ELSEVIER

Available online at www.sciencedirect.com

SCIENCE DIRECT®

Physics and Chemistry of the Earth 31 (2006) 325–335

PHYSICS and CHEMISTRY of the EARTH

www.elsevier.com/locate/pce

Identification of earthquake sources responsible for subsurface VLF electric field emissions observed at Agra

Vikram Singh [a], Birbal Singh [b,*], Manoj Kumar [a], M. Hayakawa [c]

[a] *Department of Physics, R.B.S. College, Bichpuri, Agra 283105, India*
[b] *Department of Electronics and Communication Engineering, Faculty of Engineering and Technology, R.B.S. College, Bichpuri, Agra 283105, India*
[c] *Department of Electronic Engineering, The University of Electro-Communications, Chofu, Tokyo 182, Japan*

Received 28 April 2005; received in revised form 17 June 2005; accepted 12 July 2005
Available online 15 May 2006

Abstract

Employing USGS earthquake data for Indian region and very low frequency (VLF, 3 kHz) subsurface electric field data obtained by using a borehole antenna at Agra in India, statistical analysis has been carried out to identify the earthquake sources responsible for VLF data. The correlation coefficient between occurrence number of VLF noise bursts and earthquakes are calculated and level of null hypothesis tested. The results show that seismic activities occurring close to the observing station and the main boundary fault located at the southern base of Himalaya are the main sources of VLF emissions recorded at the station.

Keywords: Borehole antenna; VLF electromagnetic emissions; Earthquakes; Statistical analysis

---

1. Introduction

The phenomena of electromagnetic emission associated with seismic activities have been studied by many workers during the last two decades using ground and satellite based observations at different frequencies ranging from DC to HF (Gokhberg et al., 1982; Warwick et al., 1982; Oike and Ogawa, 1986; Parrot and Mogilvesky, 1989; Fraser-Smith et al., 1990; Fujinawa and Takahashi, 1990, 1994; Molchanov et al., 1992, 1993, 1995; Varotsos et al., 1993; Hayakawa et al., 1996; see also the monographs by Hayakawa and Fujinawa, 1994; Hayakawa, 1999; Hayakawa and Molchanov, 2002). The generation mechanism of such emissions during earthquakes have been supported very well by laboratory experiments (Nitsan, 1997; Ogawa et al., 1985; Enomoto and Hashimoto, 1992, 1994).

Although there exists lack of enough detailed description about the claimed anomalies and proper understanding of physical processes involved in the phenomena (Park et al., 1993; Geller, 1991, 1996), continued efforts are in progress globally to find the solution of these problems convincingly. Among various ground-based techniques employed for monitoring the electromagnetic emissions, the subsurface measurement of the vertical electric field emissions at the frequencies in VLF band have provided very interesting results recently (Fujinawa and Takahashi, 1990, 1994; Yoshino, 1991; Hata and Yabashi, 1994; Qian et al., 1994). In general, it has been found that the occurrence number of VLF pulses is highly enhanced prior to the occurrence of the earthquakes and one interesting example in this respect has been reported by Fujinawa and Takahashi (1995) related to Kurile Island earthquake in Japan.

Inspired by the borehole results obtained by earlier workers, attempts have been made to extend the work at Agra (lat. 27.2°, long. 78°) in India by monitoring the vertical component of the electric field emissions at the frequency of 3 kHz using a borehole antenna. Some of the interesting results obtained at this station include the observation of VLF noise bursts not only from seismic

---

* Corresponding author. Tel.: +91 941 237 3079; fax: +91 562 285 1288.
E-mail address: birbal@sancharnet.in (B. Singh).

1474-7065/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pce.2005.07.015

locations in India but also from distant sources in Pakistan and Afghanistan (Singh et al., 1999), a positive correlation between the seismic swarm in Chamoli and VLF noise bursts activity at Agra (Singh et al., 2001), and lithosphere–atmosphere coupling of VLF seismo-electromagnetic signals by employing a terrestrial antenna in conjunction with borehole antenna (Singh et al., 2003). In the present paper, we consider seismic locations in and around India within the latitude and longitude range 0°–40°N, 60°–100°E corresponding to a period of two years between February 1998 and December 1999 for which VLF data obtained by using the borehole antenna are available and then we carry out statistical analysis to identify seismic locations which are responsible for the VLF data.

2. Experimental setup

For monitoring the electromagnetic emissions generated from earthquakes, a borehole antenna of length 120 m is installed at Agra station. The complete experimental setup is shown in Fig. 1 which is similar to that used by our earlier VLF group (Singh et al., 1999, 2000, 2001, 2003; Singh and Singh, 2000). Briefly, the borehole antenna is a naked copper wire of 120 m length and 4 mm diameter placed in a water tight PVC pipe of 3.7 cm diameter with its lower end tightly fitted with an insulating black cork at the bottom. This is placed in another PVC pipe of 7.5 cm diameter, which is opened at both ends. Another electrode is placed 3 m down in contact with the ground to provide earth terminal. The subsurface electric fields induced at the borehole antenna are fed to pre-and main amplifiers and the amplified signal is fed to band pass filter ($f = 3$ kHz, bandwidth 250 Hz). The filtered signal is then peak detected and recorded on a DC chart recorder (Model A602C, Esterline Angus, USA). The chart speed is maintained at 0.5 cm/min. The chart recorder measures the current (0–5 mA) and its internal resistance is 65 Ω. However, we have modified it to measure the current in the range 0–10 mA. The enhancement in amplitude of the noise bursts above the background level may also be measured in terms of dB on the same scale of 0–10 mA by calibrating it to read 0–20 dB as per the relation $\text{dB} = 20\log_{10}$ (amplitude enhancement). The experimental arrangement shows digital recording of data also. However, major data collection during the years 1998 and 1999 has been made by using the chart recorder and the digital recording was performed casually. In this paper, we have used the data obtained from the chart recorder. The observations are taken in remote rural area at Bichpuri, which is about 12 km from Agra city where electric and electromagnetic disturbances are very low. The observations are taken round the clock except for two breaks: 2 h in the morning during 0700–0900 h and 2 h in the evening during 1700–1900 h LT, (LT = UT + 5.5 h).

