Study of the epicentral trends and depth sections for aftershocks of the 26th January 2001, Bhuj earthquake in western India

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The Geological Survey of India (GSI) established a twelve-station temporary microearthquake (MEQ) network to monitor the aftershocks in the epicenter area of the Bhuj earthquake (M_w7.5) of 26th January 2001. The main shock occurred in the Kutch rift basin with the epicenter to the north of Bhachao village, at an estimated depth of 25 km (IMD). About 3000 aftershocks ($M_d \geq 1.0$), were recorded by the GSI network over a monitoring period of about two and half months from 29th January 2001 to 15th April 2001. About 800 aftershocks ($M_d \geq 2.0$) are located in this study. The epicenters are clustered in an area 60 km × 30 km, between 23.3°N and 23.6°N and 70°E and 70.6°E. The main shock epicenter is also located within this zone.

Two major aftershock trends are observed; one in the NE direction and other in the NW direction. Out of these two trends, the NE trend was more pronounced with depth. The major NE-SW trend is parallel to the Anjar-Rapar lineament. The other trend along NW-SE is parallel to the Bhachao lineament. The aftershocks at a shallower depth (< 10 km) are aligned only along the NW-SE direction. The depth slice at 10 km to 20 km shows both the NE-SW trend and the NW-SE trend. At greater depth (20 km–38 km) the NE-SW trend becomes more predominant. This observation suggests that the major rupture of the main shock took place at a depth level more than 20 km; it propagated along the NE-SW direction, and a conjugate rupture followed the NW-SE direction.

A N-S depth section of the aftershocks shows that some aftershocks are clustered at shallower depth ≤ 10 km, but intense activity is observed at 15–38 km depth. There is almost an aseismic layer at 10–15 km depth. The activity is sparse below 38 km. The estimated depth of the main shock at 25 km is consistent with the cluster of maximum number of the aftershocks at 20–38 km. A NW-SE depth section of the aftershocks, perpendicular to the major NE-SW trend, indicates a SE dipping plane and a NE-SW depth section across the NW-SE trend shows a SW dipping plane.

The epicentral map of the stronger aftershocks $M \geq 4.0$ shows a prominent NE trend. Stronger aftershocks have followed the major rupture trend of the main shock. The depth section of these stronger aftershocks reveals that it occurred in the depth range of 20 to 38 km, and corroborates with a south dipping seismogenic plane.

1. Introduction

The Kutch region of the western part of peninsular India is known to be vulnerable to the occurrence of major earthquakes even though it is a part of the Stable Continental Region (SCR). It has been identified as a major seismic region in India with historical seismicity of larger intensity. The damaging

Keywords. Aftershocks; Bhuj earthquake; depth section; epicentral trend; MEQ network.

Proc. Indian Acad. Sci. (Earth Planet. Sci.), **112**, No. 3, September 2003, pp. 401–412

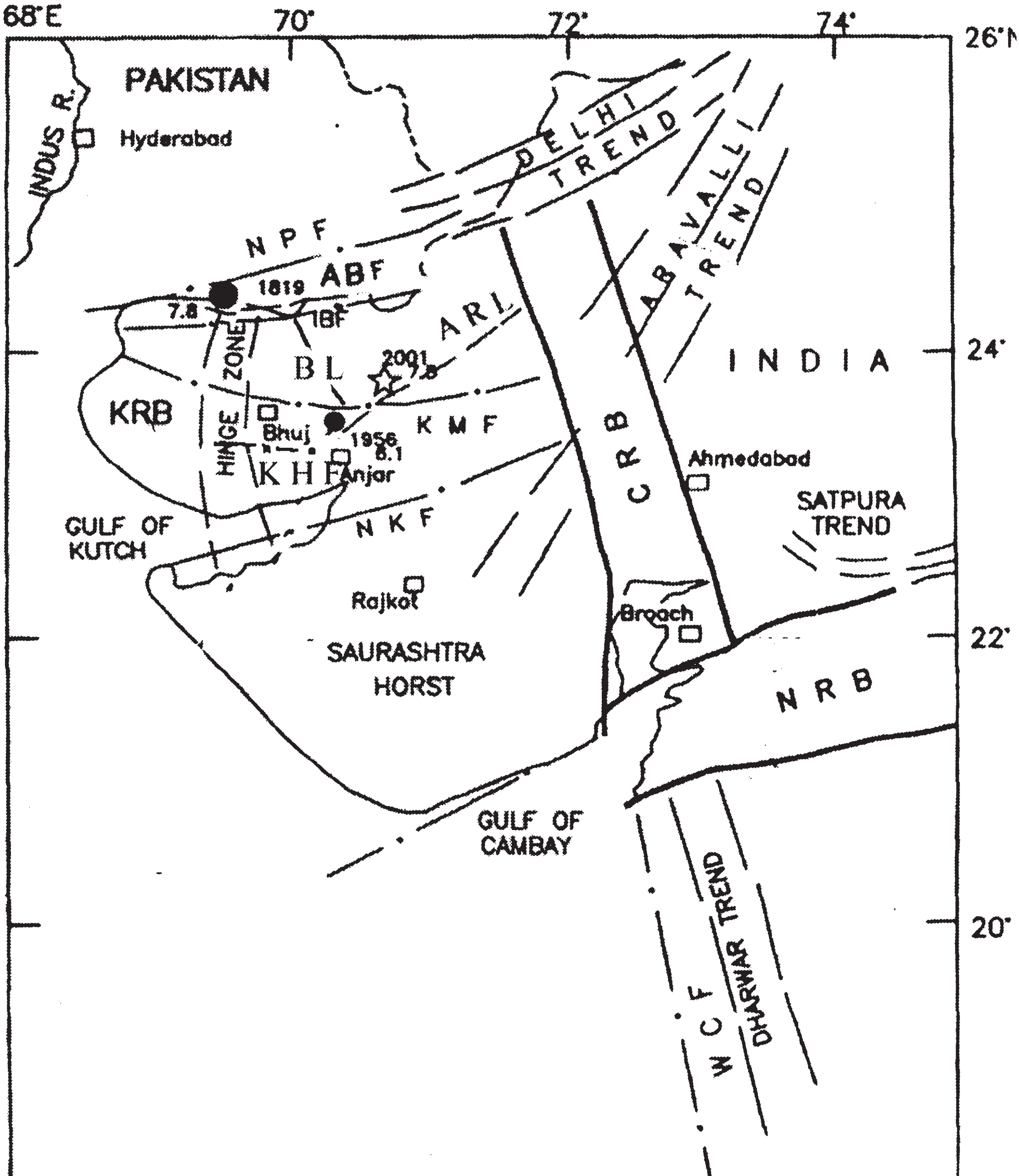

Figure 1. Map showing important tectonic features of the Bhuj area (modified after Kayal *et al* 2002). **CRB:** Cambay Rift Basin, **KRB:** Kutch Rift Basin, **NRB:** Narmada Rift Basin, **NPF:** Nagar Parkar Fault, **NKF:** North Kathiwar Fault, **ABF:** Allah Bund Fault, **IBF:** Island Belt Fault, **KMF:** Kutch Mainland Fault, **KHF:** Katrol Hills Fault, **WCF:** Western Coast Fault, **ARL:** Anjar-Rapar Lineament, **BL:** Bhachao Lineament. Epicenters of the Kutch (1819), Anjar (1956) and Bhuj (2001) earthquakes are shown with magnitude.

