Indian explosions of 11 May 1998: Analysis of regional Lg and Rayleigh waves

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This paper presents the analysis of regional Lg and Rayleigh wave data pertaining to the Indian explosions of 11 May 1998 (POK2). Strong Lg and Rayleigh waves have been recorded at several in-country stations. A comparison of Lg waves at Gauribidanur array (GBA), India corresponding to POK2 and that of the Indian explosion of May 1974 (POK1) shows an amplitude ratio of 3.7 between these events. This leads to a yield ratio of 4.83 between the two events. Analysis of Rayleigh waves revealed that Nuttli's relation for estimation of surface wave magnitude (M_s) in the period range 3.0–12.0 s based on eastern North American data is also applicable for the Indian region. The average M_s value of POK2 from regional data is obtained as 3.56. The yield estimate of POK2 as obtained from the regional data analysis is found consistent with our earlier findings and the post shot radiochemical measurements.

THREE nuclear explosives were detonated by India on 11 May 1998 at the Pokhran test site in Rajasthan. These explosions, comprising a thermonuclear device, a fission device and a subkiloton device emplaced in spatially separated shafts[1], were triggered simultaneously. The seismic waves generated by these explosions were recorded at a large number of regional and teleseismic stations. The combined yield of the two large explosions (POK2) was estimated earlier[1–3] using the following methods:

(1) By selecting the global bodywave magnitude (m_b) estimates corresponding to the constructively interfered signals from the simultaneous explosions of POK2 and using a m_b versus yield relation appropriate for the Pokhran test site[2]; (2) By comparing the global m_b estimates of 18 May 1974 explosion (POK1, used as a calibration event) with those of POK2 as recorded at eight common stations[3]; (3) By using the surface wave magnitude (M_s) estimates[3] and Murphy's relation[4] for M_s versus yield; (4) By comparing the acceleration values corresponding to POK2 with those of the explosions conducted in similar geological conditions[3].

All the above methods consistently gave yield estimates of 58 ± 5 kt (refs 2, 3). This estimate is in agreement with the yield of the thermonuclear device of POK2 obtained as 50 ± 10 kt from the post shot radiochemical analysis[5].

In this paper we report the analysis of regional Lg and Rayleigh wave data corresponding to the POK2 explosions. The inference drawn on the combined yield of the POK2 explosions based on various magnitude estimates is also summarized.

The seismic Lg wave is one of the many regional phases that propagates in the continental lithosphere. The Lg or the surface shear wave is a wave-train observed on all three components of ground motion and propagates in a crustal wave guide. The initial periods of these waves are about 0.5–6.0 s with a sharp commencement. In general, the amplitude of Lg phase at regional distances is larger than any other conventional phases for the continental paths. The group velocity of Lg waves near its onset is about 3.5 km/s. Due to the isotropic nature of Lg wave radiation pattern, reliable magnitude determination can be made from the data of only a small number of stations[6,7]. A single station with good signal to noise ratio (SNR) can provide m_b (Lg) measurements with an accuracy (one standard deviation) of about 0.03 magnitude units[8]. Therefore, Lg signals appear to provide an excellent basis for supplying estimates of the yields of nuclear explosions even down to below 1 kt, when such signals are recorded at high quality digital, in-country seismic stations, and when calibrated by access to independent yield information for a few nuclear explosions at the test sites of interest.

Nuttli[6] proposed that, since Lg represents a higher mode wave travelling with minimum group velocity, it would be appropriate to relate Lg wave amplitude (A) and distance (Δ) by the following equation:

$$A = K \cdot \Delta^{-1/3}(\sin(\Delta))^{-1/2}\exp(-\gamma\Delta), \qquad (1)$$

which is also the expression for the amplitude of dispersed surface waves measured in the time domain corresponding to the Airy phase[9]. In eq. (1), K is a constant governed by the source strength and γ is the anelastic attenuation coefficient which is related to specific quality factor Q by $Q = \pi/UT\gamma$, where U is the group velocity and T is the period of the wave. In order to obtain the value of m_b (Lg) it will be necessary to estimate γ for a particular source–receiver path. There are several methods for estimating γ, however, we have followed the one used by Nuttli[6]. Having estimated γ, m_b (Lg) can be obtained from the relation[10],

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$$m_b(Lg) = 3.81 + 0.831 \log_{10}\Delta + \gamma(\Delta - 0.09)\log_{10}e + \log_{10}A, \quad (2)$$

where Δ is in degrees and A corresponds to amplitude in microns at signal periods close to 1 second.

