISC has given $\langle m_b \rangle$ of 4.9 from 14 observations. Nair[14] determined M_s = 3.19 from the data of Quetta station ($\Delta = 5.2^\circ$) in Pakistan, whereas Marshall *et al.*[15] gave $\langle M_s \rangle$ = 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-

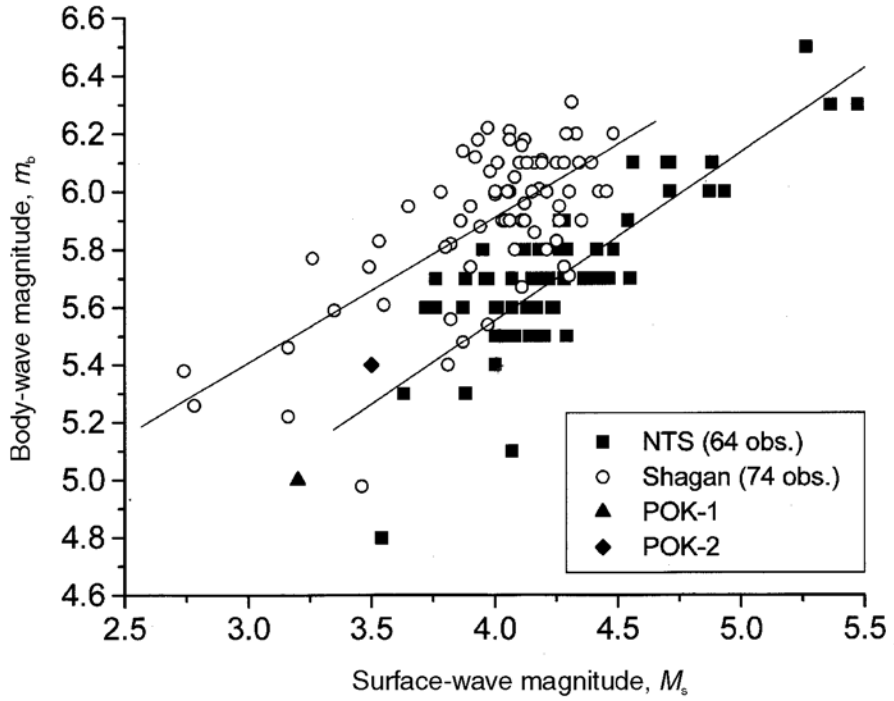

Figure 1. Plot of M_s vs m_b estimates for the nuclear explosions in NTS and SRTS. Data are taken from Stevens and Murphy[13].

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(POK2) = m_b(POK1) + 0.37 or 0.44 ~ 5.4.

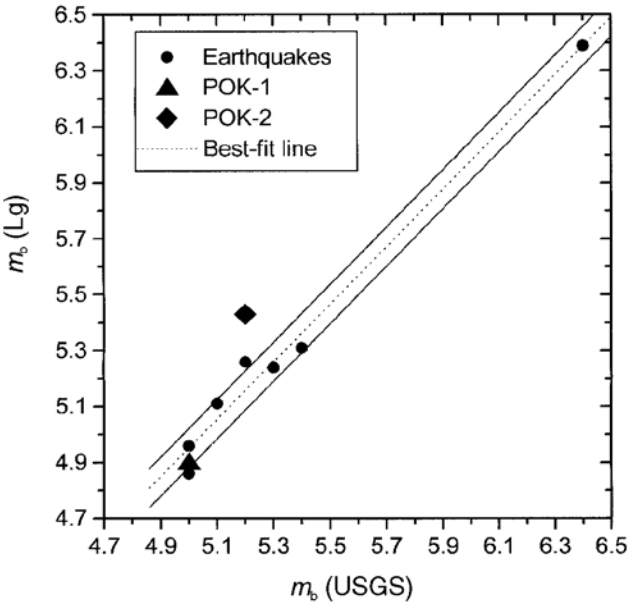

Figure 2. Comparison of m_b(USGS) and m_b(Lg) estimates of Indian earthquakes having magnitude ≥ 5.0. Estimates of POK1 and POK2 are superimposed. The best-fit line and ± 1 standard deviation lines are also shown. POK2 estimate is the only one that shows large deviation from the best-fit line, indicating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

