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Detection and identification of VLF seismo-electromagnetic signals

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The vertical electric field components of the electromagnetic emissions associated with earthquakes have been monitored at the Agra station (geographical lat. 27.2°N, geographical long. 78°E) since February 1998 using a borehole antenna. Analysis of one year of data has shown that large variations in the electric field occur, mostly in the form of noise bursts, both prior to and after the occurrence of major earthquakes. In the present paper some selected cases of noise bursts have been chosen to identify the waveforms of seismogenic emissions. We find that among various types of noise bursts recorded, the seismogenic noise bursts are either slowly varying, square wave patterns, or periodic variations. The long distance propagation of such signals is interpreted in terms of waveguide mode propagation through conductive channels across the main boundary seismic fault existing from the north-west to the north-east around 200 km from the observing station.

ELECTROMAGNETIC emissions of various frequencies ranging from ULF to HF have been observed both on the ground and in the ionosphere during earthquakes[1–6]. The association of electromagnetic emissions with seismic activities has been confirmed from laboratory experiments employing rock fracturing also[2,7–9]. Parrot[10] and Hayakawa[11] have reviewed thoroughly the work done in this field and Hayakawa and Fujinawa[12] and Hayakawa[13] have presented recent works in two excellent monographs.

Recently[14,15], we have shown by measuring the vertical component of electromagnetic emissions using a borehole antenna that electric field changes appear in the form of noise bursts which correspond to some major impending earthquakes. From a detailed analysis of the data obtained during 1998, we conclude that out of the total number of noise bursts associated with major earthquakes that occurred in different months, about 60% occurred prior to the earthquakes as precursors. This has indicated that monitoring of electromagnetic field components associated with earthquakes may prove to be an important tool in the field of earthquake prediction. In the present paper we make an attempt to identify the type of electromagnetic signals that are associated with seismic activities by identifying the type of signals that are responsible for peak noise bursts activities and by monitoring such signals using a vertical

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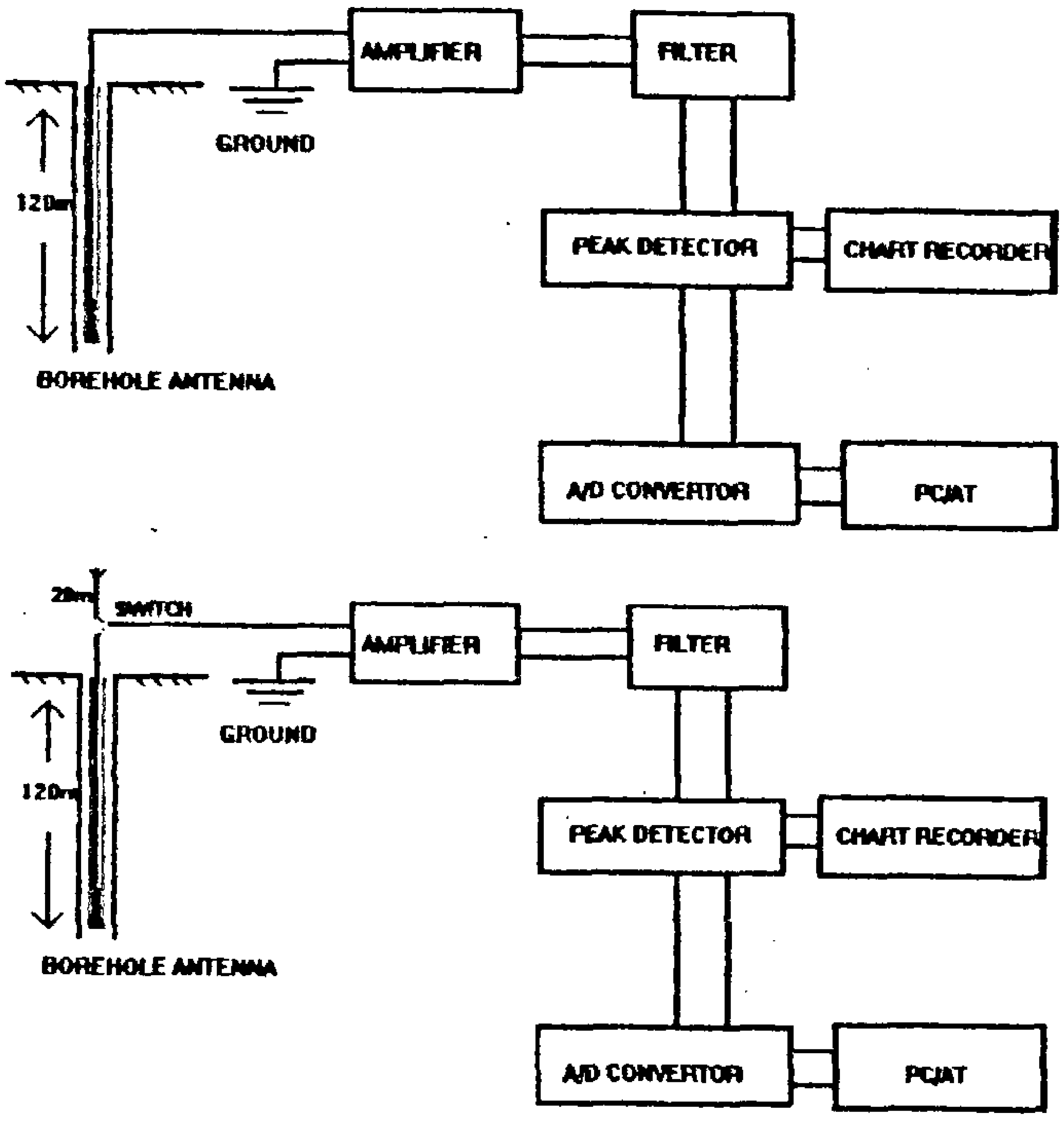