The POK2 test site and the stations used in the present study are shown in Figure 1. Figure 2 *a* shows the broad-band seismogram as recorded at Bhopal observatory (BHPL), a station run by the India Meteorological Department (IMD), India. Clear Lg and Rayleigh waves with high SNR are seen in the seismogram. It may be interesting to point out here that though the Nilore station in Pakistan (NIL, an international monitoring station) is situated at a similar distance ($\Delta = 6.68°$) from the POK2 site when compared to BHPL ($\Delta = 6.34°$), the Lg wave on NIL record is highly attenuated (SNR = 3.8, see Figure 2 *b*) in comparison to that on BHPL record (SNR = 78). This shows that Lg wave attenuation along the path between NIL and POK2 site is much higher than that along the path between BHPL and POK2 site. The large variations in the amplitudes of the Lg waves at BHPL and NIL which is located in Himalayas, may be attributed to the different geologic and tectonic settings of these locations. The m_b (Lg) estimates as obtained from three IMD stations, viz. BHPL (Bhopal), POO (Pune), BLSP (Bilaspur), and GBA (Gàuribidanur array) are listed in Table 1. The average m_b (Lg) estimate from these stations is obtained as 5.47 with a standard deviation of 0.06. The low value of standard deviation

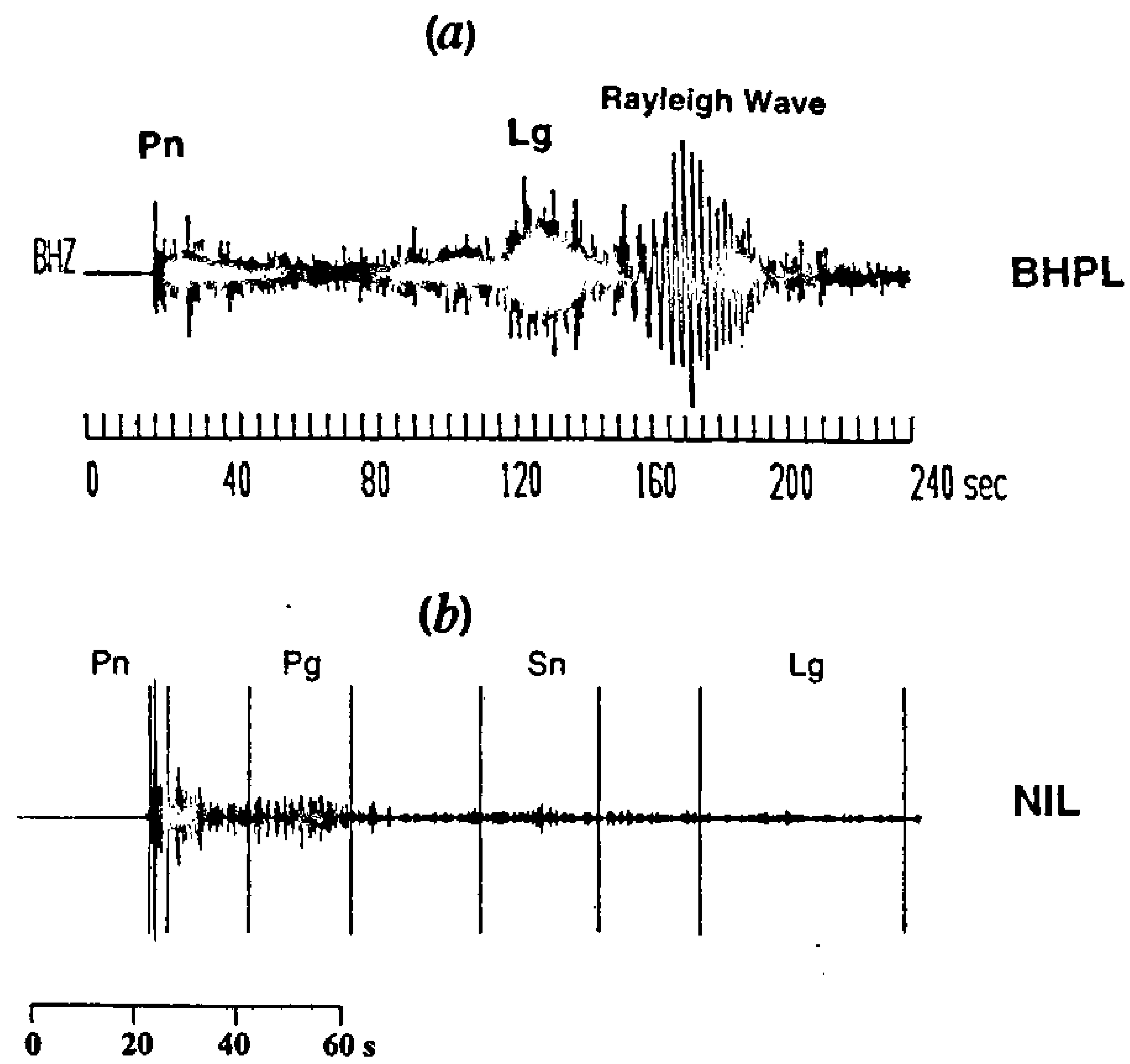

Figure 2. *a*, Broad-band seismogram corresponding to POK2 as recorded at BHPL, India; *b*, Seismogram generated by POK2 at NIL, Pakistan. High attenuation of Lg waves on NIL record in comparison to that on BHPL record is conspicuously seen. Time scales for the seismograms are given at the bottom.

Table 1. Estimates of m_b (Lg) from regional data

Station	Distance (°)	Azimuth (°)	m_b (Lg)
BHPL	6.34	126.1	5.43
POO	8.73	167.4	5.46
BLSP	10.58	115.7	5.57
GBA	14.41	157.7	5.42