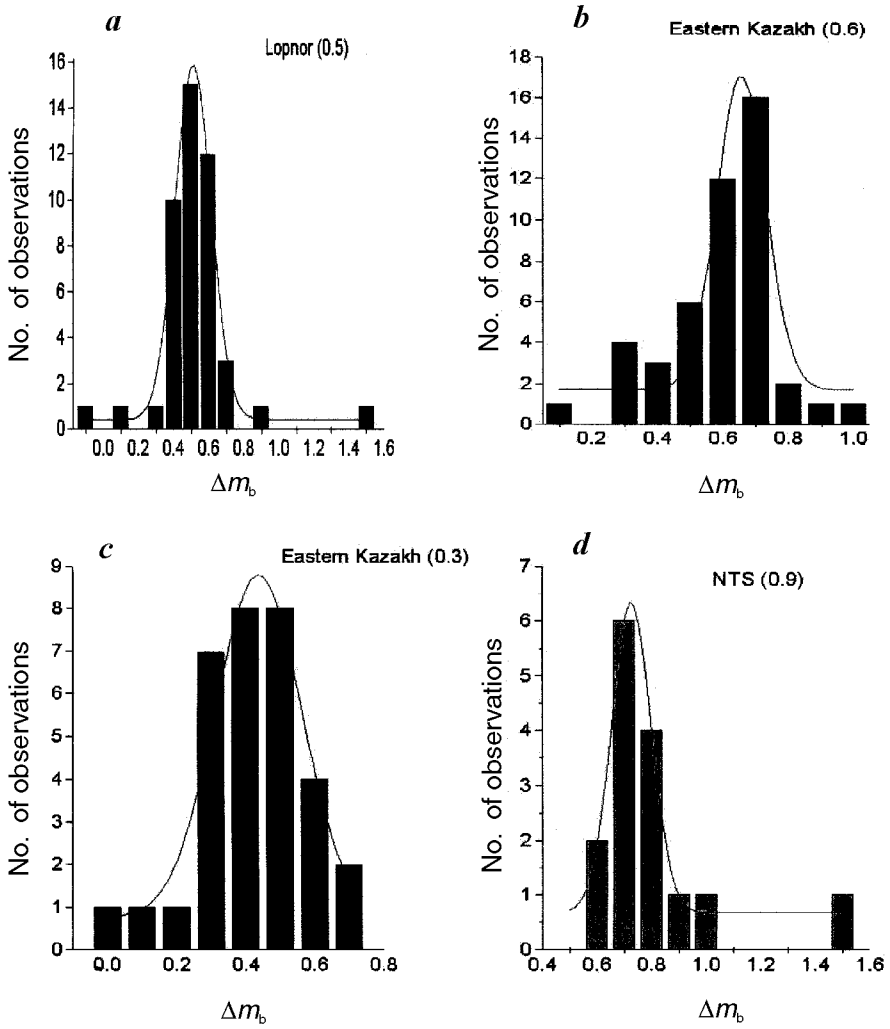

Figure 3. Plot of Δm_b values (at all available common stations) with number of observations corresponding to a pair of explosions at a given site. The USGS estimated Δm_b values for each pair of events are given in parentheses. Plots are generated from the body-wave magnitude data of (*a*) Lopnor events 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(Lg) = m_b (NEIC) ± 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