Bhuj earthquake of 26th January 2001, with a magnitude M_w7.5 and maximum intensity X in Kutch district, Gujarat, is the second largest earthquake in this region after the 1819 Kutch earthquake (M_w7.8). Immediately after the Bhuj earthquake, the Geological Survey of India established temporary microearthquake (MEQ) network in the earthquake-hit area for recording aftershocks. On the 29th and 30th January 2001, three analog stations were established at Morbi, Anjar and Rapar respectively (figure 1). A twelve station temporary network was completed in the epicentral area within a week. The G.S.I. network was in operation till April 15th 2001. About 3000 aftershocks ($M_d \geq 1$) were recorded during this period. The results of this aftershock investigation are presented in this paper.

2. Geology and seismotectonics of the region

The Precambrian basement of the Kutch rift basin is under cover of sediments ranging from Mesozoic to Holocene. Deccan traps border the sediments in the southern part. The Kutch rift basin is one of the three major rift basins in the western margin of the Indian craton; the other two being Cambay and Narmada rift basins. These three basins are controlled by the Precambrian tectonic trends of NE-SW Delhi-Aravalli trend, NNW-SSE Dharwar trend and ENE-WSW Satpura trend as shown in figure 1. The NE-SW Aravalli trend has controlled the formation of the Saurashtra arch as well as the rifting of the Kutch basin along the E-W trend (Biswas 1987). The basin is bounded by the ENE-WSW trending Nagar Parkar fault to the north and the north Kathiwar fault to the south. The other major faults namely, Allah Bund, Island belt, Kutch Mainland and Katrol Hills fault, trending in the ENE-WSW direction, further intersect the Kutch basin. A few major lineaments trending along the NE-SW, N-S as well as NW-SE directions are also identified (GSI 2000). The Lathi-Rajkot lineament trending along the N-S direction cuts across the mesozoics of the Kutch region. The NE-SW trending Chambal-Jamnagar lineament passes through the alluvial part in NE and terminates in the Gulf of Kutch. A few more lineaments along this trend are mapped in the Kutch region. One of these is the Anjar-Rapar lineament falling well within the epicentral area of the main shock. This lineament intersects the Kutch mainland fault to the south of the main shock epicenter.

The Kutch earthquake ($24°$ N, $69°$E) of June 1819 is the largest reported event for this region with a magnitude of $M_w 7.8$ (Johnston and Kanter 1990). The Anjar earthquake with a magnitude of 6.1 of 21st July 1956, is another major earthquake in the area. The epicenter ($23.3°$N, $70.0°$E) of this event lies about 30 km south west of the Bhuj earthquake (Chung and Gao 1995). The epicenter of the Bhuj earthquake ($M_w 7.5$) falls to the north of the Kutch mainland fault (figure 1).

3. MEQ temporary network

A team of geophysicists from GSI reached Gandhinagar on 28th January 2001 and established an MEQ analog station at the GSI complex. Three stations were established by 30th January 2001 with stations at Morbi, Anjar and Rapar in the main shock epicenter area. By 6th February 2001, nine more MEQ stations were established at Samkhiyali, Gadhada, Bhuj, Khavda, Mundra, Haripur, Bhimsar, Bherandiala and Dharampur. A twelve-station MEQ network was thus established with five digital and eight analog instruments in the main shock epicenter area. Rapar station was provided with both digital and analog instruments for comparison. The station locations are shown in figure 2.

4. Data analysis

About 3000 aftershocks (magnitude $\geq 1M_d$) were recorded during the period from January 29th to April 15th 2001. 1500 events ($M_d \geq 2$) were selected for analysis. Reading precision of ± 0.05 s for the P arrivals and ± 0.2 s for the clear S phases was maintained for the analog records. For digital records higher precision (± 0.01 s) could be achieved for both the phases. The over-all timing accuracy of 0.1 s for P arrivals and 0.2 to 0.5 s for the S arrivals was obtained for the analog records. The timing accuracy of the digital and analog records was found to match within over-all accuracy of ± 0.1 s, for the P arrivals at Rapar where both analog and digital instruments were installed.

The data were analysed using the SEISAN program (Havskov and Ottemoller 2000) for computation of the aftershock parameters; origin time, epicenter latitude and longitude and focal depth. The following velocity model (table 1) was used for computation; details of the velocity study is given by Kayal *et al* (2002).

Table 1. *Velocity model (after Kayal et al 2002).*

V_p (km/s)	Depth (km)
2.3	0.0
4.3	0.2
5.7	3.0
6.2	6.0
7.0	20.5
8.4	37.0

Minimum four phase data are required for computations of the earthquake parameters. However, in the present study the number of phases available from twelve stations of the network was always