3. Results and discussion

The subsurface monitoring of VLF electric field emissions at the frequency of 3 kHz using the experimental arrangement shown in Fig. 1 was started at our centre from 1 February 1998. The frequency of 3 kHz was chosen as a trade off between the unwanted noise contamination caused by higher harmonics of power line radiations and ELF atmospherics, and increasing attenuation at frequencies above 3 kHz. The anomalous electric field changes appeared in variety of waveforms of duration ranging from a few minutes to hours and amplitudes from 1 to 20 dB. For the sake of convenience, we call them as noise burst. A typical example of such a noise burst recorded on 28 March, 1999, one day before the devastating Chamoli earthquake of 29 March,1999 in the northern India, is shown in Fig. 2. In the present study we consider a noise burst occurring for one hour or less as one unit. The noise bursts whose amplitudes are 1 dB or less are not counted. Further, it may be noted that the variety of waveforms that we have recorded may have their origin in different sources

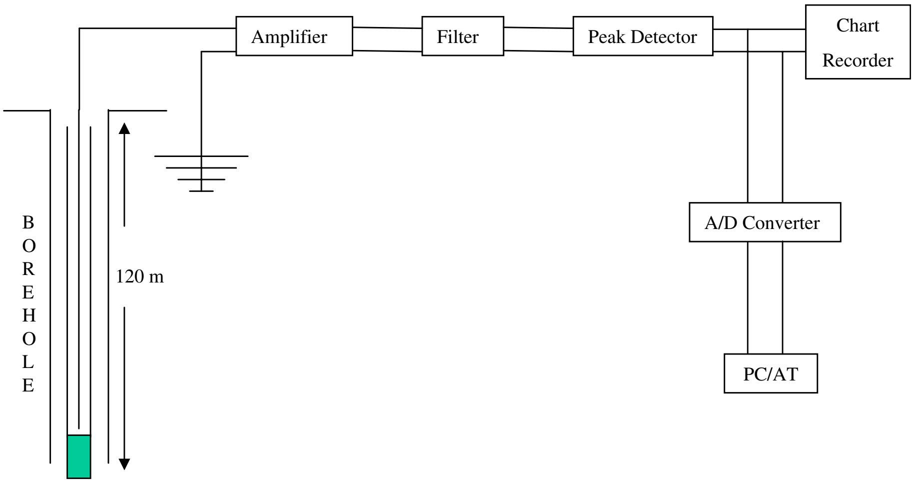


Fig. 1. Experimental arrangement for sub-surface measurement of vertical electric field emissions at Agra.

such as ionosphere, local and distant lightning, nearby radio transmission and seismic activities etc. As it is difficult to separate these waveforms from each other and identify those originated from seismic activities, we have included all types of waveforms in our present study.

In order to identify the earthquake sources which possibly produced the VLF emissions recorded by us at Agra station, we first analyze the USGS data obtained from the website (<http://neic.usgs.gov>) for the earthquakes corresponding to all magnitudes ($M > 1$) which occurred in India and surrounding region within latitude and longitude range 0°–40°N, 60°–100°E in the year 1998. The detailed earthquake epicenters are shown in the map of Fig. 3. Here it may be seen that the majority of earthquakes

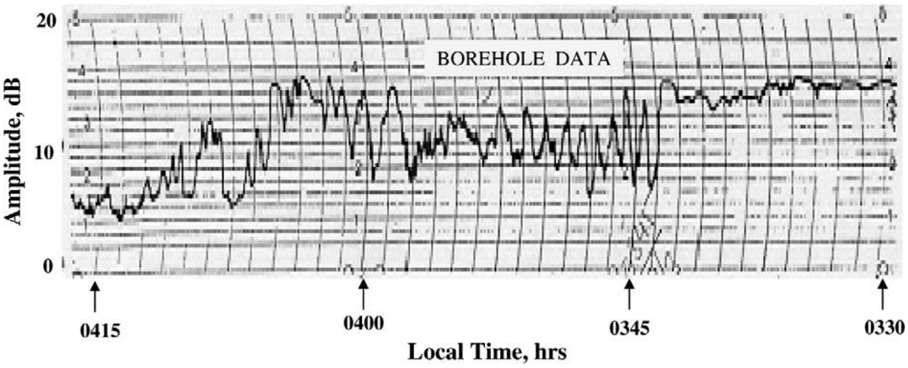


Fig. 2. Example of noise burst recorded on 28 March 1999.

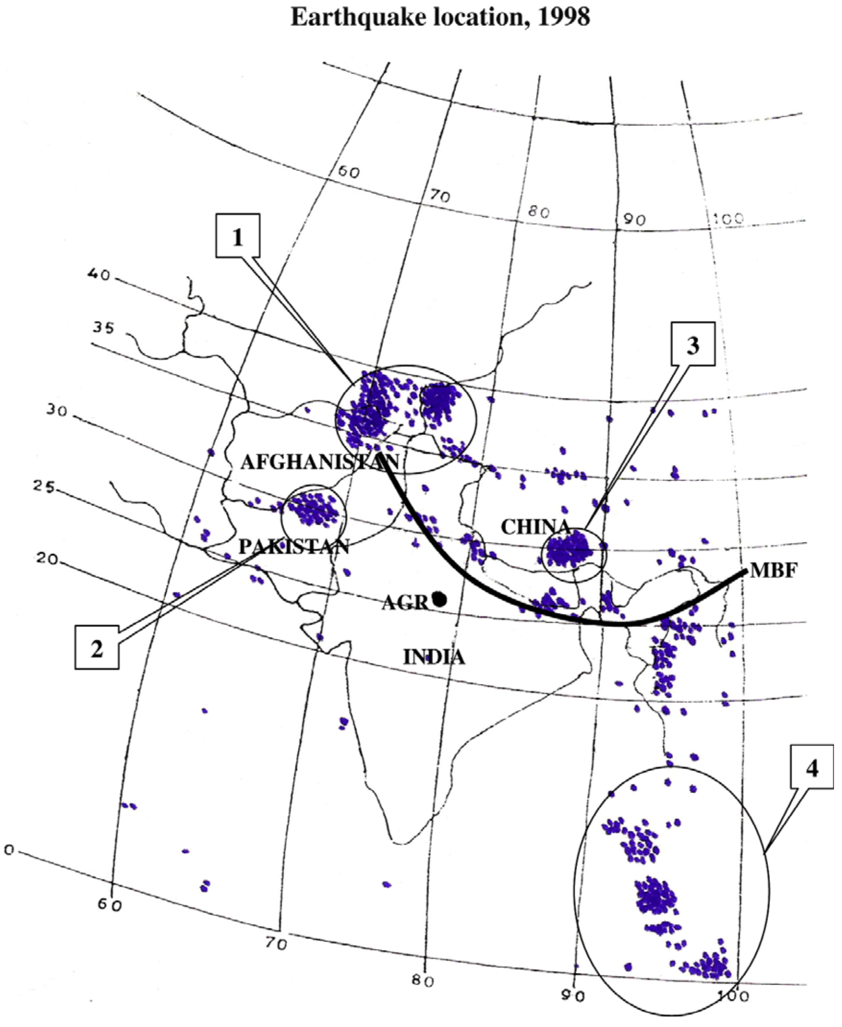


Fig. 3. A map of India and surrounding showing earthquake locations during the year 1998. Some prominent locations are encircled and marked 1–4.

occurred in four distinct locations which are encircled and marked 1–4. The observing station Agra is also indicated by the abbreviation AGR. The thick dark line existing at the southern base of Himalaya and extending from north-east India to north-west in Pakistan and Afghanistan is known as main boundary fault (MBF) along which four major earthquakes ($M > 8$) have occurred in India in the last hundred years. The four encircled locations in the map are distributed in latitude and longitude and concentrated in seismic zones of Afghanistan, Pakistan, China,

