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On the aftershock sequence of a 4·6 m_b earthquake of the Garhwal Himalaya

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Abstract. Locally recorded data for eighteen aftershocks of a magnitude(m_b) 4·6 earthquake occurring near Ukhimath in the Garhwal Himalaya were analysed. A master event technique was adopted to locate seventeen individual aftershock hypocentres relative to the hypocentre of the eighteenth aftershock chosen as the master event. The aftershock epicentres define an approximately 30 km^2 rupture zone commensurate with the magnitude of the earthquake. The distribution of epicentres within this zone and the limited amount of first motion data support the view that a group of parallel, sub-vertical, sinistral strike-slip faults oriented N46°, transverse to the regional NW-SE trend of the Garhwal Himalaya, was involved in this seismic episode. Since the estimated focal depth range for aftershocks of this sequence is 3–14 km, we infer that this transverse fault zone extends through the upper crustal layer to a depth of 14 km at least.

Keywords. Aftershocks; Himalaya; earthquakes; Garhwal.

1. Introduction

References to numerous aftershocks are included prominently in the detailed reports compiled for the four great earthquakes of the Himalayan seismic belt during the last hundred years (Oldham 1899; Middlemiss 1910; Dunn 1939; Poddar 1953; Chen and Molnar 1977 etc.). However instrumental observations of aftershocks were extensive enough only in the case of the 1950 Assam earthquake in that, they permitted estimation of its rupture zone from the estimated areal extent of their epicentres (Chen and Molnar 1977). Aftershocks of relatively lower magnitude Himalayan earthquakes have been recorded instrumentally in recent years. But, either the instruments were located outside the Himalaya or sparse networks were set up after the main shock in most of these cases (e.g. Anonymous 1992). We discuss in this article aftershocks of an earthquake with an estimated magnitude (m_b) of 4·6 only, that occurred on June 6th, 1987, near Ukhimath in the Garhwal Himalaya (figure 1). The aftershocks were recorded with a local seismograph array already installed for seismicity investigations.

2. Data acquisition and analysis

A portable seismograph array was operated from April to June, 1987, in the vicinity of the Main Central Thrust (MCT) in the Bhilangana-Alaknanda valley (figure 1) region of the Garhwal Himalaya. The stations of the array were at Ukhimath, Tilwara,

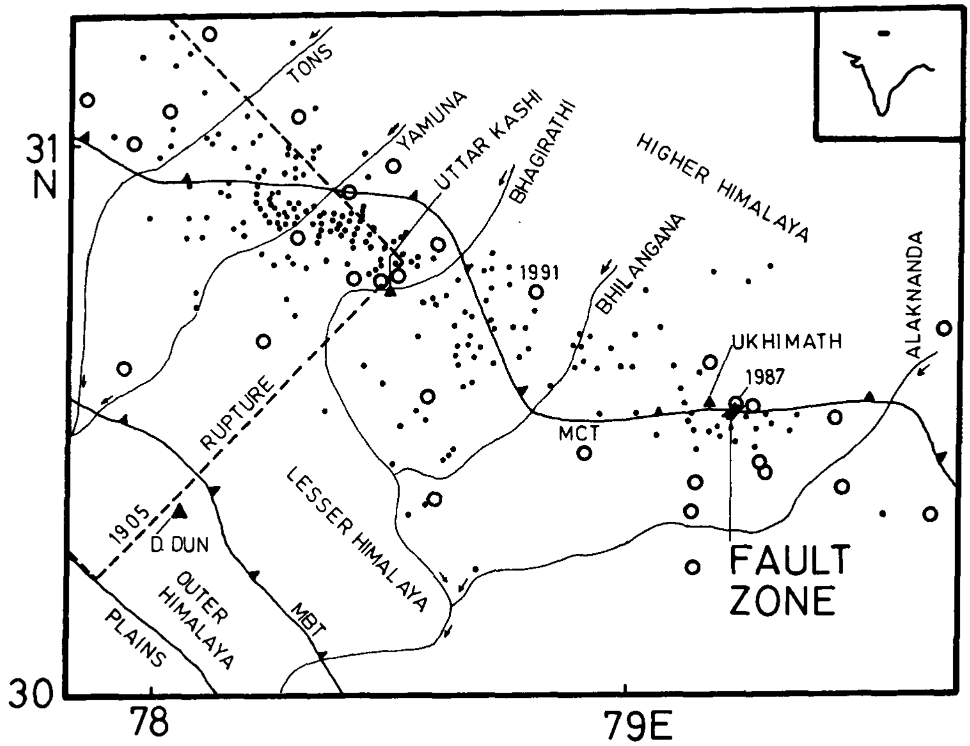

Figure 1. Seismicity of the Garhwal Himalaya. Dots indicate epicentres of locally recorded small and micro-earthquakes (after Khattri *et al* 1989; Sarkar *et al* 1993). The open circles indicate teleseismically located moderate magnitude earthquakes of the region. Two earthquakes, namely, the Uttarkashi earthquake of 1991 and the earthquake of June 6th, 1987, investigated here, are identified by the years of their occurrence. The inferred rupture zone of the 1905 Kangra earthquake is according to Gahalaut and Chander (1992). The three oblique lines near the MCT in the right half of the figure refer to the inferred fault zone.