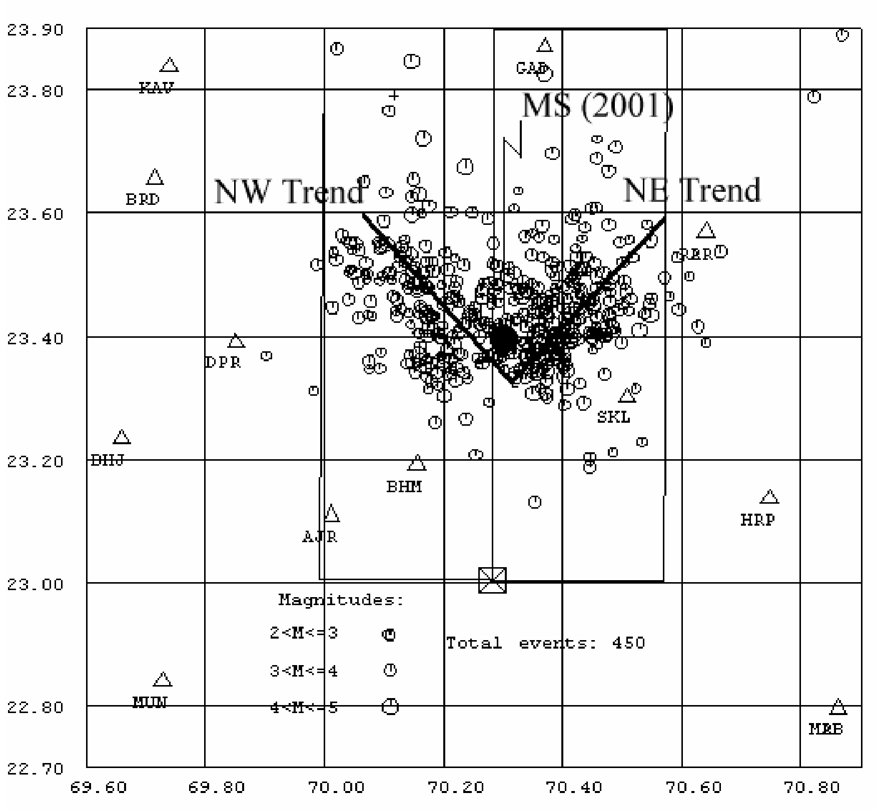

Figure 2(a). Epicentral map for 450 events in February 2001.

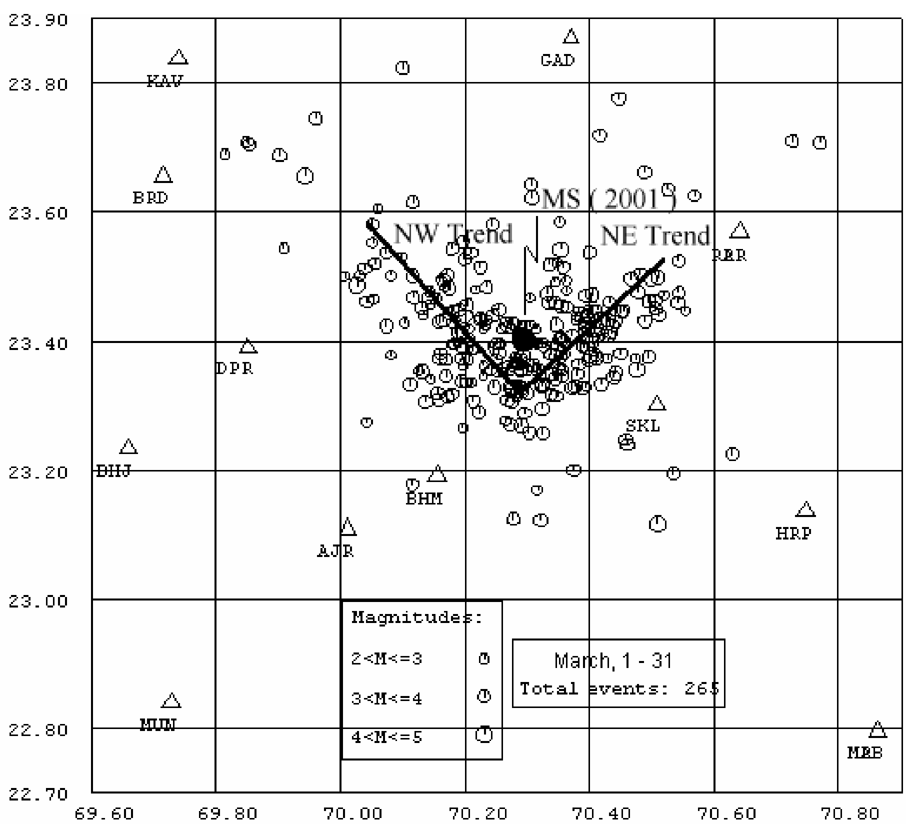

Figure 2(b). Epicentral map for 265 events in March 2001.

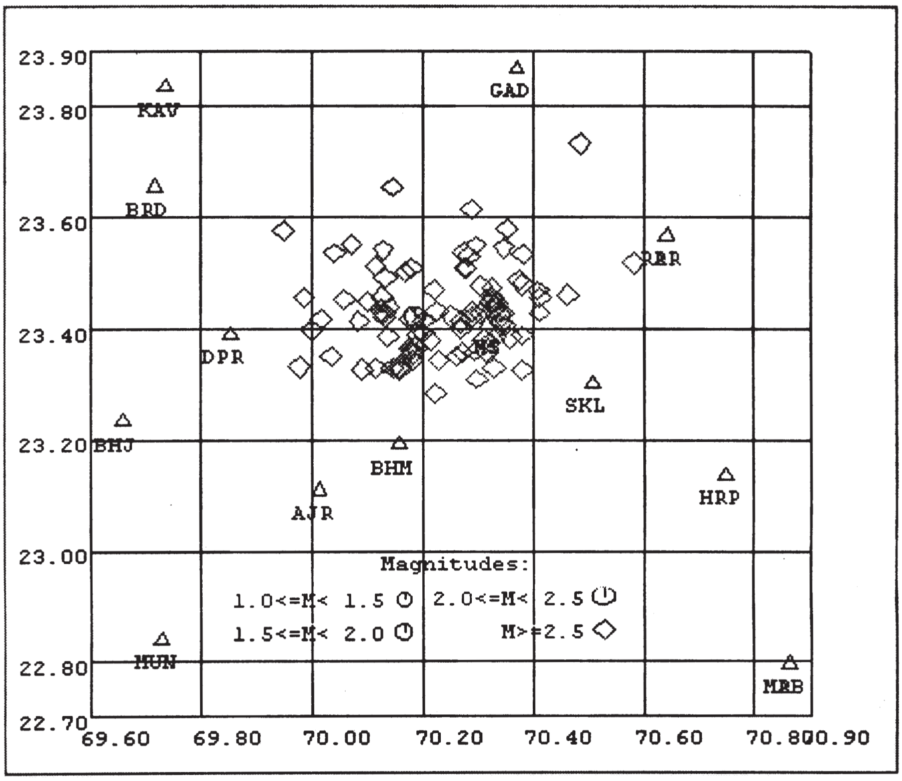

Figure 2(c). Epicentral map for events in April 2001.

more than this minimum requirement. For some of the events 20 or more phase data were available. V_p/V_s value of 1.75 was estimated by the Wadati plot method using the SEISAN program. Duration magnitude of the aftershocks was estimated using the empirical formula, $M_d = -0.87 + 2\log(T) + 0.0035D$, where, M_d = duration magnitude, T = signal duration in seconds and D = epicentral distance in kilometer (Lee *et al* 1972).

Well-located epicenters were selected applying the following criteria:

- At least 4P and 2S phases for each location.
- RMS error of ≤ 0.5 s.
- Depth (ERZ) and horizontal (ERH) errors $\leq$ 5 km except for some of the shallower events of depth less than 10 km.
- Magnitude $M_d \geq 2$.