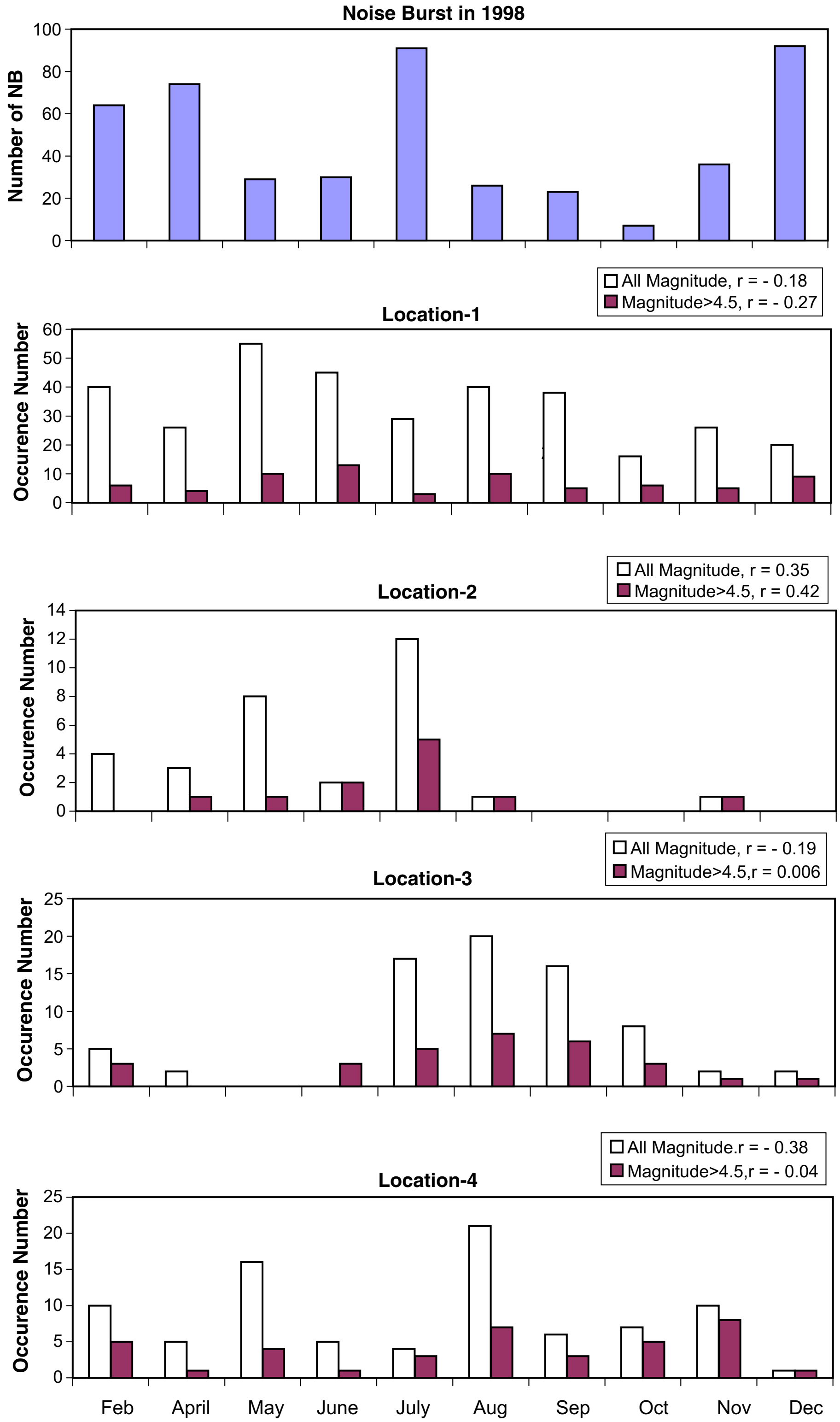


Fig. 4. Histograms of occurrence number of VLF noise bursts (top) and earthquakes of magnitudes $M > 1$ and $M > 4.5$ indicated by open and dark histograms respectively for each location.

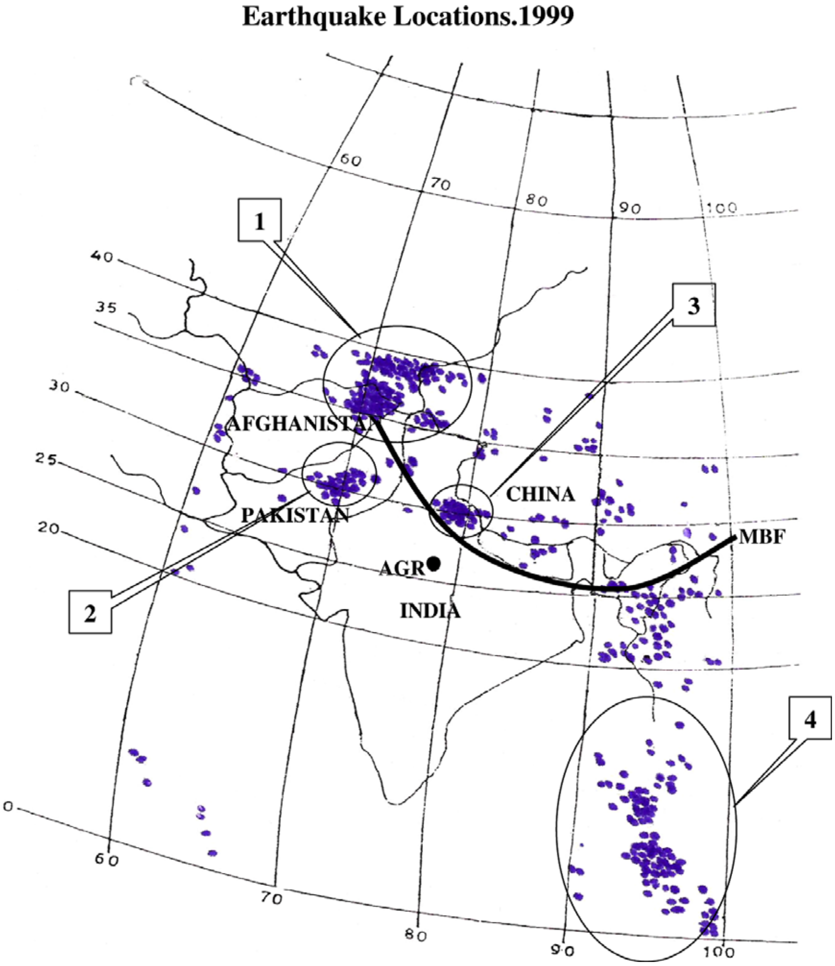


Fig. 5. The same as Fig. 3 except that the earthquake locations correspond to the year 1999.