Figure 1. Experimental arrangement for monitoring electric field emissions associated with earthquakes at Agra employing borehole antenna (top) and borehole and terrestrial antenna (bottom).

terrestrial antenna in conjunction with the borehole antenna.

The experimental set-up is shown in Figure 1. It is similar to the one we had used earlier[14,15] except that here a vertical terrestrial antenna has been employed later in conjunction with the borehole antenna. The borehole antenna is a naked copper wire of 120 m length and 4 mm diameter placed in a water-tight PVC pipe of 3.75 cm diameter with its lower end tightely fitted with an insulating black cork at the bottom. This is placed in another PVC pipe of 7.5 cm diameter which is open at both ends and is used to reduce the upward thrust (buoyancy) of underground water on the pipe containing the antenna. Another electrode is placed 3 m down in contact with the ground to provide earth terminal. The natural potential between these two electrodes is found to be about 20 mV in a noise-free environment. These two electrodes are connected to amplifiers (transistorized pre and main amplifiers of gains 40 dB each) and the amplified signal is passed through the active band pass filter (peak frequency 3 kHz, BW~ 250 Hz), peak detector, and finally to a DC ink chart recorder model A602C, Esterline Angus, USA. The frequency of the band pass filter is chosen to be 3 kHz as a trade off between the unwanted noise at lower frequencies caused by power line radiations and their harmonics, atmospherics, etc. and increasing attenuation with frequency. The chart speed was earlier set at 1.87 cm (3/4") per minute but later slowed down to 0.5 cm (1/5") per minute. The chart recorder measured the current (0–5 mA) and its internal resistance was 65 Ω. However, we have modified it to measure the current in the range 0–10 mA. The enhancement in the amplitude of 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 dB = $20\log_{10}$ (amplitude enhancement).

Observations were taken round the clock except for a couple of breaks, two hours in the morning between 0700 and 0900 h and two hours in the evening between 1700 and 1900 h, mostly using the borehole antenna at Bichpuri, a rural area, about 12 km west of Agra where local electric and electromagnetic noises are very low. The terrestrial antenna of height 20 m has been used occasionally from December 1998 onwards. It has been switched on intermittently during the onset of noise bursts to compare the results with those obtained by the borehole antenna.

In our earlier paper[15], we had shown the various types of noise bursts which have been recorded at our station, some of which were similar to those recorded by earlier workers also[16]. This is reproduced in Figure 2, where the variation during normal calm days is shown by a straight line in the panel O, whereas noise bursts shown in panels E, F and G are due to identified sources such as a nearby radio station, local lightning, and solar flare effects, respectively. The sources of other waveforms shown in panels Q to D are not known, but they have been commonly observed during large seismic activity days. We will show later that seismo-electric signals identified by us are similar to these waveforms.

We have mentioned earlier that the noise burst activities are enhanced in a majority of the cases prior to occurrence of earthquakes. As an example, we show in Figure 3, reproduced from our earlier paper[15], the results obtained during February to December 1998. Similar results have been obtained during the other months also. In Figure 3 the solid and dashed lines indicate the diurnal variation of the noise burst occurrence and average variation, respectively (the average variation is repeated for each month). The downward arrows indicate the major earthquakes that occurred during the respective months and crosses indicate non-availability of data. Intensities of the earthquakes are mentioned above the arrows. The source of earthquake data is India Meteorological Department (IMD), New Delhi. Here, the data for a limited latitude and longitude range between 25° and 40°N, and 60° and 100°E, respectively are considered which cover most seismically-active regions in and around India.