Considering the reading accuracy and azimuthal control, proper weightages were assigned to the digital and analog data to finally accept 800 locations. The epicenter maps and depth sections were prepared using these well-located events.

5. Results and discussions

5.1 *Epicentral trends*

The epicenters of the 450 well-located aftershocks recorded in February 2001 is shown in figure 2(a). It is seen that the aftershocks are distributed over an area of 60 km × 30 km, latitudes 23.3°N–23.6°N and longitudes 70.0°E–70.6°E. The main shock epicenter falls within this zone. The map shows two prominent trends, one in the NE direction and the other in the NW direction. The epicenters of the well-located aftershocks recorded during March 2001 are shown in figure 2(b). The distribution of aftershocks is similar except for a few scattered events located outside the aftershock cluster area. These are probably due to the growth of the fractures caused by secondary effects with time. The two prominent NE and NW trends of the aftershocks are maintained in this map. The aftershock map of April 2001, however, shows that the aftershock activity has reduced in the NW direction, the NE trend remaining unchanged (figure 2c). The aftershock clusters as well as the main shock lie to the north of the surface trace of the Kutch mainland fault. The NE and NW trends intersect in the vicinity of Bhachao. The isoseismals of intensity IX and X (Ravi Shanker and Pande P 2001) correlate with the NE epicentral trend. The aftershocks that trend along the NE-SW direction possibly represent the major rupture direction, and the NW-SE trend indicate a conjugate rupture. The aftershock trend along the NW direction correlates with the NW-SE Bhachao lineament.

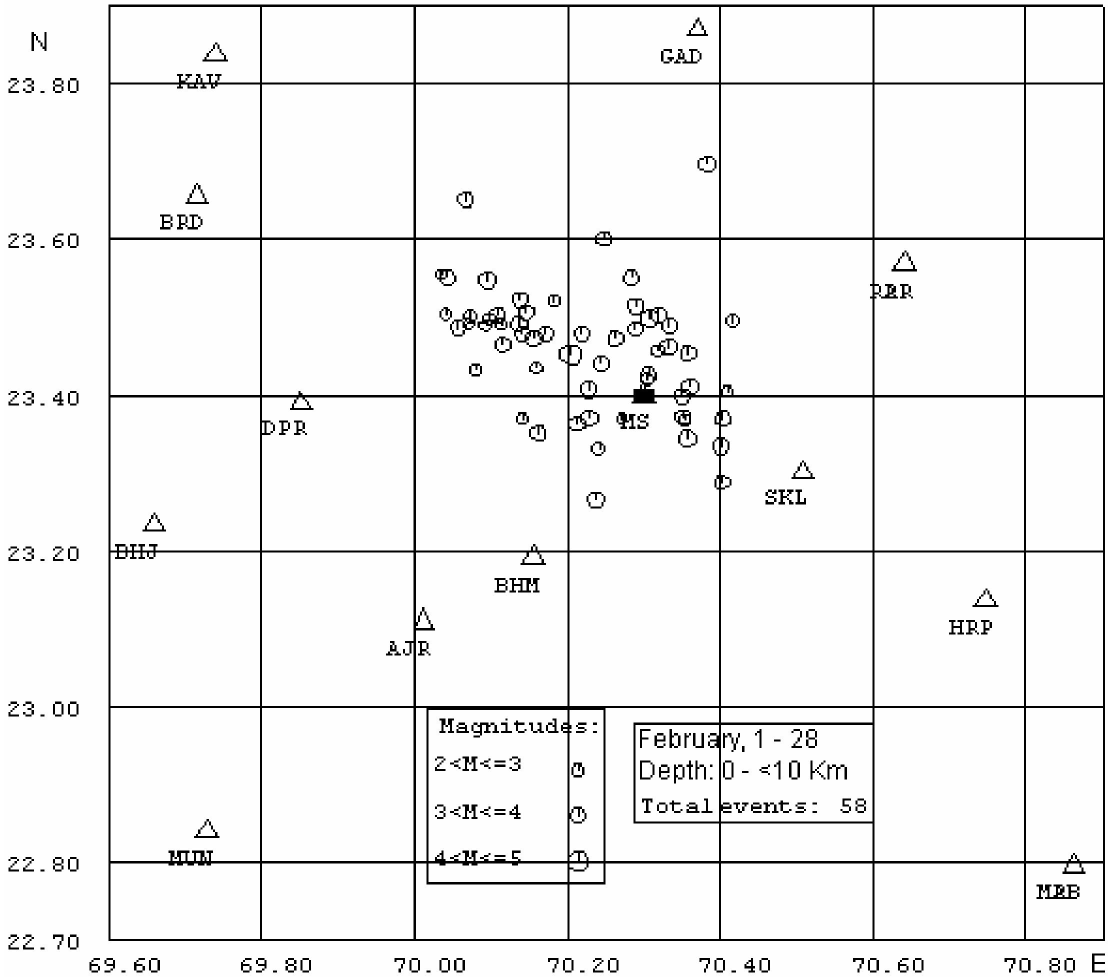

Figure 3(a). Epicentral map for depth slice, < 10 km, for February 2001.

Epicentral maps were also prepared at different depth levels to examine the variation of rupture trends with depth (figure 3a, b and c). In this exercise we have used the aftershock data of February 2001, i.e., the events recorded within one month of the main shock. It is interesting to note that only the NW-SE epicentral trend is present at the shallower depth range (0–10 km), in the upper crust (figure 3a). The epicentral distribution at a depth range of 10–20 km shows that both the NE and NW trends are well developed. In the lower crust, at a depth range of 20–38 km, both the trends are maintained, but the NE trend shows more intense activity. Considering the focal depth of the main shock at 25 km, the intense activity along the NE-SW direction may be related to the propagation of the main rupture along this direction. However, the focal depth of the main shock and the intense aftershock activity at a depth of 20–38 km indicates that the Bhuj earthquake sequence is not a typical shallow SCR event. The Bhuj earthquake occurred by reactivation of a hidden fault at the base of the paleorift.

5.2 *Depth sections*

Depth sections of the aftershocks were studied to understand the seismogenic nature of different crustal layers in the study area as well as the dip direction of the seismogenic faults. A N-S depth section of the 450 aftershocks of February 2001 is shown in figure 4(a).