Indonesia and in nearby Islands. In the top panel of Fig. 4 we show the number of VLF noise bursts which were recorded in each month of the year 1998 at Agra station, and in the next four panels of Fig. 4 we show the occurrence number of earthquakes corresponding to all magnitudes ($M > 1$) by open histograms and those of large magnitudes ($M > 4.5$) by dark histograms, which occurred in the corresponding months. We then calculate the correlation coefficients between the occurrence number of earthquakes and noise bursts for each location. The results are shown in the top corner of each panel. Here, it may be seen that correlation coefficients are negative for both types of earthquakes for locations 1 and 4, negative and insignificant for location 3, and positive and significant for location 2. The location 2 is in Pakistan at a distance of ≈1170 km from Agra station. The positive and significant correlation in this case is possibly due to the reason that since the whole area is highly prone to seismic activity, the location 2 may be connected with the MBF by sub-faults. The location 3 is at a smaller distance from Agra (1120 km), but it is located in China beyond Himalaya where sub-faults may not be existing. In order to confirm the above result that VLF noise bursts recorded at Agra station are related to earthquakes that occurred near the observation site and main boundary fault, we repeat the above exercise with the data corresponding to the year 1999. In the map of Fig. 5, we show all seismic locations out of which the four prominent locations are encircled and numbered 1 to 4 as in Fig. 3. On comparing these locations with those in Fig. 3, it is seen that all are almost the same except 3, which has moved from a place in China to Chamoli, a place in northern India in the south-west of Himalaya. This location is about 400 km from our observing site at Agra and very close to MBF. In the top panel of Fig. 6, we show the number of noise bursts in each month of the year 1999 and in the next four panels we show the number of earthquakes of magnitudes $M > 1$ and $M > 4.5$ for all the four locations. The results of correlation coefficients are shown in the top corner of each panel. Here we see that the correlation coefficients are positive and significant for locations 1 and 3 and negative and insignificant for other two locations. The correlation coefficient 0.49 for all the magnitudes of earthquakes and 0.57 for magnitude $M > 4.5$ for location 3 are the best correlations in all the cases considered in the two years of data. This is due to the reason that this location is very close to our observing

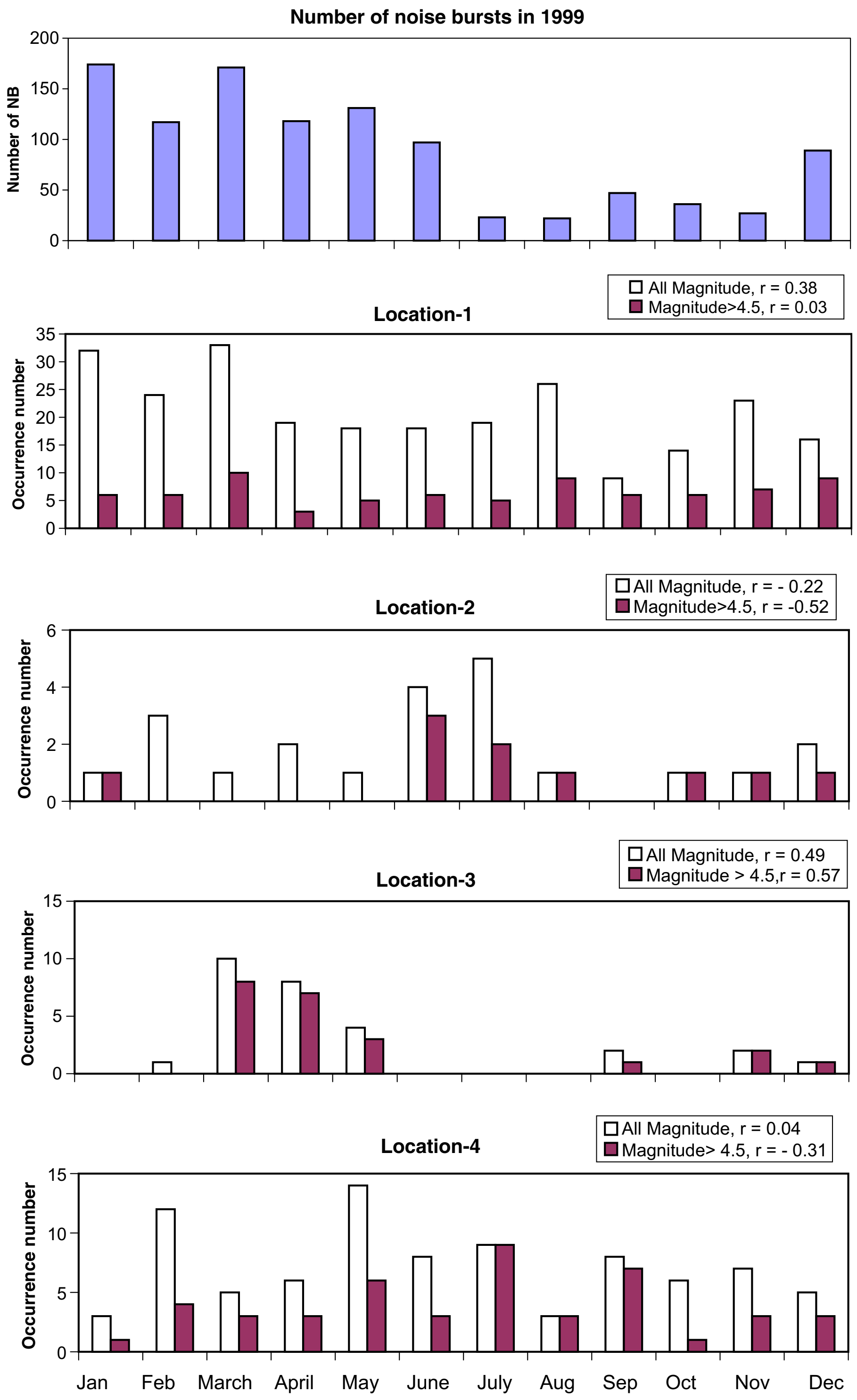


Fig. 6. The same as Fig. 4 except that the data correspond to the year 1999.

station and lies on the main boundary fault. Further, there occurred a seismic swarm between 29 March and 18 April within 50 km area in this location. A correlation of 0.38 for the earthquakes of all magnitude in location 1 which is far away in Afghanistan is surprising, but this region is known to be highly prone to seismic activities and in the present case the locations of the earthquakes are very dense on the fault in comparison to the previous case. Further, it may be noted that in the present case negative and insignificant correlation are found between the VLF data and earthquakes in location 2. This may possibly generate a question as to why this location plays a major role during 1998 and no role in the next year 1999. In order to explain this, it may be mentioned here that the role of location 2

Table 1
Test for null hypothesis using the data of the year 1998

Location	M	Coefficient of correlation R	Test statistic computed for null hypothesis	Probability for $R = 0$
Location-2	$M > 1$	0.35	1.057	0.321
	$M > 4.5$	0.42	1.310	0.226
Location-3	$M > 4.5$	0.006	0.017	0.986

Table 2
Test for null hypothesis using the data of the year 1999

Location	M	Coefficient of correlation R	Test statistic computed for null hypothesis	Probability for $R = 0$
Location-1	$M > 1$	0.38	1.299	0.223
	$M > 4.5$	0.03	0.095	0.926
Location-3	$M > 1$	0.49	1.777	0.105
	$M > 4.5$	0.57	2.194	0.052
Location-4	$M > 1$	0.04	0.127	0.901

was masked by that of location 3 in the year 1999 because of seismic swarm during the months of March and April at Chamoli which is relatively much closer to Agra station and located at main boundary fault. However, a better acceptance of this explanation will be possible after we analyse the digital data for more years in due course of time.