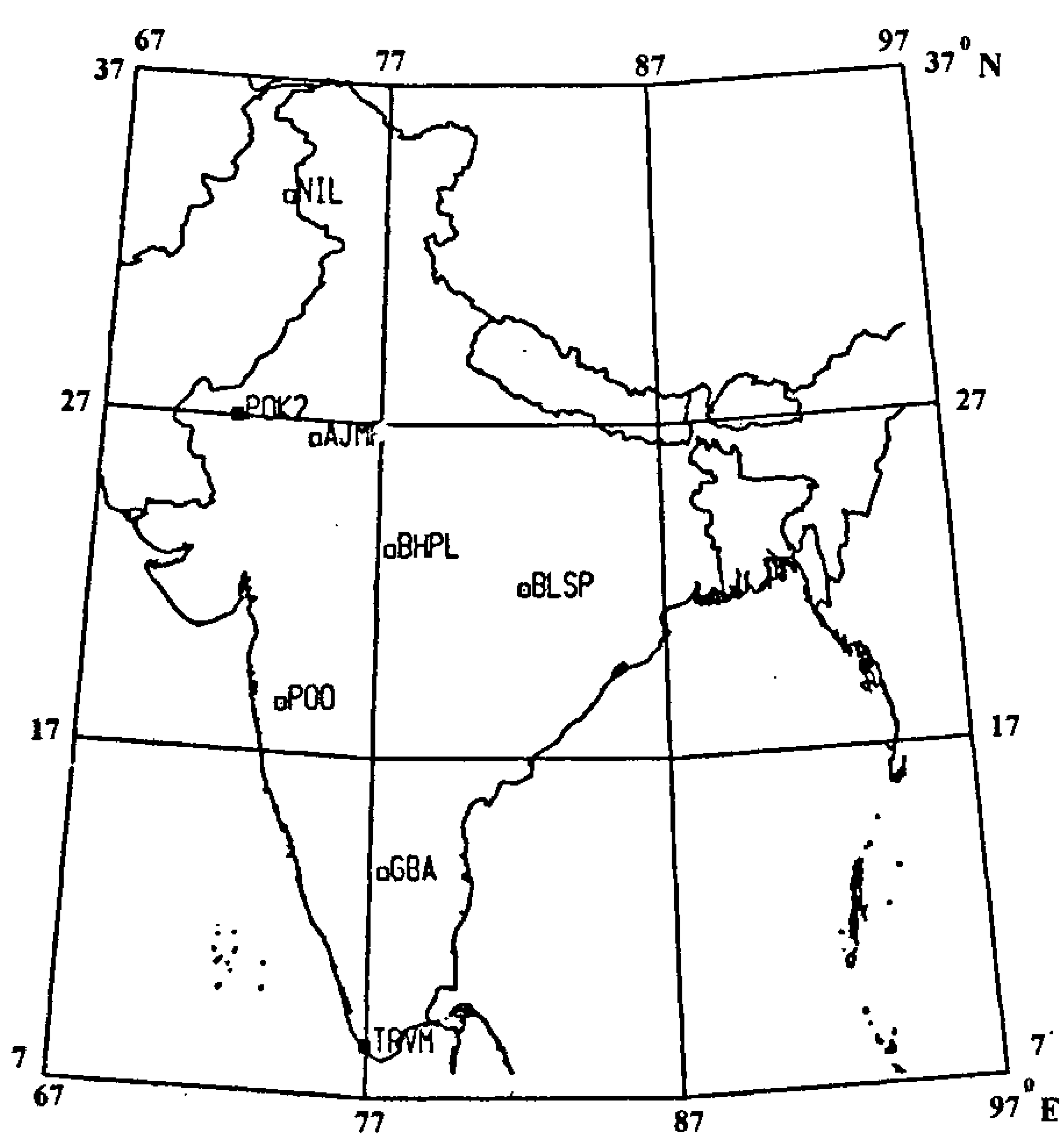

Figure 1. Map showing the POK2 site and the stations used in the present study.

implies that the average value of Q_0 (Q at 1 Hz) is approximately constant over an area containing the epicenter and the stations lying in the azimuth range of 115.7° to 167.4°. It may be noted (Figure 3) that the Trivandrum observatory (TRVM, $\Delta = 19.12°$) of the IMD recorded strong Lg waves of ~4 s period on LP seismograms. As the short period data from TRVM is not available, estimation of m_b (Lg) using 1 s period Lg wave could not be done. Nevertheless, the amplitude of 4 s period Lg wave is apparently consistent with the average m_b (Lg) estimate as obtained from data at the other four stations. However, the Ajmer observatory (AJM, $\Delta = 2.57°$) of the IMD recorded much attenuated Lg waves compared to the other five stations. This could be due to its proximity to the Aravali ranges. Thus, the path between the POK2 site and AJM is characterized by a higher γ value than that of the other five stations. This is not surprising due to the fact that a similar phenomenon related to the Lg wave attenuation has been observed in

North America[6] and Middle East[11]. In view of the above, we feel that the data of AJM should be analysed separately by using the coda of the Lg wave[12].

Figure 4 shows the short period seismogram of GBA. The GBA seismogram, like that of BHPL, also has very strong Lg wave. From GBA data the amplitude ratio of Lg waves between POK2 and POK1 (ref. 13) at 1 s period is obtained as 3.7 which gives the difference in magnitudes (Δm_b(Lg)) between these two events as 0.57.

For POK2, very few stations at teleseismic distances have reported M_s estimates based on the amplitude around 20 s period. To be precise, there were only four teleseismic M_s observations when compared to 160 observations corresponding to m_b as reported by the United States Geological Survey (USGS), the International Data Center (IDC), USA and the Kyrgyz network (KNET). However, at the regional distances ($\Delta < 20°$)