In order to identify the seismo-electric signals, we have chosen four cases in which noise bursts occurred before the earthquakes and four other cases in which noise bursts occurred after the earthquakes. These cases are taken from the panels corresponding to February, April, September, May, June, July, October and

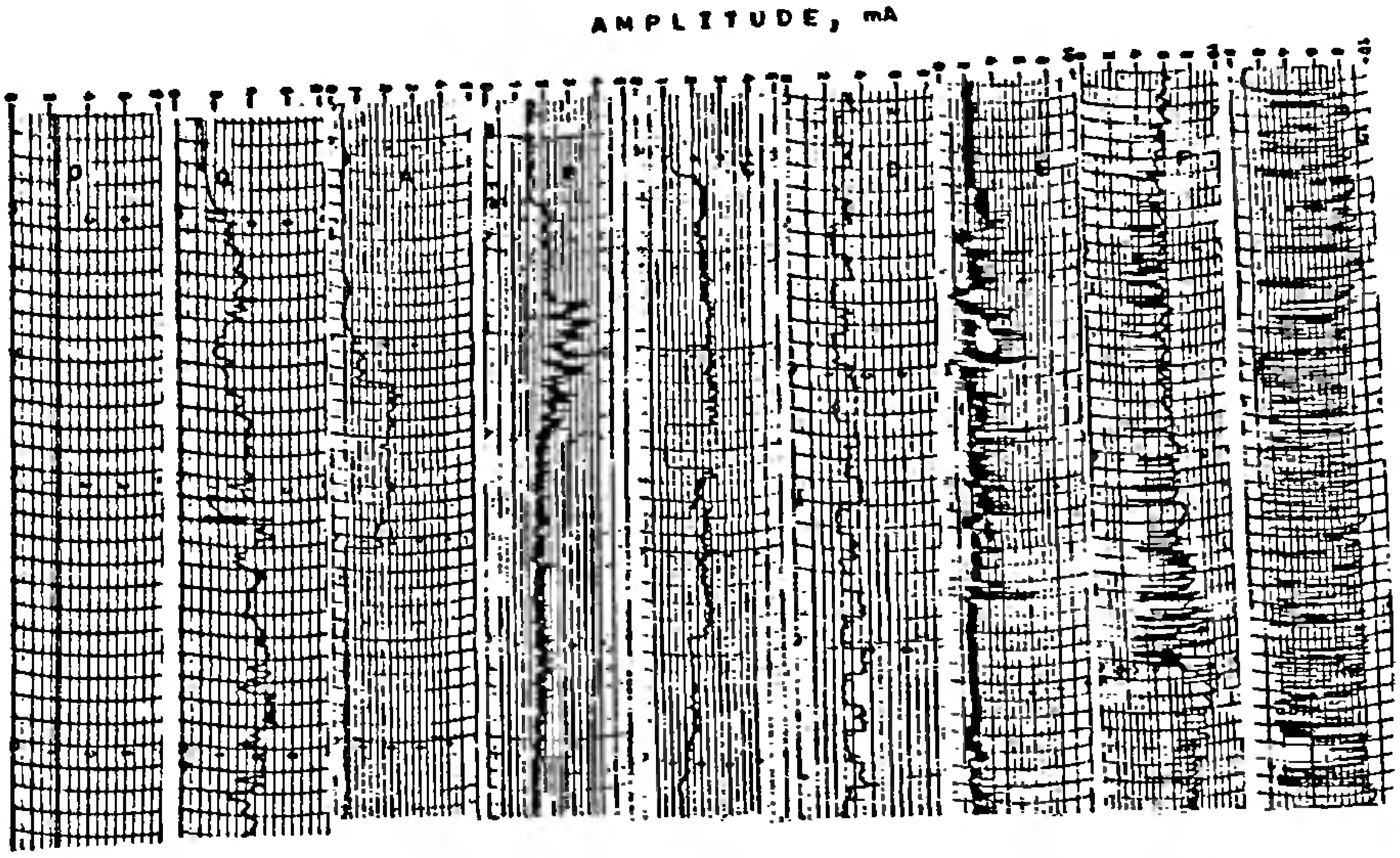

Figure 2. Waveforms of different types of noise bursts recorded at Agra.