In Tables 1 and 2, we have tested the level of null hypothesis for positive correlations between the two kinds of data during the years 1998 and 1999 respectively. The tables show the magnitudes of earthquakes (M), correlation coefficients between number of earthquakes and number of noise bursts (R), test statistics computed for null hypothesis, and probability for $R = 0$ which is the test of null hypothesis. The values in the last column should lie between 0.01 and 0.05 for best results. In Table 1 the lowest value of 0.226 corresponds to the earthquakes of magnitude ($M > 4.5$) in location 2. This is not a very satisfactory result in view of the criteria of null hypothesis even though a significant positive correlation exists between the two kinds of data. In Table 2, the best results are obtained for location 3 which are 0.05 for $M > 4.5$ and 0.105 for all magnitudes. The level of null hypothesis in this case confirms our result that emissions are generated from location 3. This result is due to the reason that beside the location being closest to observing station and main boundary fault, there was a seismic swarm activity which lasted for long period from 29 March 1999 to April 1999. Singh et al. (2003) have shown that during this period the noise burst activity recorded by the borehole antenna was higher than that recorded by the terrestrial antenna, indicating that during seismic swarm period electrical activity under the ground is enhanced considerably.

In order to make a complete picture and give further support to our finding that VLF noise bursts recorded at Agra station are correlated with seismic activities, we plot a graph similar to that of Figs. 4 and 6 in Fig. 7 for a cumulative number of earthquakes including all locations for both the years and find correlation with noise bursts recorded at the station in the respective year. It may be seen here that the correlation is negative for the year 1998 and very good for the year 1999 for all magnitudes of earthquakes. This is in conformity with the earlier results in which the relationship between noise bursts and earthquakes for the year 1998 was not approved by null hypothesis, whereas the same for the year 1999 was highly approved. As we have mentioned earlier a possible reason for good relationship between the two events for the year 1999 may possibly be the fact that location 3 was very close to Agra station and located at main boundary fault. Since during the year 1998 all the locations were at relatively longer distances from Agra , it is possible that seismogenic signals were masked by other types of natural and man-made signals such as lightning, local radio transmission and other types of noises, hence there was no good correlation with the earthquakes.

Next, we calculate the percentage of correlation between the number of days of earthquakes and number of days of noise bursts occurring on the same days for all the four locations. An example of the method of calculation is as follows; if there were 10 days of earthquakes and 24 days of VLF noise bursts in the month of May, and out of 10 days of earthquakes 8 days coincided with the same number of days of noise burst, then the percentage of correlation will be 80%. The results of calculation are shown for the two years in top and bottom panels of Fig. 8. From the top panel it is seen that the correlations are high during the months between April and June and October and December and low between July and September. A possible reason for low correlation during July to September is that these months correspond to rainy season at Agra during which VLF data generated from earthquakes are vitiated by VLF emissions produced by lightning. In the bottom panel, the large percentage of correlation during the months of March and April is due to the seismic swarm activity in the Chamoli region as mentioned earlier.

Now the question arises how the VLF signals propagate from earthquake sources located in Afghanistan, Pakistan and Chamoli in India to our observing station at Agra in view of high attenuation at such frequencies in the crust and skin effect. In order to solve the problem of long distance propagation of seismo-electromagnetic signals, it has been suggested that signals generated at source are propagated through seismic fault in a manner similar to propagation in earth–ionosphere waveguide and reached the observing station without much attenuation. The concept of waveguide in the crust was generated first by Wait (1971) on the basis of theoretical treatment and later on studied extensively by others (Yoshino, 1991; Kingsley, 1989). Since we have a similar case of existence of a big fault and there are transverse conducting channels across it near Delhi and Agra (Arora and Reddy, 1995), it is possible that the VLF signals generated from above-mentioned