Beenagaon, Odadhar and Gauchar (figure 2). The techniques of field data acquisition were the same as reported by Gaur *et al* (1985), Khattri *et al* (1989) and Sarkar *et al* (1993).

The estimated epicentral location of the earthquake of June 6th, 1987, was at 30·517°N, 79·216°E according to the International Seismological Centre bulletin. This location is about 10 km east of Ukhimath (figure 2). The reported focal depth was 38 km. Not only this earthquake but many of its aftershocks were also recorded by the above seismograph array over a thirty-six hour period. In all, data for eighteen aftershocks could be utilized in the present analysis. The bases for identifying the earthquakes investigated as aftershocks of the above earthquake were as follows. Firstly, the seismograms showed relatively intense seismic activity for about thirty-six hours immediately following the above earthquake, however they were routinely quiet before and after this period. Secondly, although the earthquakes recorded during this period had varying magnitudes, their seismograms exhibited remarkably similar shapes and durations indicating that they had originated from a relatively narrow volume of the upper crust.

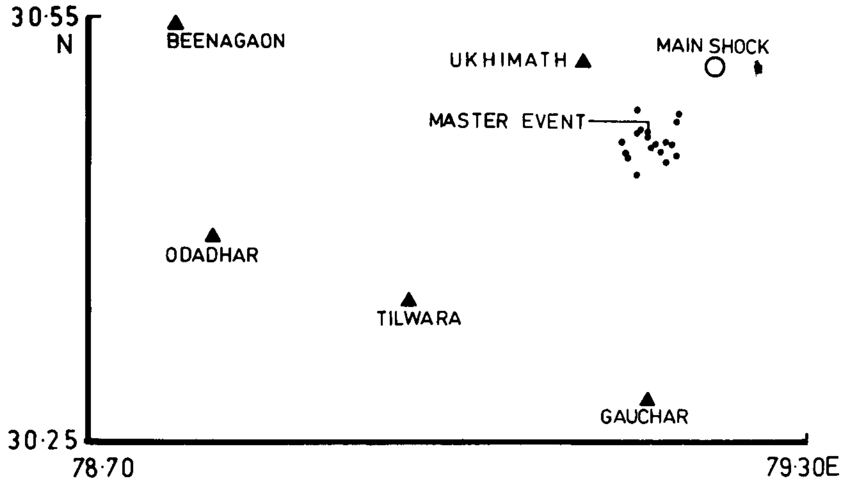

Figure 2. Epicentral positions of the main shock (according to International Seismological Centre bulletin) and the aftershocks (according to this study) are plotted along with the positions of the recording stations. The aftershock chosen as the master event is identified.

2.1 *Hypocentral locations by the master-event technique*

Conventional procedures (e.g. Bolt 1960 and Sarkar *et al* 1987) yield hypocentral parameter estimates of individual earthquakes in a global co-ordinate system. The estimated standard errors in these cases indicate uncertainties about their absolute locations. On the other hand, in a master event technique, hypocentral parameters of an earthquake are estimated relative to those of the master event. It is assumed that the data about the master event are known *a priori*. Hence the estimated standard errors in this case signify uncertainties in hypocentral location of the earthquake relative to the hypocentral location of the master event. The standard errors of location are usually smaller with master event techniques than in the conventional techniques. Consequently, we obtain a more reliable three-dimensional visualization of the mutual spatial relationship amongst the hypocentres of the master event and the investigated earthquakes, though the errors in their absolute locations may not have decreased.

This point is borne out in the present case. Mathur (1988) adopted the conventional hypocentral location procedure of Sarkar *et al* (1987) for these eighteen aftershocks. She estimated standard errors of the order of 5·0 km and 7·0 km for the epicentral locations and focal depths, respectively. We estimated the hypocentral parameters of the aftershocks from arrival time data for high quality direct *P* and *S* phases using a master event technique (Fitch 1975; Roecker 1985; Chatterjee 1993). The corresponding estimated errors in the epicentral co-ordinates and focal depths in the present study are of the order of 1·5 km and 2·0 km respectively.