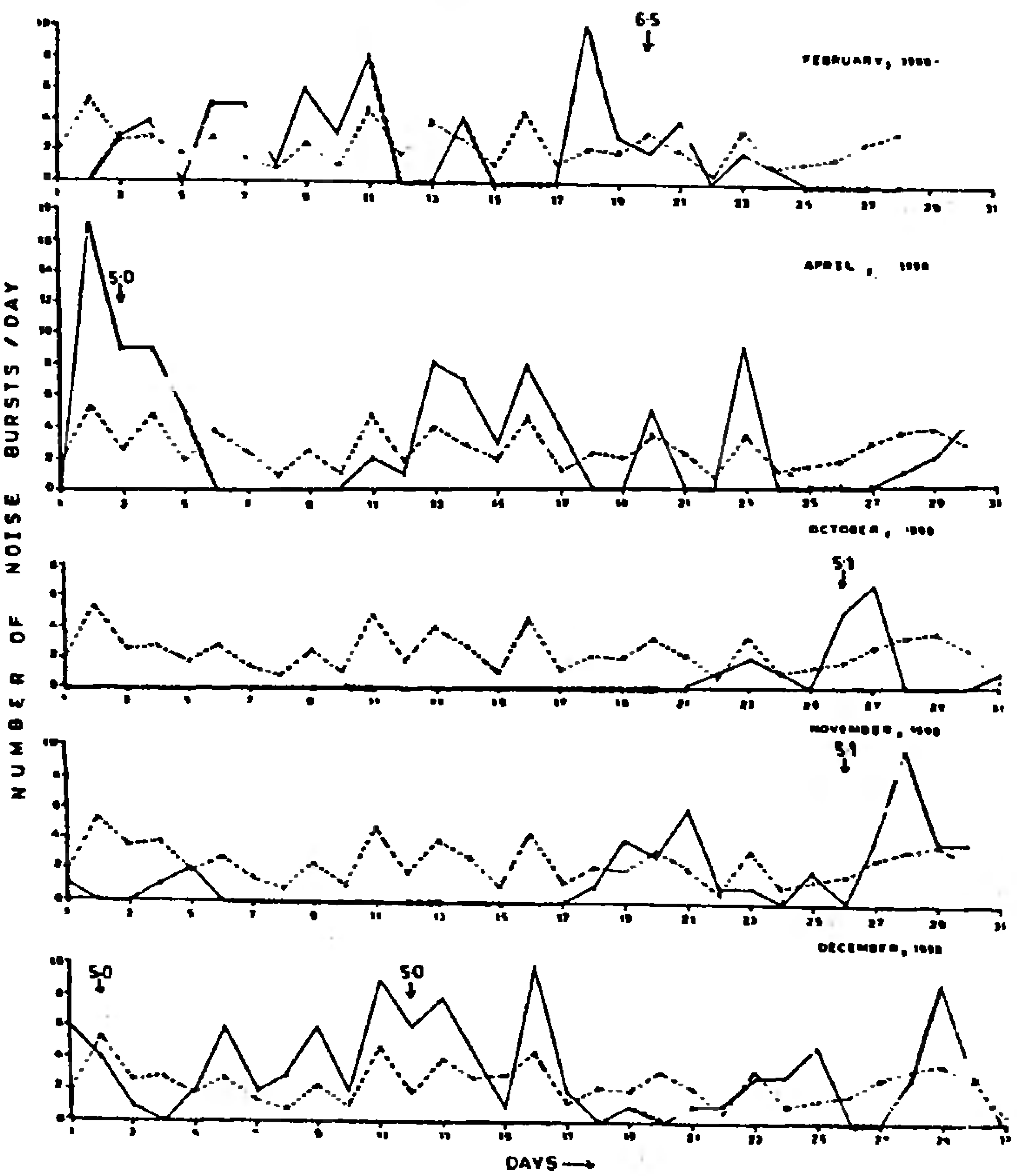

Figure 3. Variation of occurrence number of noise bursts in different months in which spheric activities were pronounced at Agra. The downward arrows indicate the days on which major earthquakes occurred in the month. The intensities of the earthquakes are indicated above the arrows. The dashed lines indicate the average occurrence number for the five months which are repeated in each panel.