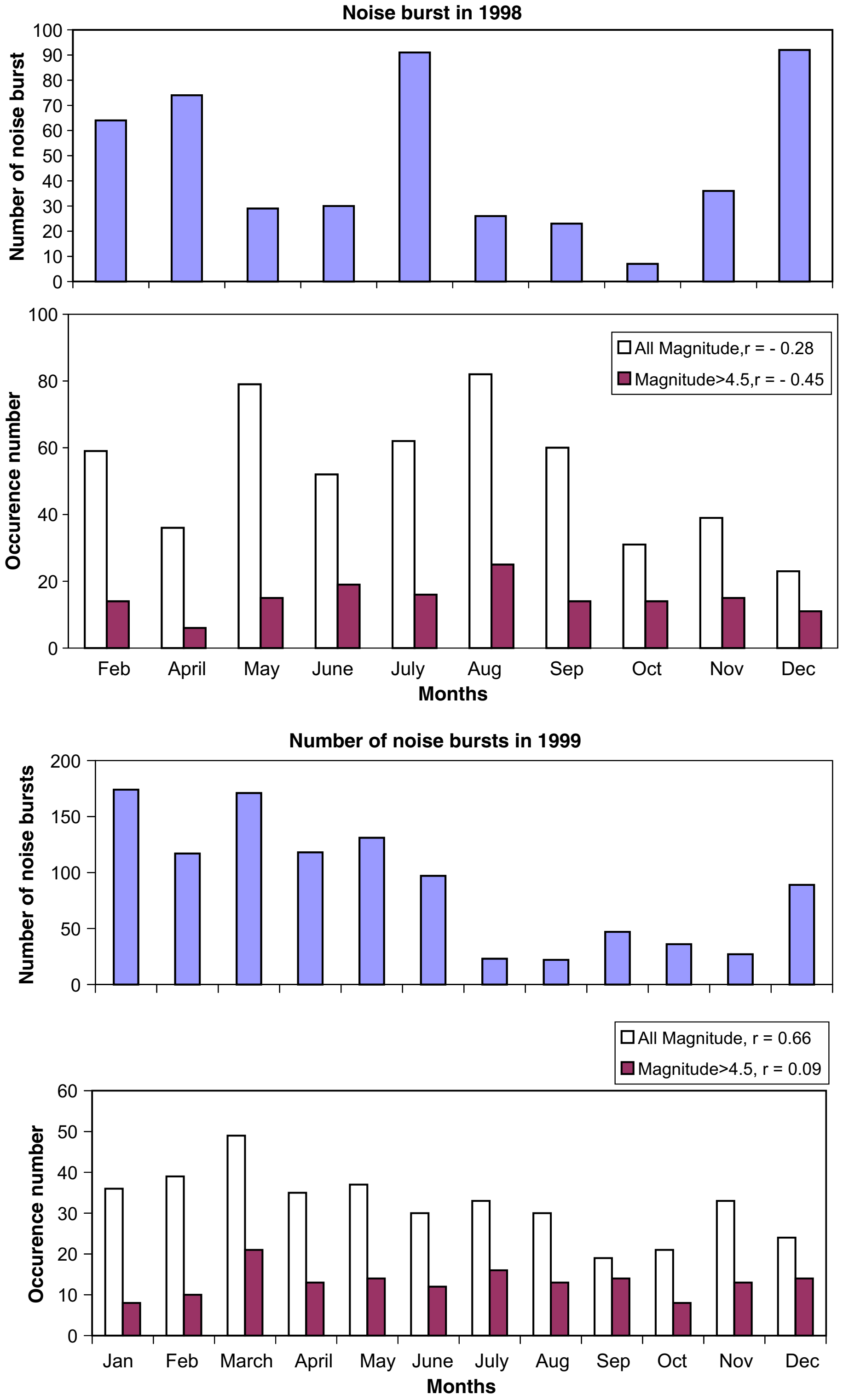
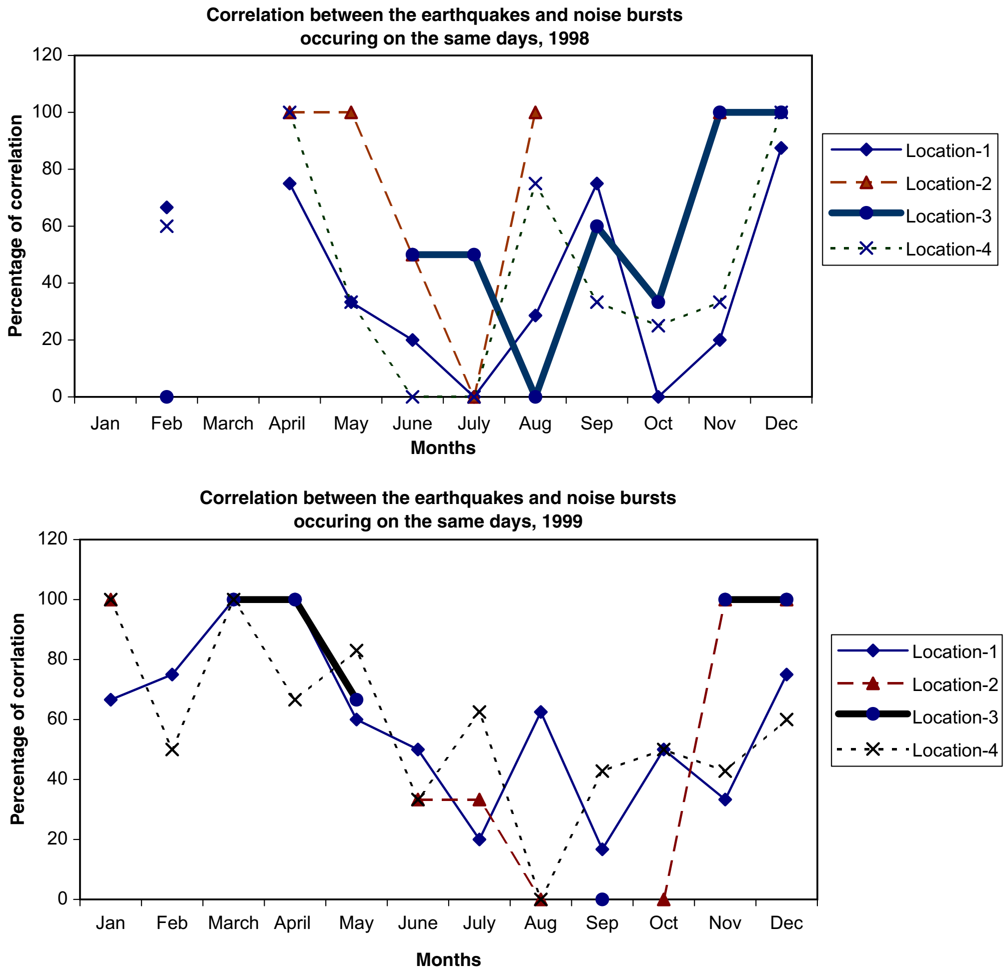


Fig. 7. Correlation between noise burst activities and cumulative number of earthquakes occurring in the four locations for the years 1998 and 1999.

seismic sources are propagated to Agra through MBF and transverse conducting channels. However, this explanation fails to be accepted in view of the fact that the conductivity in a fault is higher than those in the surrounding rocks. Further, a fault filled with air is unlikely and conductivity in water filled fault will be much higher. It is for this reason that Park et al. (1996) have considered resistivity of 1000 Ω m for the surrounding rocks and 10 Ω m for a 500 m wide and 20 km deep fault to explain the propagation of low frequency signals. The other possibility is that since foci of most of the devastating earthquakes lie in the middle layer crust approximately between 7 and



Correlation between the earthquakes and noise bursts occuring on the same days, 1998

Correlation between the earthquakes and noise bursts occuring on the same days, 1999

Fig. 8. Percentage of correlation between the days of earthquakes and the days of VLF noise bursts observed on the same days for the years 1998 and 1999.

35 km which is characterized by low conductivity in the range 10^{-4} to 10^{-6} S/m, the VLF signals generated from the source region are propagated to long distances through the middle layer itself which acts as waveguide. This model was suggested by Tsarev and Sasaki (1994) for ULF–ELF propagation to long distances. They suggested that such signals could be observed on earth surface through "windows" of low conductivity in the upper layer which are formed as a result of some special geological formation. Employing this model and conductivity of middle layer as mentioned above, they have made estimates of propagation distances for ULF and ELF signals. They have shown that the ULF signals may be propagated 100–1000 km and ELF signals 10–100 km in this model. Though this model appears to be good for ULF and ELF signals, it may not be so for VLF signals of frequency 3 kHz because the computed distance will be very small as compared to that between Chamoli and Agra which is 400 km. Singh et al. (2004) have calculated the attenuation suffered by VLF signals by employing two models; one for upper crust and skin layer (conductivity = 10^{-2} S/m) and the other for middle layer crust (conductivity = 10^{-4} S/m). They have found that attenuation at 3 kHz in the upper layer crust is 94 dB/km and in the middle layer crust it is 13 dB/km. Keeping in view the large attenuation of VLF signals in the crust, they have suggested a model in which the signal is transmitted over the epicenter of the earthquakes through the "windows" of low conductivity created by some special geological formation and then propagated to Agra in earth–ionosphere waveguide propagation where it is picked up by borehole antenna in significant amplitude because of its large size. This model was, in fact, suggested first by Mognaschi (2002) for the reception of ULF–ELF signals on the ground and then by Singh et al. (2003) for explaining the positive correlation between the VLF data and seismic activity in Chamoli. However, a question not answered properly by these authors is that if the signal propagated through the earth–ionosphere waveguide, it should have been recorded by terrestrial antenna also.