2.1a *Choice of the master event*: The main shock is selected usually as the master event for hypocentral locations of aftershocks. However, the local recordings of the main shock could not provide clear, unambiguous arrival time data for both *P* and *S* phases in the present case. We thus chose the first aftershock giving clear *P* and *S* phases as the master event. We adopted the absolute location given by Mathur (1988) for this aftershock and estimated the hypocentral locations of the remaining aftershocks relative to that location.

3. Results

3.1 *Aftershock epicentres*

Positions of aftershock epicentres located in this study are plotted in figure 2 along with the main shock epicentre determined by the International Seismological Centre. The epicentres of the aftershocks define a rupture zone of 30 km^2 area approximately for the main shock. This size of the rupture zone is consistent with the reported magnitude ($m_b = 4{\cdot}6$) of the earthquake (e.g., Kasahara 1981, pp. 141 and pp. 161).

3.2 *Aftershock focal depths*

The estimated focal depths of all these aftershocks are in the range of 3–14 km below mean sea level, with 80% of them lying between 3 km and 10 km. Depth sections along planes striking parallel (NW-SE) and transverse (SW-NE) to the regional trend of the Himalaya are displayed in figure 3. The figure reveals projected areas of 50 km^2 and 40 km^2 in the NW-SE and SW-NE cross-sections respectively.

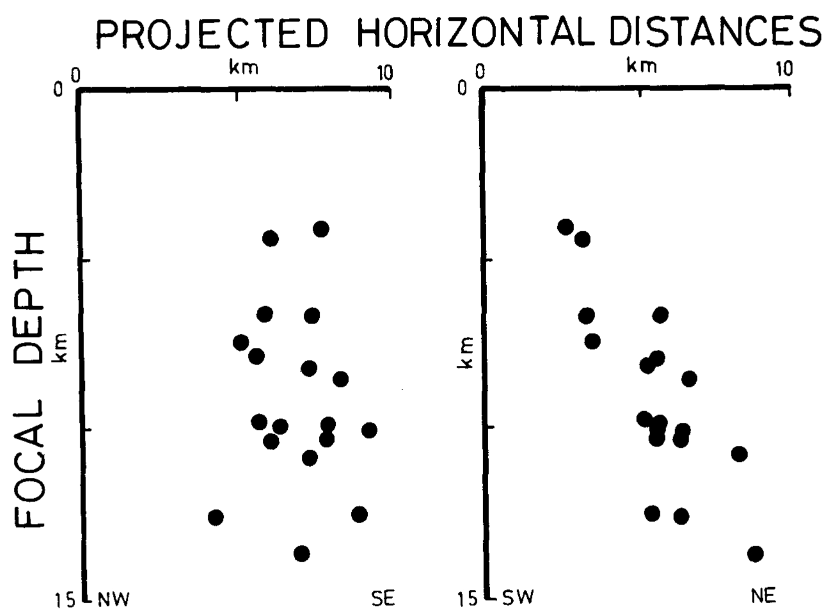

Figure 3. Depth sections of aftershock hypocentres drawn parallel (NW-SE) and transverse (SW-NE) to the regional trend of the Garhwal Himalaya are shown in the left and right parts respectively.