It is observed that the maximum activity is concentrated in the mid crust and lower crust at 15–38 km. The activity in the upper crust at shallower depth (< 10 km) is much less. Almost no activity is observed at a depth range of 10–15 km. The aseismic nature of the crustal layer at 10–15 km is in conformity with the observation for continental earthquakes (Chen and Molnar 1990). The activity is sparse below 40 km indicating that the seismic activity is mostly confined in the crust. The depth section of 265 events located for March 2001, shows

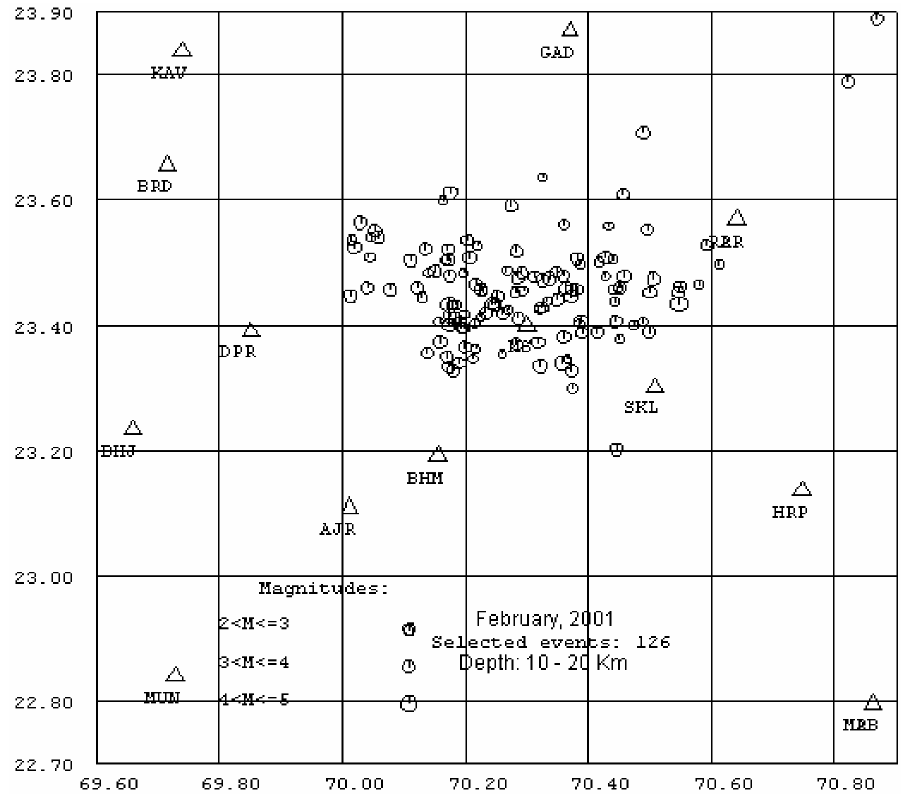

Figure 3(b). Epicentral map for depth slice, 10–20 km.

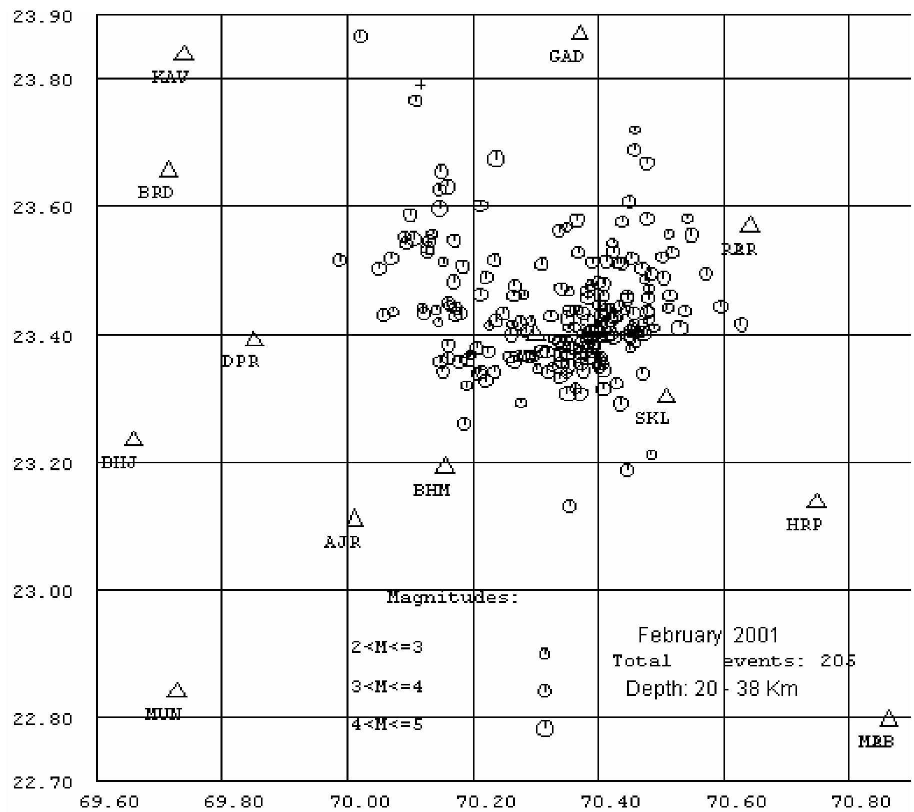

Figure 3(c). Epicentral map for depth slice 20–38 km.

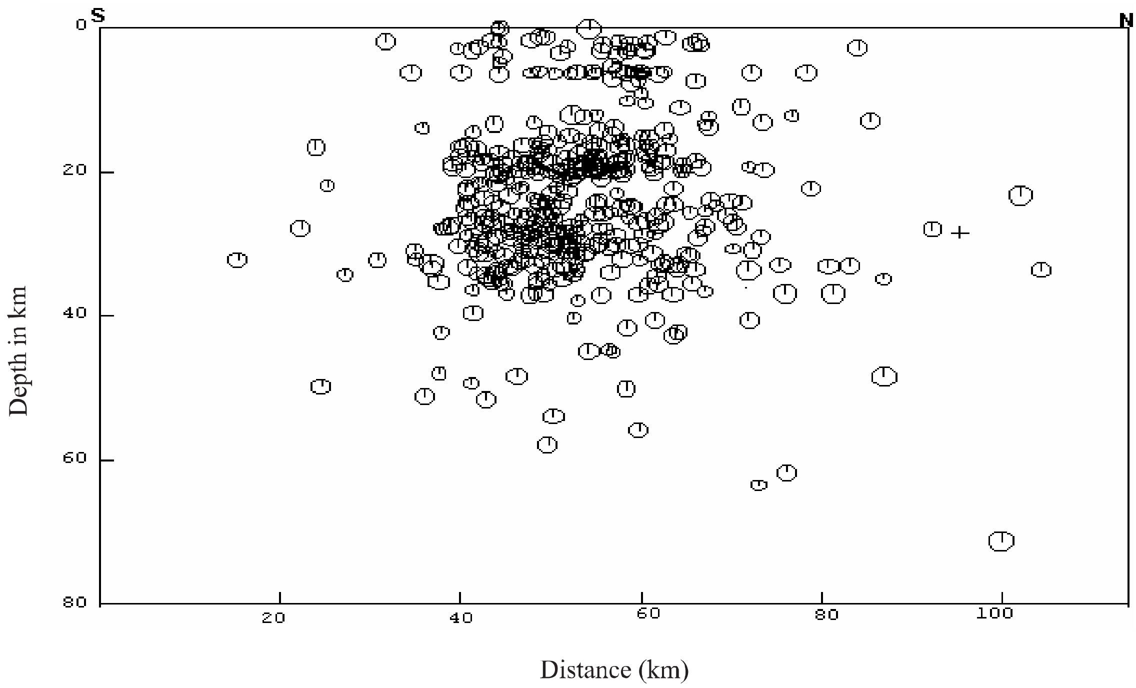

Figure 4(a). N-S Depth section of 450 events of February 2001.