Although, the problem of long distance propagation of VLF signal is yet to be solved on a sound footing based both on experimental observation and theoretical treatment, we suggest a possible mode of propagation through the middle layer crust itself to long distances. The model we

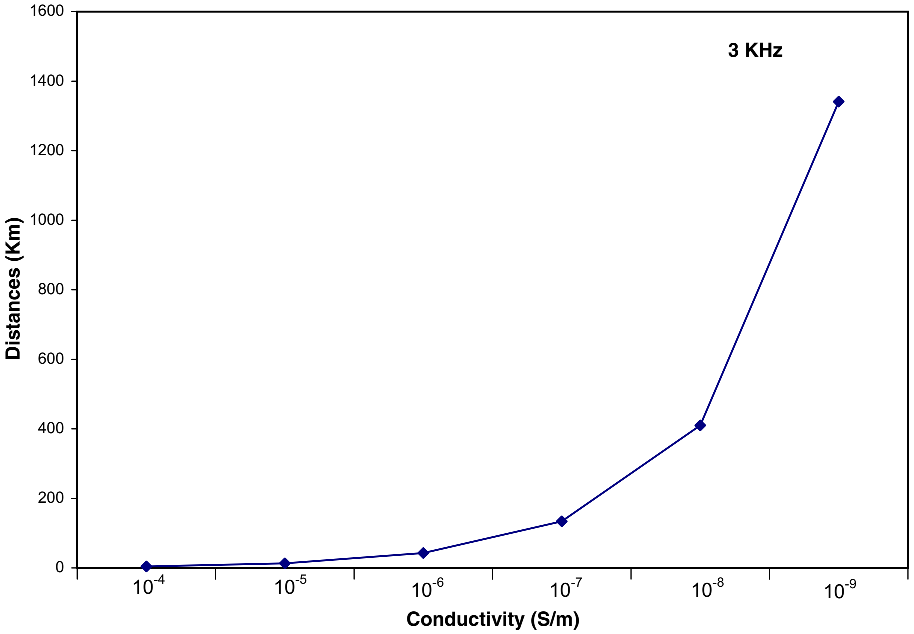


Fig. 9. Variations of distance traveled by 3 kHz VLF electromagnetic signals at different conductivities in the middle layer crust.

consider is similar to that of Tsarev and Sasaki (1994), but the conductivity of the middle layer crust is less than 10^{-6} S/m. Here, we make an estimate of the distance of propagation for the signals of frequency 3 kHz in the modified model.

We use the expression (Miah, 1982).

$$E_x = E_0 e^{-\alpha x} \tag{1}$$

where

E_0	electric field strength at the source
E_x	electric field observed at the distance x from the source
α	$\sqrt{\sigma\omega\mu/2}$ – attenuation constant
μ	$4\pi\times10^{-7}$ H/m, magnetic permeability of the medium
ω	angular frequency
σ	conductivity

Further, we assume that VLF electromagnetic wave is attenuated up to 99% of its strength during the propagation in the medium of conductivity σ and only 1% reach the observing station.

$$\text{Then } E_x/E_0 = 1/100 = e^{-\alpha rmx} \tag{2}$$

$$\text{Hence, } x \approx 6.5/\sqrt{\sigma\omega\mu}\ \text{m} \tag{3}$$

Using expression (3) we first calculate the distances traveled by signals of frequencies 100 Hz, 1 kHz, and 3 kHz in a crust model having conductivity $\sigma = 10^{-6}$ S/m. We find the distances to be 233 km, 72 km, and 48 km, respectively. The first two distances are within the range of 100–1000 km and 10–100 km as reported by Tsarev and Sasaki (1994), but the distance for the signal of frequency 3 kHz is very small (~48 km) in comparison to that between Chamoli and Agra (~400 km). Hence, the VLF signals cannot propagate to Agra in this model. To ascertain the order of conductivity required for signal propagation to a distance of 400 km, we repeat the calculation in different conductivity models and present the results in Fig. 9. Here, it may be noted that the conductivities shown at the abscissa of the figure are assumed for the purpose of determining the required travel distance for the signal of frequency 3 kHz and they should not be taken as the observed conductivity of the medium. From Fig. 9, we find that the required conductivity allowing a travel distance of 400 km is ~10^{-8} S/m. Now, the question arises whether the middle layer crust between Chamoli and Agra may be characterized by a conductivity of this order. In order to answer this question, we may mention here that till now there is no direct in situ measurement of the electrical conductivity of the middle layer crust in the region. However, there are evidences of conductivity measurements of rock samples in laboratory experiments and one example may be quoted of Keller (1989). He has deduced conductivities of rock samples taken from oceanic crust and middle layer continental crust and found them to be ~10^{-10} S/m and 10^{-8} S/m respectively. This result suggests that the conductivity of the middle layer crust may be of that order. One possibility for such a reduced conductivity may be due to existence of prominent fault in this region. However, a detailed in situ measurement is required to confirm the existence of low conductivity and its relation with the fault.

Acknowledgements

The authors are thankful to the Department of Science and Technology, New Delhi for providing financial support in the form of a major research project. This work is supported partially also by CSIR, New Delhi through a research grant under Emeritus scientist scheme for which two of the authors (B. Singh and Manoj Kumar) are highly grateful to CSIR.

References

Arora, B.R., Reddy, C.D., 1995. Deep conduction structure of frontal belt of the Garhwa Himalaya and their seismotectonic significance. In Uttarkashi earthquake. Geol. Soc. India, Memoir. No. 30, pp. 109–124.

Enomoto, Y., Hashimoto, H., 1992. Transient electrical activity accompanying rock rupture under indentation loading. Tectonophysics 211, 337.

Enomoto, Y., Hashimoto, H., 1994. Anomalous electric signal detected before recent Earthquakes in Japan near Tsukuba. In: Hayakawa, M., Fujinawa, Y. (Eds.), Electromagnetic phenomena related to earthquake prediction. Terra. Sci. Pub. Co., Tokyo, pp. 261–270.

Fraser-Smith, A.C., Bernardi, A., McGill, P.R., Ladd, M.E., Helliwell, R.A., Villard Jr., O.G., 1990. Low frequency magnetic field measurements near the epicenter of the $M = 7.1$ Loma Prieta earthquake. Geophys. Res. Lett. 17, 1465–1468.

Fujinawa, Y., Takahashi, K., 1990. Emissions of electromagnetic radiation preceding the Ito seismic swarm of 1989. Nature 347, 376–378.

Fujinawa, Y., Takahashi, K., 1994. Anomalous VLF subsurface electric field changes preceeding earthquake. In: Hayakawa, M., Fujinawa, Y. (Eds.), Electromagnetic phenomena related to earthquake prediction. Terra. Sci. Pub. Co., Tokyo, pp. 131–148.

Fujinawa, Y., Takahashi, K., 1995. Electromagnetic radiations at the time of the great Kurile Island earthquake of 1994. Paper presented at IUGG meeting, Boulder, Colorado, July 2–14.