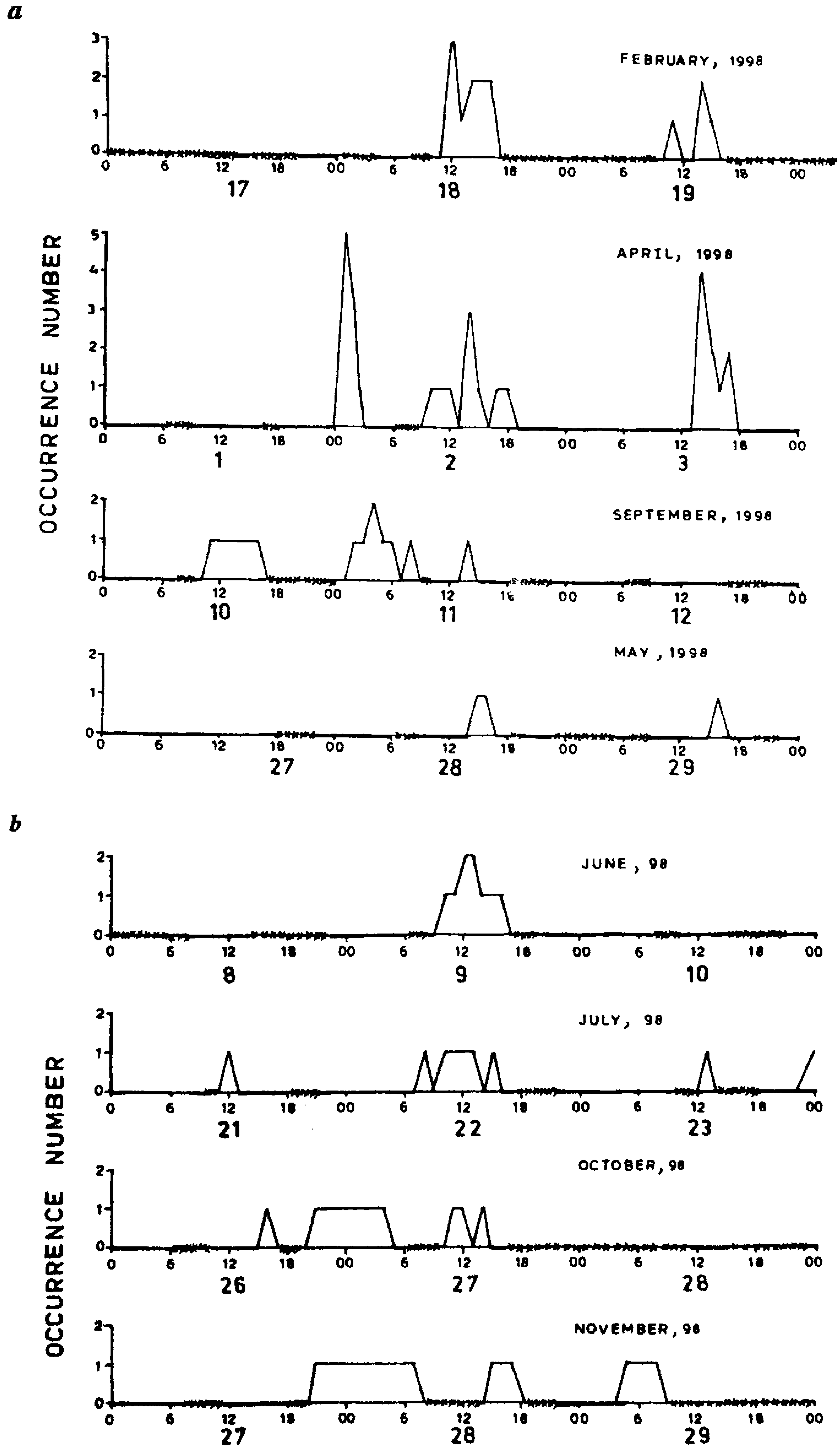

Figure 4. ***a***, Temporal variation of the occurrence number during three days corresponding to major peaks which preceded the earthquakes; ***b***, Same as in ***a***, but corresponding to major peaks which followed the earthquakes.

November, respectively. The results for February, April, October, and November can be seen from Figure 3, whereas those for the other months are not shown for the sake of brevity in the paper. We have plotted the temporal variation of occurrence number for all these cases starting from one day before and ending one day after the days on which peak activities had occurred. The results are shown in Figure 4 *a* and *b*. Assuming that the peak noise bursts associated with earthquakes are produced either due to enhanced activities at a particular time or due to prolonged activities for few hours, we utilize these figures to measure the precursory and delay times of the noise bursts relative to occurrence time of the earthquakes. We find that precursory time of noise bursts lie between 1 h and 2.3 days whereas the delay times lie between 3.5 h and 2.7 days. Further, the waveforms of these seismogenic noise bursts which correspond to the peak and prolonged activities in Figure 4 *a* and *b* resemble to a great extent those shown in panels Q to D in Figure 2.