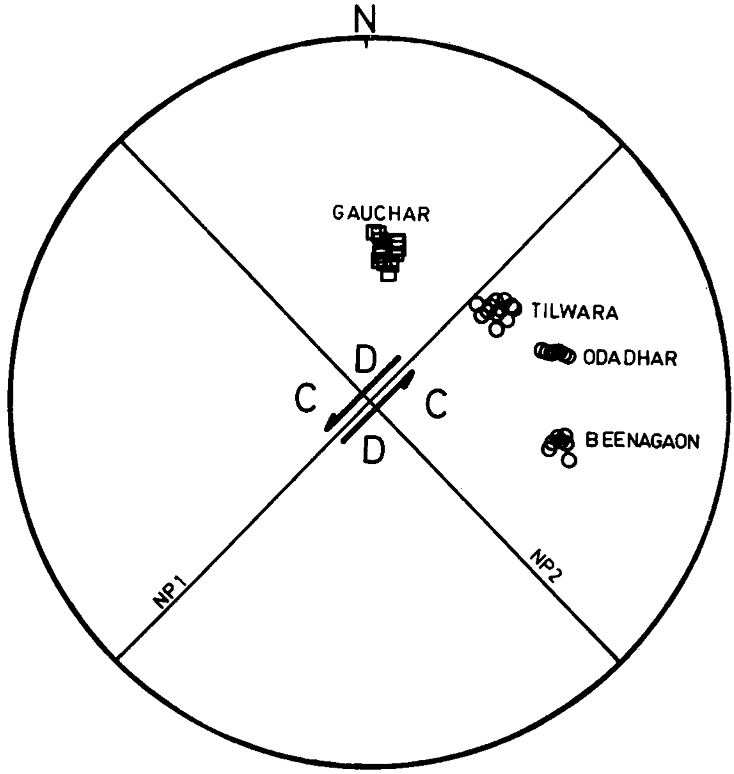

Figure 4. A lower hemisphere plot of the available first-motion data for the aftershocks. Clusters of readings are identified by the stations at which they were recorded. Nodal planes corresponding to solution VI of table 1 are drawn. Compressional and dilatational quadrants are identified by *C* and *D* respectively. Nodal plane NP1 is the preferred fault plane for reasons discussed in the text.

3.3 *Aftershock magnitudes*

The coda magnitude of all the eighteen aftershocks is estimated (Lee *et al* 1972) to be in the range of 1·0 to 3·0.

3.4 *Composite fault plane solution*

Available seismograms for the eighteen aftershocks yielded forty-seven reliable *P*-wave first motion data. These were plotted on an equal area projection of the lower half of the focal sphere (Aki and Richards 1980, pp. 109) for determining a composite fault plane solution (figure 4). Since the aftershock hypocentres are clustered in a small volume of the upper crust (figures 2 and 3), their polarity data for different stations are clustered correspondingly in different small zones on the equal area net (figure 4). The data constrain the nodal planes very weakly. The range of permissible fault plane solutions covers pure dip-slip on reverse/thrust as well as normal faults, pure strike-slip on sub-vertical faults as well as oblique-slip on moderately dipping reverse/thrust and normal faults. Six prominent solutions satisfying the first-motion observations are

Table 1. Numerical data for the various composite focal mechanism solutions which satisfy the first-motion data for eighteen aftershocks.

Solution no.	Nodal plane 1			Nodal plane 2		
	Strike	Dip	Slip	Strike	Dip	Slip
I	90	42	90	270	48	90
II	0	36	−90	180	54	−90
III	30	76	118	325	28	30
IV	24	60	−128	324	48	−136
V	19	90	0	110	90	180
VI	46	90	0	137	90	180

listed in table 1. But we note also that the first motion data are definitely inconsistent with the reverse/thrust type composite fault plane solution proposed by Khattri *et al* (1989) for earthquakes of the region of interest.

3.4a *Fault zone*: Of the various composite fault plane solutions, our preference is for solution VI of table 1, with the nodal plane having a N46° strike, steep dip and pure sinistral strike-slip motion as the fault plane. This is because the majority of the aftershock epicentres, within limits of standard errors of location, cluster along a few parallel lines oriented N46° (figure 5). These lines could be projections of buried

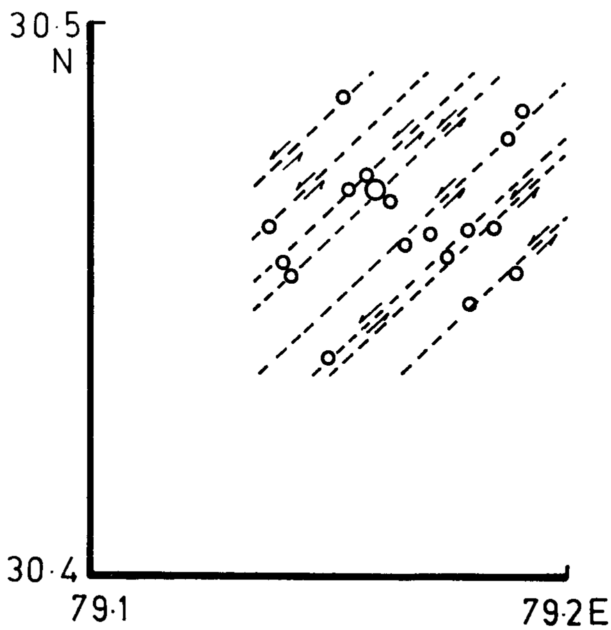

Figure 5. A detailed plot of aftershock epicentres (open circles). The circle of larger size identifies the master event epicentre. The dashed lines have the orientation of NP1 in figure 4. They represent in map view, the subsurface sinistral strike-slip faults on which these aftershocks could have occurred. The collection of these faults constitutes the inferred fault zone.