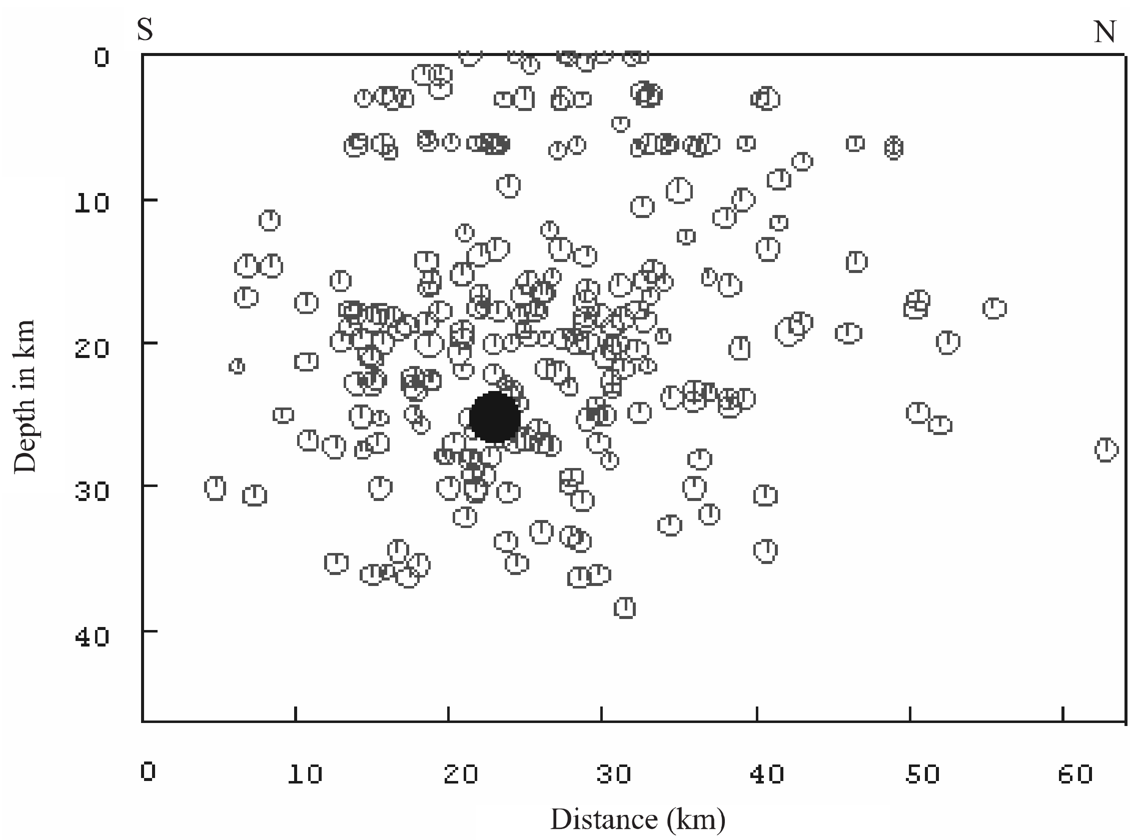

Figure 4(b). N-S Depth section of 265 events of March 2001.