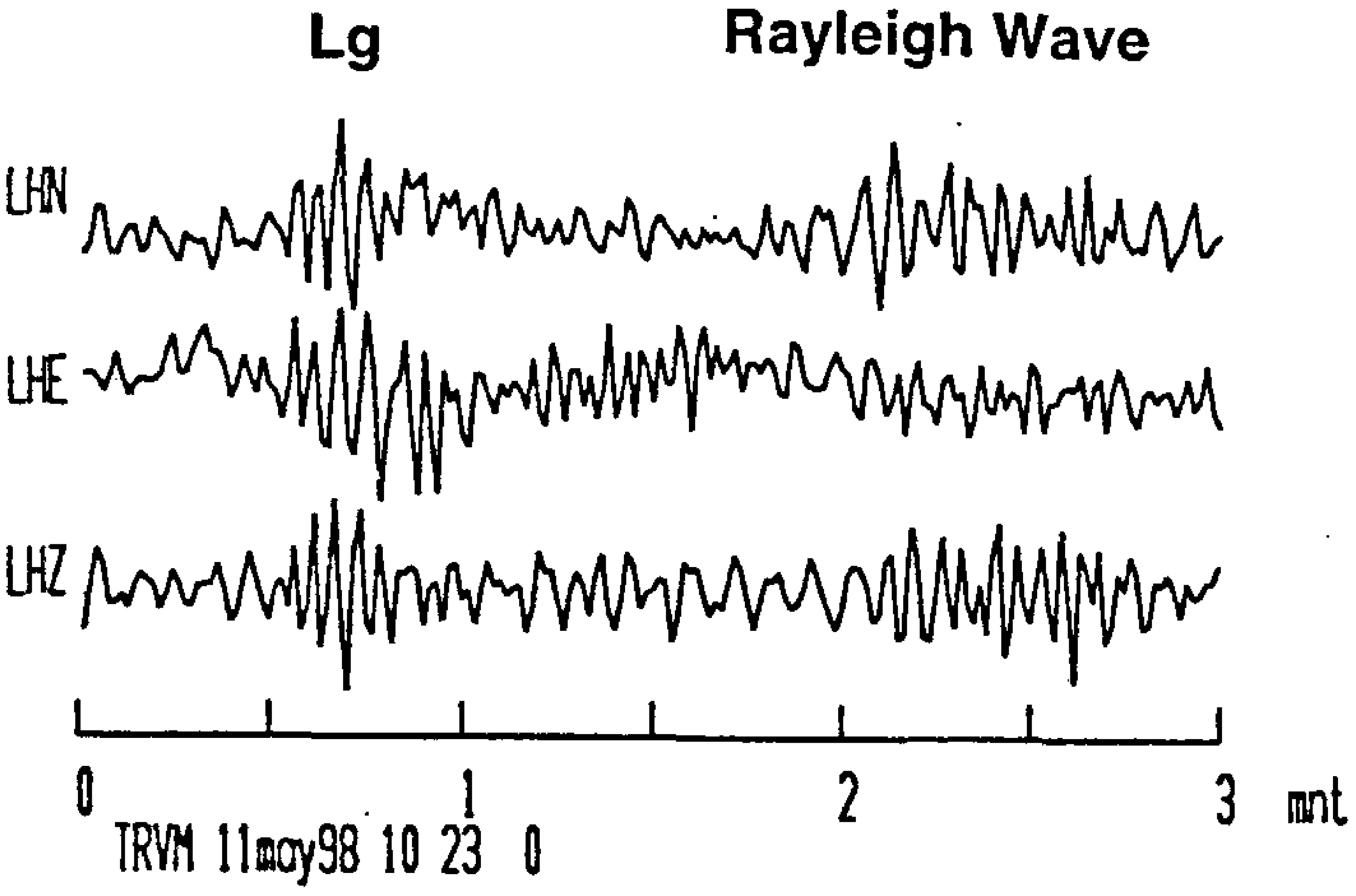

Figure 3. Long period 3-component seismograms at TRVM, India, as generated by POK2. Clear Lg and Rayleigh waves are seen on the seismograms.