In order to confirm that the enhanced VLF noise activities are due to earthquakes we have operated the vertical terrestrial antenna intermittently in conjuction with the borehole antenna after the onset of a noise burst. If the source is located either above the surface of the earth between the earth ionosphere waveguide as lightning and spheric activities, or in the ionosphere due to solar flare effect, the amplitude of the noise bursts picked up by the terrestrial antenna would be larger than that picked up by the borehole antenna. This could be because the signals penetrating the ground would suffer higher attenaution in the thin surface layer of the upper crust as a result of skin effect[17]. In contrast, if the seismogenic signals are propagated in the crustal region from underground sources, the borehole antenna will pick up larger amplitudes than the terrestrial antenna. In Figure 5 we have shown two examples in which the borehole antenna has measured larger amplitudes than the terrestrial antenna (first two panels, marked by T), and two examples in which the terrestrial antenna has measured larger amplitude than the borehole antenna (last two panels). The first two examples are associated with the earthquakes that occurred on 2 December 1998 in Assam and 6 December 1998 in Afghanistan, respectively, corresponding to prolonged seismic activities between 8 and 12 December 1998. On the other hand,

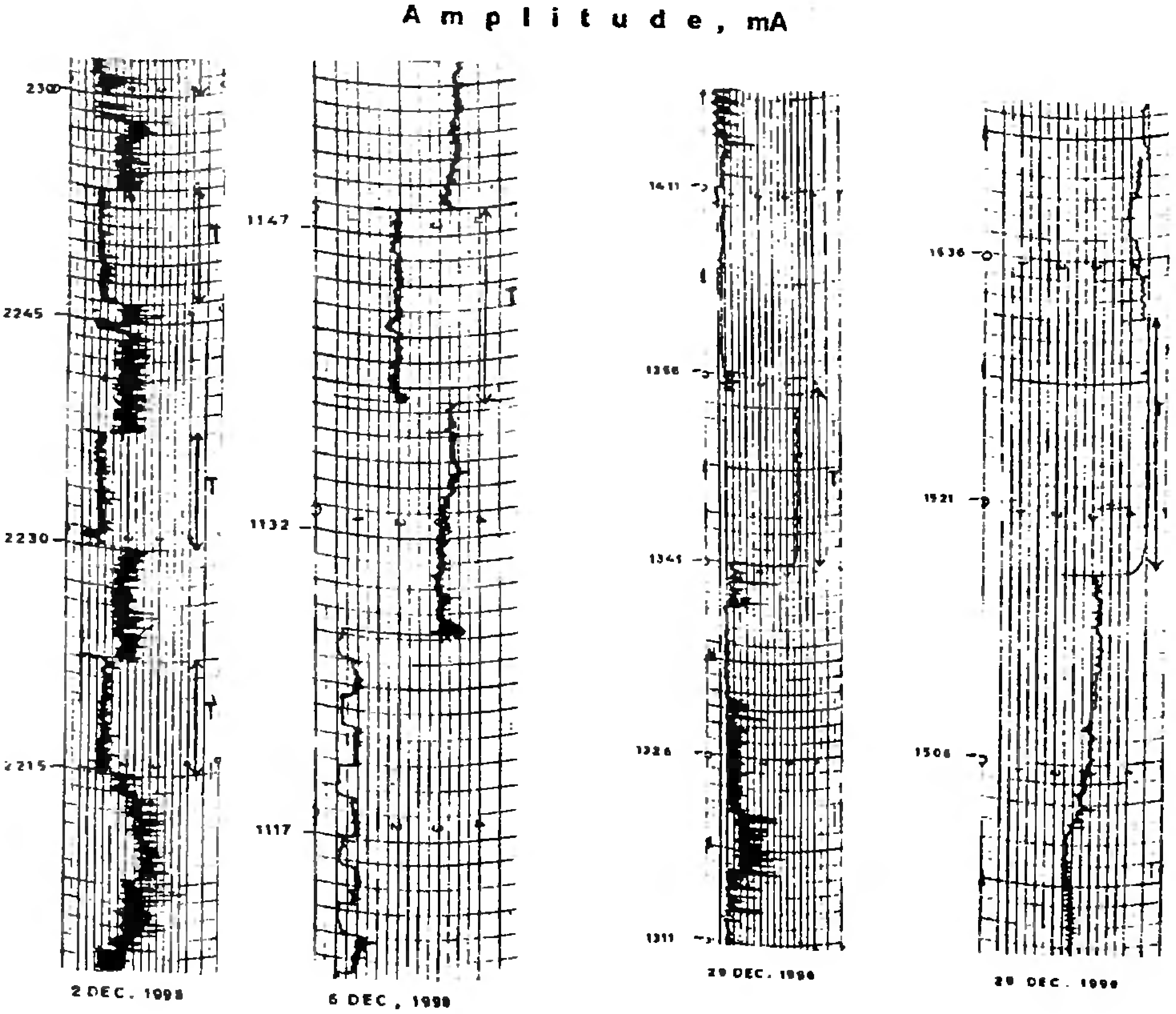

Figure 5. Results of the observations taken by both the borehole and terrestrial antennas during the onset of noise bursts. Segments marked T are those taken by the terrestrial antenna. The first two panels correspond to the days of seismic activities whereas last two correspond to non-seismic days.