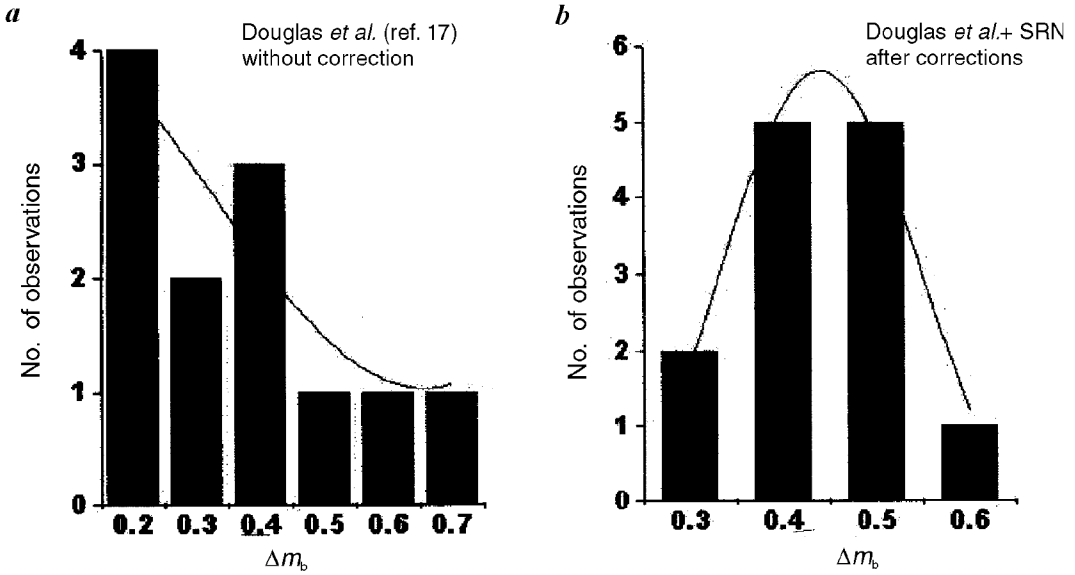

Figure 4. Common station Δm_b estimates of (***a***) Douglas *et al.*[17] corresponding to POK2 and POK1 showing one-sided distribution; and (***b***) Between POK2 and POK1 showing a Gaussian distribution after incorporating appropriate corrections to the data of Douglas *et al.*[17] (see Sikka *et al.*[9],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

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

Station	Distance (°)	Azimuth (°)	$\text{Log}(A/T)_{\max}$	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.

1. Ringdal, F., Marshall, P. D. and Alewin, R. W., *Geophys. J. Int.*, 1992, **109**, 65–77.
2. Murphy, J. R., *Identification of Seismic Sources – Earthquake or Underground Explosion* (eds Husebye, E. S. and Mykkeltveit, S.), Reidel, Dordrecht, 1981, pp. 201–205.
3. Evernden, J. F. and Marsh, G. E., *Phys. Today*, August 1987, pp. 37–44.
4. Murphy, J. R., *Bull. Seismol. Soc. Am.*, 1977, **67**, 135.
5. Barker, B. *et al.*, *Science*, 1998, **281**, 5385.
6. Wallace, T. C., *Seismol. Res. Lett.*, 1998, **69**, 386–393.
7. Shumway, R. H., *Pure Appl. Geophys.*, 2001, **158**, 2275–2290.
8. Sikka, S. K., Roy, F., Nair, G. J., Kolvankar, V. G. and Kakodkar, Anil, *BARC Newsl.*, 1998, **178**, 1–5.
9. Sikka, S. K., Roy, F. and Nair, G. J., *Curr. Sci.*, 2001, **81**, 885–887.
10. Manohar, S. B., Tomar, B. S., Rattan, S. S., Shukla, V. K., Kulkarni, V. V. and Kakodkar, A., *BARC Newsl.*, 1999, **186**, 1–5.
11. Roy, F. *et al.*, *Curr. Sci.*, 1999, **77**, 1669–1673.
12. Fisk, M. D., Jepsen, D. and Murphy, J. R., *Pure Appl. Geophys.*, 2002, **159**, 865–888.
13. Stevens, J. L. and Murphy, J. R., *ibid*, 2001, **158**, 2227–2251.
14. Nair, G. J., Some Seismic Results of Rajasthan Explosion of 18 May 1974, AG224, Procurement Executive, MOD, UK.
15. Marshall, P. D., Springer, D. L. and Rodean, H. C., *Geophys. J. R. Astron. Soc.*, 1979, **57**, 609–638.
16. Bache, T. C., *Bull. Seismol. Soc. Am.*, 1982, **72**, S131.
17. Douglas, A., Marshall, P. D., Bowers, D., Young, J. B., Porter, D. and Wallis, N. J., *Curr. Sci.*, 2001, **81**, 72–74.
18. Evernden, J. F., *Phys. Soc.*, 1998, **27**, 10–11.
19. Bhadauria, Y. S. and Roy, F., *BARC Report*, 2000, E/032.
20. Nuttli, O. W., *J. Geophys. Res.*, 1973, **78**, 876–885.
21. Sikka, S. K., Roy, F. and Nair, G. J., *Curr. Sci.*, 1998, **75**, 486–491.
22. Rezapour, M. and Pearce, R. G., *Bull. Seismol. Soc. Am.*, 1998, **88**, 43–61.

ACKNOWLEDGEMENTS. We thank Dr G. J. Nair for many useful discussions. We also express our thanks to IRIS consortium for making the data available in their web site.

Received 27 May 2002; revised accepted 24 September 2002