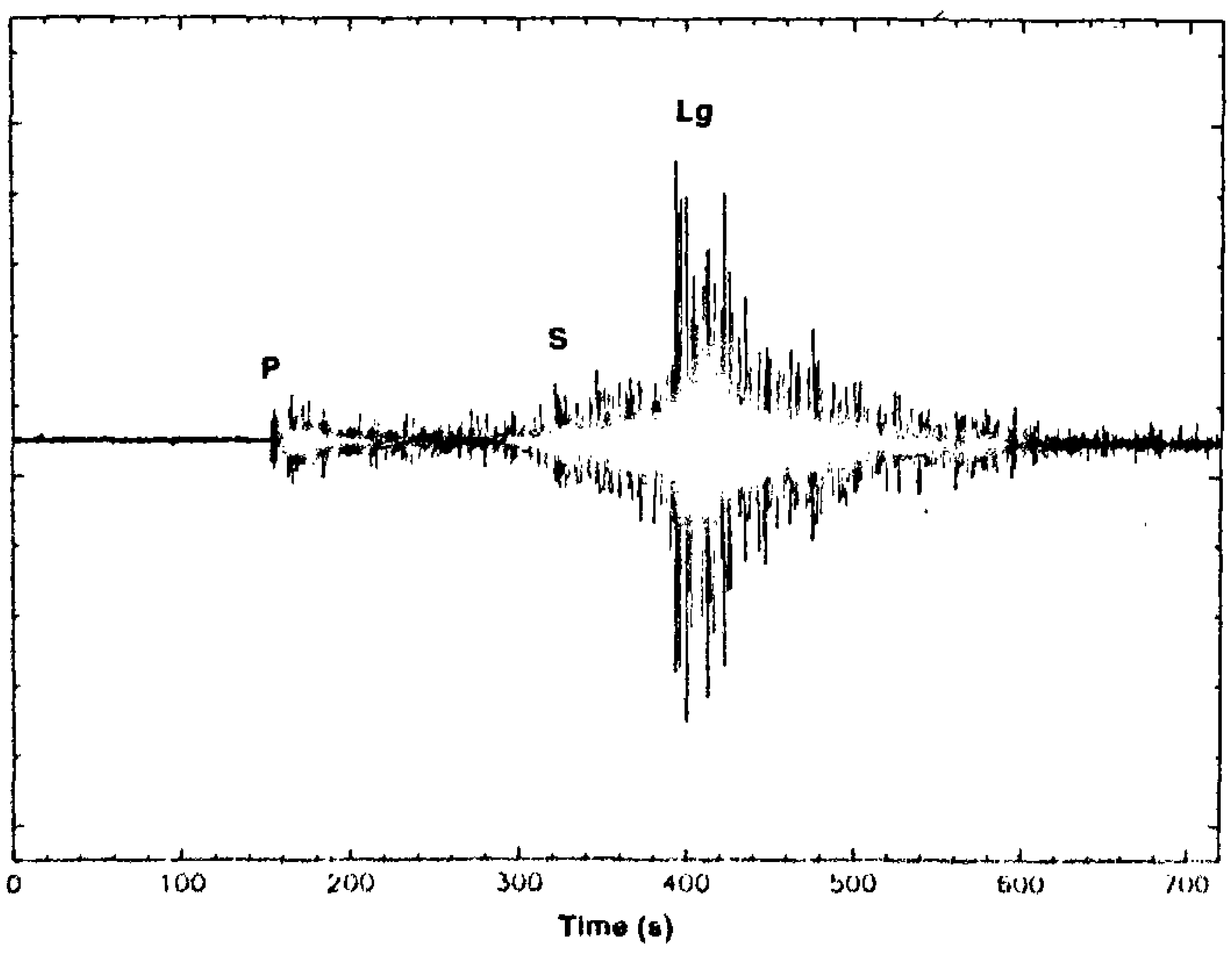

Figure 4. Short period seismogram as generated by POK2 at GBA, India. Strong Lg waves are recorded at GBA from these explosions.

Table 2. Estimates of M_s from regional data

Station	Distance (°)	Azimuth (°)	M_s (Nuttli)	M_s (authors)
AJM	2.57	103.4	3.32	3.41
BHPL	6.34	126.1	4.00	4.03
POO	8.73	167.4	3.20	3.21
BLSP	10.58	115.7	3.74	3.74
GBA	14.41	157.7	3.55	3.53
TRVM	19.12	164.4	3.54	3.50

Rayleigh waves in the period range 3.5–7.0 s with high SNR have been observed at several stations. The Rayleigh wave detection capability is sensitive to rapidly changing noise levels and signal interference. Nuttli[6] in his study with central US earthquakes noted that though the Rayleigh waves of 3–12 s periods at regional distances yielded M_s value as high as 4.08 no teleseismic surface waves of 20 s period were detectable for a given event. Nuttli concluded that 20 s period waves for this event were too small to be observed at large distances and the microseismic level was also too high.