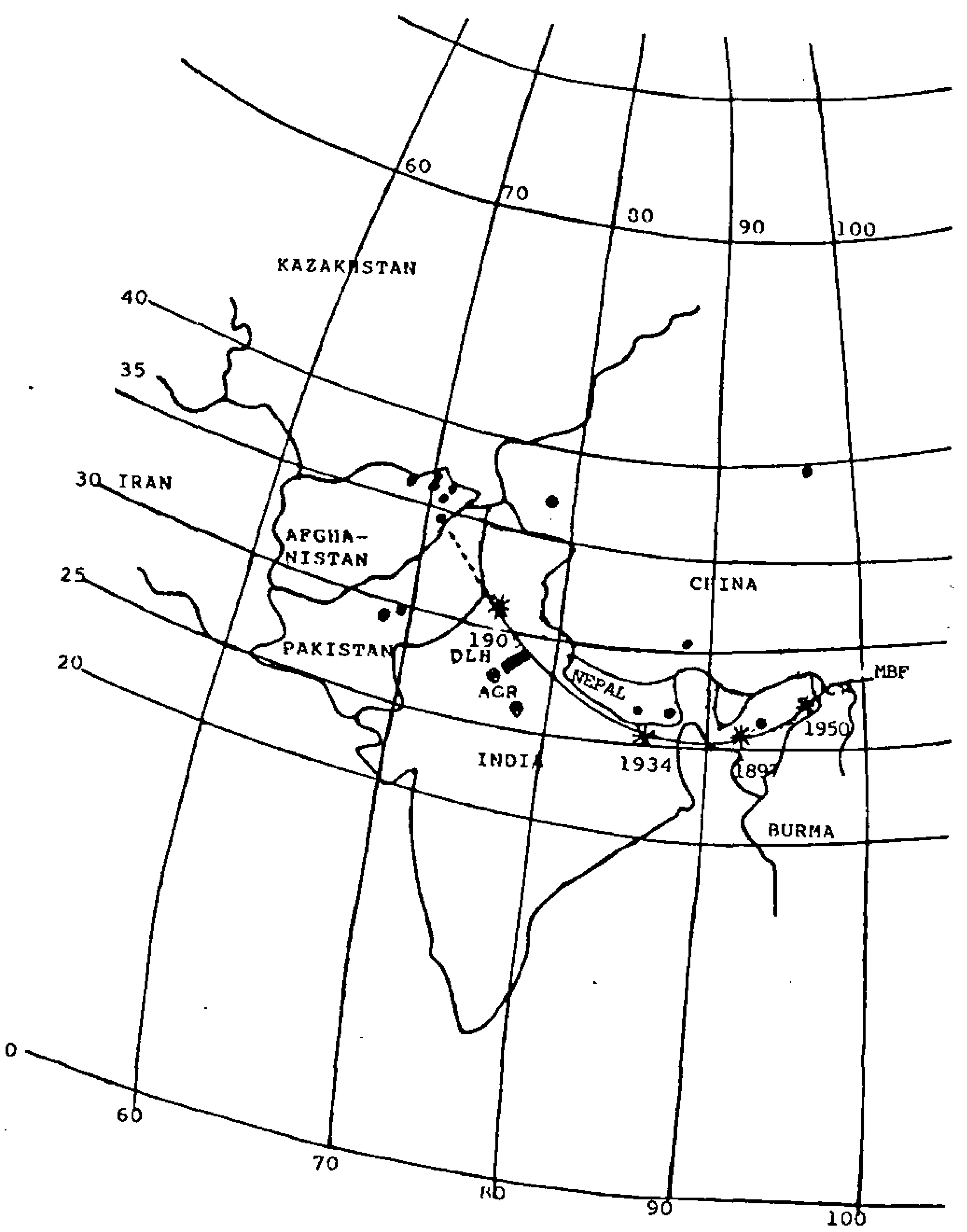

Figure 6. Map showing the location of the observing station at Agra and epicentres of earthquakes (solid circles). The solid curve indicates a main boundary fault. Thick solid line across the fault indicates the conductive channel which is about 200 km from the observing station.

the other two examples are not associated with any seismic activity and may be attributed to local and atmospheric noises produced by sources above the ground.

Our result that there is an increase in the occurrence number of VLF noise bursts prior to an impending earthquake in the majority of cases finds support from the results of earlier workers also. Notable among them are Fujinawa and Takahashi[18] and Enomoto and Hashimoto[19] who have clearly shown precursory time of the noise bursts lying between 0.4 h and 7.8 days measured at several stations in Japan. Similarly, there are also evidences for anomalous electromagnetic radiations occurring before and after the earthquakes[1,20].