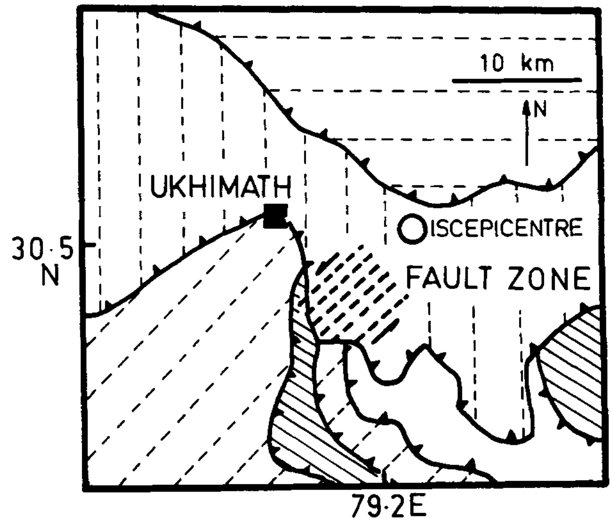

Figure 6. The relationship between the inferred fault zone and the mapped thrust faults in the vicinity of Ukhimath (after Valdiya 1980). The hatching identifies different lithounits but it is schematic otherwise. Although the epicentre of the main shock located by International Seismological Centre (ISC) is shown, we suggest that its actual location should be within the inferred fault zone.

sub-vertical faults on which the corresponding aftershocks occurred through reactivation. This collection of parallel faults lying close to each other constitutes a fault zone with sinistral slip. The strike of this zone is transverse to the regional trend of the Garhwal Himalaya.

Also, the strike of the proposed fault zone and inferred sense of slip across its individual faults are comparable to the N50° strike and sinistral slip along prominent lineaments discernible on Landsat imageries of the region (Jain 1987; see abstract).

The proposed strike-slip fault zone is shown by dashed lines in a geological map (figure 6) extracted from the book of Valdiya (1980).

4. Discussion

4.1 *Comparison of the estimated hypocentral locations of the mainshock and its aftershocks*

4.1a *Epicentral locations*: The main shock epicentre should lie within the rupture zone defined by the aftershock epicentres (Richter 1958, pp. 70). However it is seen to be well outside this zone in figure 2. The comparison here has to be between absolute epicentral locations of the main shock based on teleseismic data and the aftershock chosen as the master event based on locally recorded data. Both the mainshock and master event epicentres are mislocated due to various errors of observation as well as limitations of data. It is our opinion (Sarkar 1983; Gaur *et al* 1985; Sarkar *et al* 1987; Adams 1993) that the chances of error are greater for the mainshock than for the aftershock selected as the master event. Thus the rupture zone (figures 1, 2 and 5) delineated here from aftershock epicentres represents our local estimate of the area in which the main shock epicentre should have been located.

4.1b *Focal depths*: Similarly there is a very large difference in the estimated focal depth of aftershocks, all less than 14 km, and the mainshock focal depth of 38 km estimated by the International Seismological Centre. Again, while admitting that the focal depth estimate for the aftershock selected as the master event could also be in error, it is our view based on revised focal depths of many moderate magnitude Himalayan earthquakes (Ni and Barazangi 1984; Molnar 1990; Zhao and Helmberger 1991) as well as recent US Geological Survey estimates for Garhwal earthquakes using depth phases, that the reported mainshock focal depth may be overestimated by at least 25 km.

4.2 *Comparison of aftershock seismicity with general seismicity of the region*

The main seismicity results for the Garhwal Himalaya summarized by Khattri *et al* (1989) and supported further by recent studies (e.g. Sarkar *et al* 1993) are as follows. Firstly, the small and micro-earthquakes occur in the Garhwal Himalaya in a relatively narrow belt astride the MCT (figure 1). On the basis of figures 1 and 2 we conclude that the estimated epicentral positions of all the eighteen aftershocks are within this belt. Secondly, the small and micro-earthquakes of the Garhwal Himalaya occur mostly in the upper crust with the vast majority occurring at depths less than 13 km (Khattri *et al* 1989; Sarkar *et al* 1993). The estimates of the focal depths of the eighteen aftershocks being in the range 3–14 km, we may conclude that they too occurred in the upper crust.

5. Conclusion

This case history of eighteen aftershocks of a relatively small earthquake in the Garhwal Himalaya could be examined through a set of fortunate circumstances in which a local seismograph array was in position and recording. Using a master event technique, the estimated errors of location for the aftershock epicentres and focal depths are of the order of 1·5 km and 2·0 km respectively. The epicentres define a 30 km^2 rupture zone for the main shock. All the estimated hypocentral depths of the aftershocks are in the 3–14 km depth range.

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