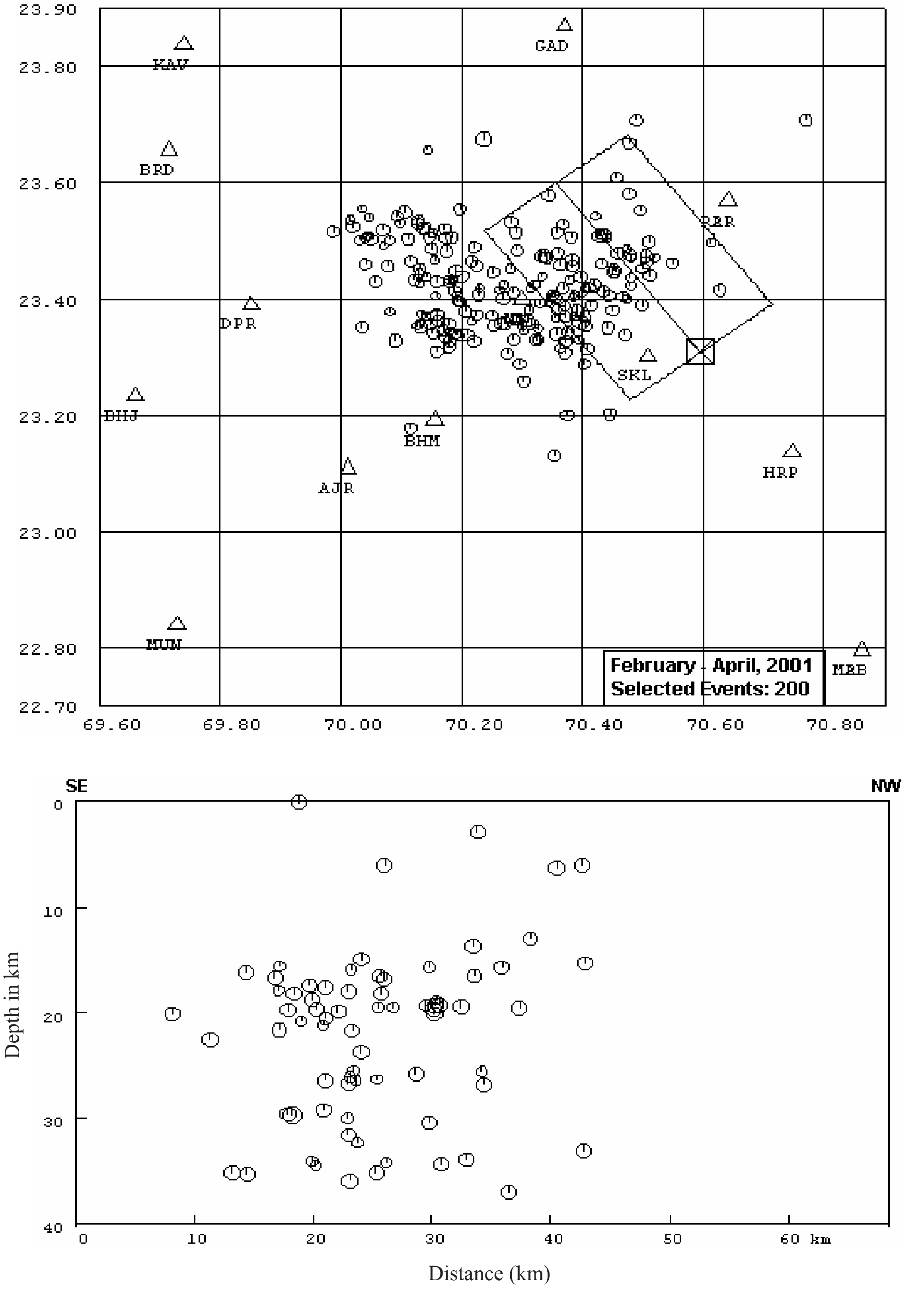

Figure 5(a). Epicentral map of best located events of February–April 2001 and depth section across N-E trend.

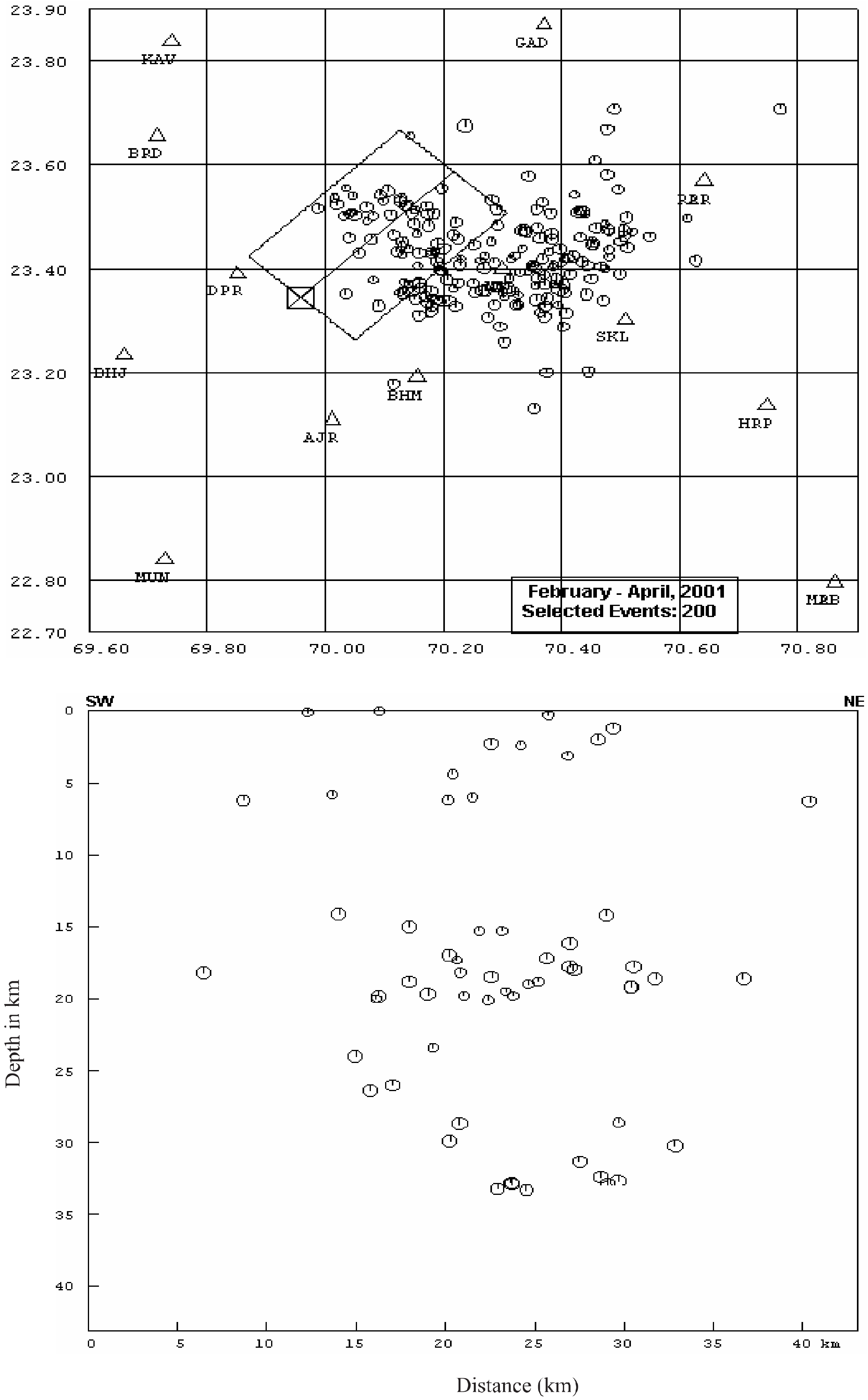

Figure 5(b). Epicentral map of best located events of February–April 2001 and depth section across N-W trend.