The average surface wave magnitude for POK2 using the four teleseismic observations of the USGS is obtained as 3.57 based on the formula adopted by the International Association for Seismology and the Physics of the Earth's Interior (IASPEI)[14]. Using the value of $M_s = 3.57$ and the regional data from six stations corresponding to POK2 having signal periods between 3.5 and 7.0 s, a relation for M_s (authors) is obtained as

$$M_s = 2.75 + 1.51 \log(\Delta) + \log(A/T)_{max}. \quad (3)$$

For regional distances between 2° and 20°. Nuttli[6] has proposed the formula

$$M_s = 2.6 + 1.66 \log(\Delta) + \log(A/T)_{max}, \quad (4)$$

where Δ is in degrees and $(A/T)_{max}$ is the maximum value of A/T in microns per second (A is zero to peak value) for vertical component of Rayleigh waves having periods between 3 and 12 s. Nuttli has used eastern North American data for arriving at the above relation. The M_s estimates obtained using these two relations are listed in Table 2. It may be seen that both the estimates are extremely close to each other. Nuttli's relation gives an average M_s value of 3.56. The estimates of standard deviations for M_s (authors) and M_s (Nuttli) are obtained as 0.259 and 0.263, respectively. As the difference between these standard deviations is very small, we conclude that Nuttli's relation, which has been derived from the data of some independent events, is applicable for the Indian region as well.

The amount of energy transmitted as seismic energy due to an underground explosion is only a small fraction of the total energy. Further, the strength of the seismic signals generated also depends on the host medium. Moreover, the signals recorded at a seismic station depend not only on the above factors but also on the wave transmission characteristics of the path which varies from region to region. Therefore, in order to remove these uncertainties the strength of an explosion from seismic signals should be estimated in relation to a nearby calibration explosion, the yield of which is already known[15]. The ratio of yields between two explosions can be evaluated by using the difference in their magnitudes, ΔM, expressed as

$$\Delta M = C \log(Y/Y_C), \quad (5)$$

where Y and Y_C are the yields of the given explosion and the calibration explosion, respectively and C is a constant.

The value of Δm_b (Lg) = 0.57 at GBA together with a value of $C = 0.833$ corresponding to unsaturated material[7] gives the yield ratio between POK2 and POK1 as 4.83 based on Lg waves. This is almost close to the yield ratio of 4.46 obtained earlier from P wave data of eight global stations which were common to both the 1974 and 1998 events[3]. Using the reported yield of POK1 as 12 to 13 kt (refs 13, 16), the yield of POK2 based on Δm_b and Δm_b (Lg) values (Y_p and Y_{lg}, respectively) is obtained as 54 kt < Y_p < 58 kt and 58 kt < Y_{lg} < 63 kt, respectively. Combining these two estimates we get the yield, Y, of POK2 as 54 kt < Y < 63 kt. It may be added that the rock mechanics phenomenology calculations based on the reported yield of POK1 reproduced the measured cavity radius, spall velocity and the extent of the rock fracturing[17]. The reported yield of POK1 was also found consistent with the analysis of global data carried out by Marshall *et al.*[18] and Bache[19].

The average M_s value from six regional stations has been estimated as 3.56. Using Murphy's relation between M_s and yield[4] Y_s, for less than 100 kt explosions,

$$M_s = 2.14 + 0.84 \log(Y_s), \quad (6)$$

Y_s for POK2 is obtained as 49 kt. However, relation of Evernden and Marsh[20],

$$\log(Y_s) = 0.762\, M_s - 1 \quad (7)$$

which is applicable to explosions in hard rock *anywhere*, gives Y_s as 52 kt.

The above yield estimates which are found consistent with the yield obtained from post shot radio-chemical analysis of rock samples show that the yield estimates of Barker *et al.*[21] and Wallace[22] are too low. The low yield values may be attributed to the fact that these authors have used only teleseismic P wave data and not taken into account the source geometry of POK2, source parameters and the site-specific geophysical parameters. Moreover, they have not used the global M_s observations for estimating the yield of POK2, as done by Evernden[23], which lead to a value closer to our estimates.

After going through a detailed analysis of the data corresponding to POK2, the following conclusions are arrived at.