Figure 6 shows the earthquakes (solid circles) which have been considered in the present analysis. We find that most earthquakes are concentrated in the north-west and north-east directions, away (>1000 km) from our observing station at Agra. This raises the question as to how the seismo-electromagnetic radiations generated from these places could be propagated to such long distances and observed at Agra. We may refer to the work of Kingsley[21] who has suggested a model indicating that propagation along fault lines might give propagation conditions that are somewhat closer to those of free space. This is a good model for upward (toward the surface) propagation of the emitted radiation. Since in our case the earthquake occurred at a long distance (> 1000 km), active faults lying in the direction from north-west to north-east and passing close to the observing station at Agra are needed to explain the results. From a detailed study of seismicity in India, we find that such an active fault does exist in this direction and has been discussed thoroughly by Indian workers[22,23]. This is shown in Figure 6 by a solid curve. This is the main boundary fault (MBF) along which four most severe earthquakes ($M > 8$) have occurred in the last 100 years. The extension to Afghanistan longitudes by dotted lines has been done arbitrarily by us to show the existence of the fault in this region also and its connection to the MBF. Arora and Reddy[24] have studied the electrical characteristics of some regions near the fault and have found a conductive channel perpendicular to the MBF perhaps aligned along the Delhi–Haridwar fault. This is shown by a thick solid line between Delhi and MBF. Since Agra, Delhi and surrounding areas are in seismic belts and conductive channels lie within 200 km from our station, it will not be difficult for the seismo-electromagnetic waves to be observed at Agra. The long distance precursory signals have been observed by other workers also who conducted observations at different frequencies and measured electric and magnetic fields of the seismogenic emissions. For example, Warwick *et al.*[2] have observed electromagnetic emissions at 18 MHz, 6 days prior to the great Chilean earthquake of 22 May 1960 at distances about 10,000 km from the epicentre. Yoshino and Tomizawa[25] have considered seismo-electromagnetic emissions in the frequency range from 36 Hz to 82 kHz, generated from a number of locations lying between the vicinity of observing station and about 10,000 km, in their statistical analysis to obtain a clear explanation of the source mechanism. It has been suggested that depending upon the conductivity characteristics of rocks, signals generated due to the mechanical distortion may be propagated from hundreds to thousands of kilometers away from the epicentre.

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Luminescence chronology and facies development of Bhur sands in the interfluve region of Central Ganga Plain, India

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Bhur sand ridges in the upland interfluve surface are a distinctive feature of the Ganga Plain and occur as arcuate, linear and oval geomorphic highs. Their sedimentary sequence shows a few meter thick aeolian sand cover invariably underlain by fluvial channel deposits in the form of point bar succession. Infra-red stimulated luminescence (IRSL) dating of the topmost part of the channel sand and the overlying aeolian sediments yielded stratigraphically consistent results and indicated that the fluvial channel activity in the region ceased sometime during 7 to 5 ka. This was followed by a phase of deposition of aeolian sand, suggesting a phase of weakened monsoon and increased aridity.

THE Ganga Plain is a part of Himalayan foreland basin where fluvial sedimentation has been the dominant sedimentation process since the Middle Miocene[1-5]. It is considered that distinctive geomorphic features such as upland interfluve surfaces (terrace-T_2), river valley terrace (terrace-T_1), present-day flood plain (terrace-T_0), alluvial ridges and ponds in the alluvial plains formed in response to the climate and associated sea-level changes during the Late Quaternary[5]. Upland interfluve surface, the most prominent geomorphic feature of the Ganga Plain constitutes a topographic high, in which major rivers and their valleys are entrenched. It has been suggested that these surfaces began accreting since the last interglacial (~128 ka) (ref. 5).

The Central Ganga Plain shows extensive development of interfluve surfaces with relict alluvial landforms such as abandoned channels, alluvial ridges, abandoned meander belts, etc.[6]. Alluvial ridges (termed as Bhur sand deposits) occur on the upland interfluve surfaces as stabilized sandy mounds and comprise oxidized, brown-yellow, fine to medium grained micaceous sand[7]. Earlier workers mapped Bhur sands/alluvial ridges as aeolian deposits. However, some workers like Pandey *et al.*[8] consider these as older fluvial sands partly reworked by aeolian agencies.

The present study is aimed to characterize the facies, geometry, the mode of occurrence and chronology of alluvial ridges at Gahira Bypass and near Gangaganj described previously by Singh *et al.*[9]. Figure 1 shows some of the shapes of alluvial ridges seen commonly in the Western Ganga Plain. The oval ridges that occur in clusters are smaller in size with a relief of ~2 m, width 50–75 m and are traceable up to 250 m. The linear ridges have a relief of 2–5 m, width 50–200 m and are traceable for 0.5–2.5 km. The arcuate ridges occur as fragments of abandoned meander belt with a relief of

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