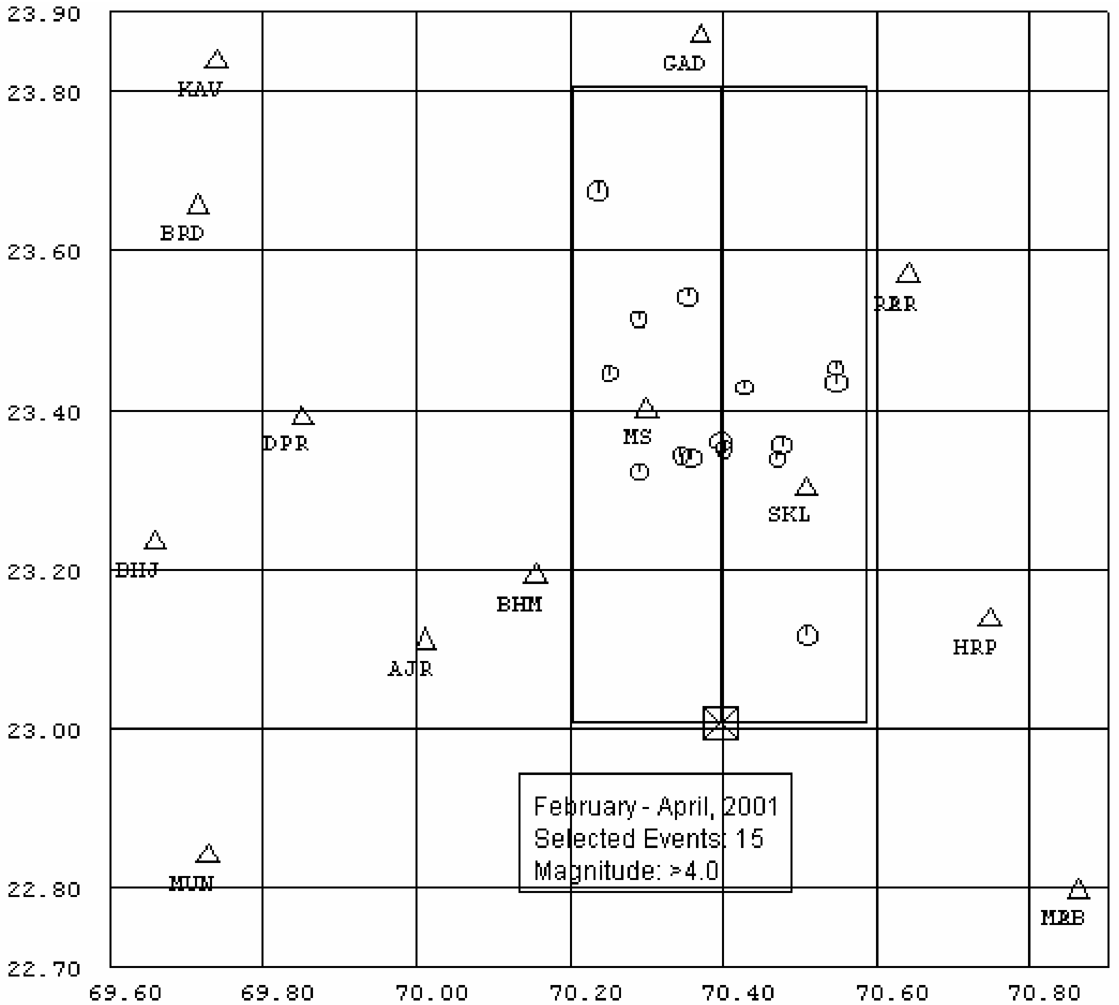

Figure 6(a). Epicentral map for aftershocks with $M_d > 4.0$.

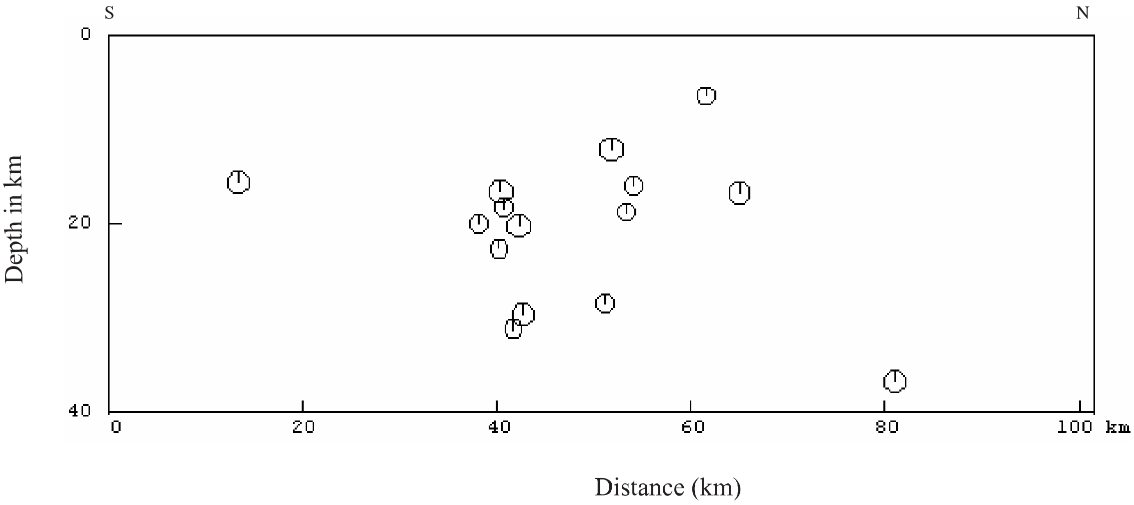

Figure 6(b). Depth section along N-S profile for $M_d > 4.0$.

similar observations, but with dispersion of aftershocks in more volume with time (figure 4b).

The epicentral maps and depth sections of the best located events (RMS < 0.2 sec) are illustrated in figure 5. The two major epicentral trends along NE and NW, and intense activity at 15–38 km are clearly indicated. The depth sections show that NE trending aftershocks deepen to the SE (figure 5a), and the NW trending aftershocks deepen to the SW (figure 5b).

5.3 *Stronger aftershocks* ($M_d > 4.0$)

Epicentral distribution and depth section of higher magnitude ($M_d > 4.0$), aftershocks recorded during the period from February 2001 to April 2001 were studied separately as large magnitude aftershocks are expected to follow the major rupture trend of the main shock. Epicenter map and depth section for these events are shown in figure 6. The two major aftershock trends in NE and NW directions are visible in the epicenter map (figure 6a), which reflect the major rupture directions as mentioned above.

The NE trend is comparatively stronger than the NW trend. A south-dipping seismogenic plane is also evident in the N-S depth section with maximum activity in the depth range of 15 to 39 km. The isolated two events falling to the NW and NE, reflect the secondary growth in the peripheral zone.

6. Conclusions

Aftershock studies were carried out for the Bhuj earthquake of 26th January 2001 in Bhuj area, Kutch district, Gujarat, through monitoring by a twelve-station MEQ network over a period of two and a half months after the main shock. It is observed that the aftershock epicentral area is restricted to an area between 23.3°N and 23.6°N and 70°E and 70.6°E with dimensions of 60 km × 30 km and lies to the north of the Kutch mainland fault. Two major epicentral trends along NE and NW directions were observed which indicate the rupture directions of the main shock; the NE trend is dominant at a greater depth (15–38 km) and the NW trend is more prominent at a shallower depth (10 km).

The NE and NW trends corroborate with the Anjar-Rapar and Bhachao lineaments respectively. The maximum aftershock activity is restricted to crustal depths at 15–38 km, and corroborates with the depth of the main shock at 25km. The main shock probably originated at the base of paleorifts by activation of a subvertical hidden fault, dipping to the south. The crustal layer between 10 and 15 km depths was found to be aseismic.

Acknowledgement

The authors thank the Director General, Geological Survey of India, for his kind support and guidance for the aftershock investigation and for permitting us to present this paper in the international seminar at New Delhi. The authors are also thankful to the Dy. Director Generals, GSI (CR), Nagpur and the authorities of the GSI (ER, NR and WR) for logistic support. We thank all our colleagues who helped in the fieldwork.

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