Geller, R.J., 1991. Shake-up for earthquake prediction. Nature 352, 275–276.

Geller, R.J., 1996. ed-1 debate on evaluation on VAN method. Geophys. Res. Lett. 23, 1291–1452.

Gokhberg, M.B., Morgunov, V.A., Yoshino, T., Tomizawa, I., 1982. Experimental measurements of electromagnetic emissions possibly related to earthquake in Japan. J. Geophys. Res. 87, 7824–7828.

Hata, M., Yabashi, S., 1994. Observations of ELF radiations related to volcanic and earthquake activities. In: Hayakawa, M., Fujinawa, Y. (Eds.), Electromagnetic phenomena related to earthquake prediction. Terra. Sci. Pub. Co., Tokyo, pp. 159–174.

Hayakawa, M., 1999. Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes. TERRAPUB, pp. 996.

Hayakawa, M., Fujinawa, Y., 1994. Electromagnitic Phenomena Related to Earthquake Prediction. TERRAPUB, pp. 667.

Hayakawa, M., Molchanov, O.A., 2002. Seismo Electromagnetics: Lithosphere–Atmosphere–Ionosphere Coupling. TERRAPUB, pp. 478.

Hayakawa, M., Kawate, R., Molchanov, O.A., Yumoto, K., 1996. Results of ultra low frequency magnetic field measurement during the Guam earthquake of 8 August 1993. Geophys. Res. Lett. 23, 241–244.

Keller, G.V., 1989. In: Practical handbook of physical properties of rocks and minerals. John Willey & Sons, N.Y., p. 361.

Kingsley, S.P., 1989. On the possibilities for detecting radio emissions from earthquakes. Nuova Cimento 12, 117.

Miah, M.A.W., 1982. Fundamentals of electromagnetics. Tata McGraw-Hill Publishing Company Limited, pp. 284–285.

Mognaschi, E.R., 2002. On the possible origin propagation and detectability of electromagnetic precursors of earthquakes. Atti Ticinencidi Scienze delta Terra 43, 111–118.

Molchanov, O.A., Kopytenko, Yu.A., Vormov, P.M., Kopytenko, E.A., Matiashvili, T.G., Fraser-Smith, A.C., Bernardi, A., 1992. Results of ULF magnetic field measurement near the epicenter of Spitak ($M = 6.9$) and Loma Prieta ($M = 7$) earthquakes: Comparative analysis. Geophys. Res. Lett. 19, 1495–1498.

Molchanov, O.A., Mazhaera, O.A., Goliavin, A.N., Hayakawa, M., 1993. Observation by the Intercosmos-24 satellite of ELF–VLF electromagnetic emissions associated with earthquakes. Ann. Geophys. 11, 431–440.

Molchanov, O.A., Hayakawa, M., Rafalsks, V.A., 1995. Penetration characteristics of electromagnetic emissions from an underground seismic sources into the atmosphere, ionosphere and magnetosphere. J. Geophys. Res. 100, 1691–1712.

Nitsan, U., 1997. Electromagnetic emissions accompanying fracture of quartz bearing rocks. Geophys. Res. Lett. 4, 333–337.

Ogawa, T., Oike, K., Miura, T., 1985. Electromagnetic radiations from rocks. J. Geophys. Res. 90, 6245–6249.

Oike, K., Ogawa, T., 1986. Electromagnetic radiations from shallow earthquakes observed in the LF range. J. Geomag. Geoelectic. 38, 1031–1040.

Park, S.K., Johnston, M.J.S., Madden, T.R., Morgan, F.D., Morrison, F., 1993. Electromagnetic precursor to earthquakes in ULF band: A review of observation and mechanism. Rev. Geophys. 31, 117–132.

Park, S.K., Srauss, P.J., Aseves, R.L., 1996. In: The critical review of VANEarthquake prediction from seismic electric signal. Word Scientific Publishing Co., Singapore, p. 257.

Parrot, M., Mogilvesky, M.M., 1989. VLF emissions associated with earthquakes and observed in the ionosphere and magnetosphere. Phys. Earth Planet Inter. 23, 86–99.

Qian, A., Yian, J., Cao, H., Shi, S., Lu, Z., Li, J., Ren, K., 1994. Results of observations on seismo-electromagnetic waves at two earthquake experimental areas in China. In: Hayakawa, M., Fujinawa, Y. (Eds.), Electromagnetic phenomena related to earthquake prediction. Terra. Sci. Pub. Co., Tokyo, pp. 205–211.

Singh, R.P., Singh, B., 2000. Detection and identification of VLF seismo-electromagnetic signals. Curr. Sci. 78 (4), 492–498.

Singh, B., Singh, R.P., Bansal, V., Kumar, M., Hayakawa, M., 1999. Anomalous VLF subsurface electric field changes associated with earthquakes and nuclear explosions observed at Agra. J. Atmos. Electr. 19, 119–134.

Singh, R.P., Singh, B., Bansal, V., 2000. VLF electromagnetic noise bursts related to major seismic activities at Agra. J. Atmos. Electr. 20, 7–20.

Singh, R.P., Mishra, P.K., Singh, B., 2001. Anomalous VLF electric field perturbation associated with Chamoli earthquake of March/April 1999. Curr. Sci. 80 (11), 101–106.

Singh, R.P., Singh, B., Mishra, P.K., Hayakawa, M., 2003. On the lithosphere atmosphere coupling of seismo-electromagnetic signals. Radio Sci. 38 (4), 1065. doi:10.1029/2002RS 002683.

Singh, R.P., Singh, B., Kushwah, V., Singh, R.V., 2004. Attenuation of ULF–VLF seismo-electromagnetic signals and their propagation to long distances. Indian J. Radio Space Phys. 33, 189–195.

Tsarev, V.A., Sasaki, H., 1994. Low frequency seismogenic electromagnetic radiations: How does it propagate in the earth's crust and where can it be detected? In: Hayakawa, M. (Ed.), Atmospheric and ionospheric electromagnetic phenomena associated with earthquakes. Terra. Sci. Pub. Co., Tokyo, pp. 383–393.

Varotsos, P., Alexopoulos, K., Lazaridov-Varotsos, M., Nagao, T., 1993. Earthquake predictions issued in Greece by seismic electric signals since February 6, 1990. Tectonophysics 224, 269–288.

Wait, J.R., 1971. Electromagnetic wave propagation in the Earth's crust. Reprints of International Symposium on Electromagnetic Wave Theory, USSR, Tbilisi, September 15,1971, "Nauka" Moscow, pp. 830–835.

Warwick, J.W., Stocker, C., Meyer, T.R., 1982. Radio emission associated with rock fracture: possible application to the great Chilean earthquake of May 22, 1960. J. Geophys. Res. 87, 2851–2859.

Yoshino, T., 1991. Low frequency seismogenic electromagnetic emissions as precursors to the earthquakes and volcanic eruptions in Japan. J. Sci. Explor. 5, 121–144.