(1) At the regional distances, Lg waves having high SNR were observed at several stations. Average m_b (Lg) obtained from such data was 5.47. Though the NIL station in Pakistan and BHPL in India are situated at similar distances from the POK2 site, the observed Lg wave amplitude at BHPL was much higher than that observed at NIL. It may be further emphasized that not only BHPL, but several other in-country stations including GBA have recorded Lg waves with high SNR. This suggests that the attenuation of Lg waves in the peninsular Indian region is, in general, lower than that along the path between NIL and POK2 site. The amplitude ratio of Lg waves at GBA between POK2 and POK1 at 1 s period was obtained as 3.7, resulting in an yield ratio of 4.83 between these events.

(2) Rayleigh waves observed at regional distances gave an average $M_s = 3.56$. For Indian region, Nuttli's relation[6] for estimating M_s based on 3–12 s period Rayleigh waves was found applicable.

(3) From Δm_b and Δm_b (Lg) values between POK2 and POK1, the yield of POK2 is estimated as 54 kt < Y < 63 kt in comparison to that of POK1 as 12 kt < Y < 13 kt.

In short, the yield estimates obtained from both teleseismic as well as regional data are consistent with each other and the estimates are in agreement with the radiochemical analysis of rock samples recovered by post shot drillings[5].

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In vitro haemorrhage-like activity of Russell's viper (*Vipera russelli russelli*) venom from Eastern India with mice organs

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***Vipera russelli russelli* (Indian subspecies of Russell's viper) envenomation causes severe haemorrhage in different organs of the victim's body. Application of crude venom extracted from Russell's viper of Eastern Indian origin on sliced tissues of BALB/c mice shows that among the target organs like lungs, kidneys, heart, brain, eye balls, etc. liver is most potent in terms of release of haemoglobin and hence blood. Spectral and size-exclusion HPLC analysis indicate that it is only haemoglobin that gives absorption of the extract at 540 nm. Release of haemoglobin follows second-order kinetics depending on both concentration of venom and amount of tissue incubated. The reaction is completely inhibited by venom antibody indicating absence of artifacts in the process. Approximately 20% of the release of blood may be accounted for fibrinolytic and haemolytic activity of the venom. Treatment of different inhibitors with venom shows that in cases where *in vitro* release of blood was partly or fully inhibited, good correlations were observed with *in vivo* haemorrhage and also with lethality. Thus the protocol may be developed for an emperical assay system to assess antihaemorrhagic property of a substance.**

SNAKE envenomation is a WHO identified occupational hazard for paddy farmers in South-east Asian countries. Incidents of snake bite leading to death are common in many tropical countries during or after the rainy season because of increased human settlements at the natural habitats of snakes. *Vipera russelli russelli* (Indian subspecies of Russell's viper) is one of the four major classes of snakes that causes death in the Indian subcontinent. Its venom consists of many active compounds that cause coagulopathy, necrosis, renal failure, neurotoxicity, myotoxicity, cardiotoxicity, convulsions, hypotensive, anticoagulation, etc. Among these, haemorrhage from the site of bite, unhealed wounds, liver, lung, kidney, intestine, eye ball, brain, etc. of the victim is severe and is a major manifestation of envenomation though renal failure is considered as the primary cause of death[1].

The observed haemorrhage may be the combination of three major factors like rupture of capillary membranes carrying blood, fibrinolytic activity to melt clots and inhibition of one or more blood clotting factors. Whatever may be the contribution of each factor, it is relatively easy to measure haemorrhage among other pathophysiological factors of venom because of ease and quantitation of released haemoglobin. It may be noted that the only treatment available in the market for snake envenomation is application of antivenom and its application is continued as long as the blood clotting time of the victim falls within the normal range.

Therefore, inhibition of haemorrhagic potential of the venom toxins by certain compounds may be considered as a preliminary index of its antivenom character. However, there is an intriguing variation in the clinical manifestation of envenoming by Russell's viper from neighbouring countries like Sri Lanka, Burma, Thailand, China and Taiwan[1,2]. Though haemorrhage is common, some pathological effects are either variable or questionable or absent altogether. Even venom composition of Russell's viper from different regions of the Indian subcontinent was found to be distinctly different as revealed by sodium dodecylsulphate-polyacrylamide gel electrophoresis[3]. Moreover, haemorrhagic toxins purified from Russell's viper from different geographical locations have shown organ specificity in test animals – e.g. the most basic phospholypase A_2 of Southern Indian

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