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Seismicity of Tehri Area of the Himalayan Region, India

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Abstract

A database for the seismicity of the Tehri region (29.5˚N - 31.5˚N and 77.5˚E - 79.5˚E) from November 1, 1853, to March 31, 1989, has been prepared using a Compatible Personal Computer System. The seismicity database is complete for events with mb ≥ 4.5 only since 1963. It is inferred that the general seismicity of the area is considerably low, which is associated with four main tectonic features identified based on the spatial distribution of events in the area. Earthquakes in the Tehri area is of shallow focus, and maximum seismic activity is confined in the region beyond 60 km east and northwest of Tehri. The cumulative Number of Events as a Function of Time (CNET) for the period from 1963 to 1988 has indicated that precursory swarms do not precede the medium-sized earthquakes of the Tehri area. However, the CNET curves for total events and those with mb ≥ 4.6 have indicated a sharp 2-fold seismicity rate increase from 1986 compared to the preceding period. The October 20, 1991 (IST) earthquake of mb = 6.5 of Uttarkashi is believed to be associated with this seismicity rate change. The continuous increasing trend of the CNET curve before 1986 has been attributed to the detection changes.

Keywords

Himalayan Seismicity, b-Value, Earthquake Precursors, Seismicity Rate

1. Introduction

The Himalayan region is seismically very active and has experienced several large earthquakes in the past. The intense folding, faulting and thrusting that took place during the Himalayan Orogeny have given rise to several tectonic provinces characterised by changes in seismicity. The deformation of the Indian Plate has resulted in several stress regimes such as the Western and Eastern Syntaxes, the

Frontal Arc and others. The Himalayan Frontal Arc, flanked by the Arakan-Yoma in the east and the Chaman fault in the west, forms one of the most seismically active segments of the Alpide belt [1] [2]. Focal mechanism solutions of earthquakes in the Himalayan region have revealed that over 607 events are of thrust fault type [3].

Seismological investigations in the Himalayan region have been undertaken by many researchers [4]-[15]. [16] observed that the high seismicity of northeastern Kumaon and adjoining Nepal is primarily related to strike-slip movement along some transverse faults. The seismicity of the Himalayan region has been attributed to movement along either the Main Boundary Thrust [17] [18] or with the Main Central Thrust [19]. Detailed studies of the Himalayan seismicity and surrounding regions have been carried out by [19] [20] based on the contouring of a-values ranging from 3.0 to 7.0 and identified various seismically active areas. These studies have been undertaken in a large area, indicating that the Himalayan region's different parts are highly active. Such studies must be confined to a particular area to better understand the seismicity associated with a single tectonic unit. Such studies are pre-requisite for pattern recognition.

The study area (**Figure 1**) is situated at the boundary of the Lower and Higher Himalayas and is probably traversed by the Main Boundary Fault [21]. The central part of the area has experienced intensity VIII (Rossi-Forel scale) isoseismal of the great Kangra earthquake of 1905 [22].

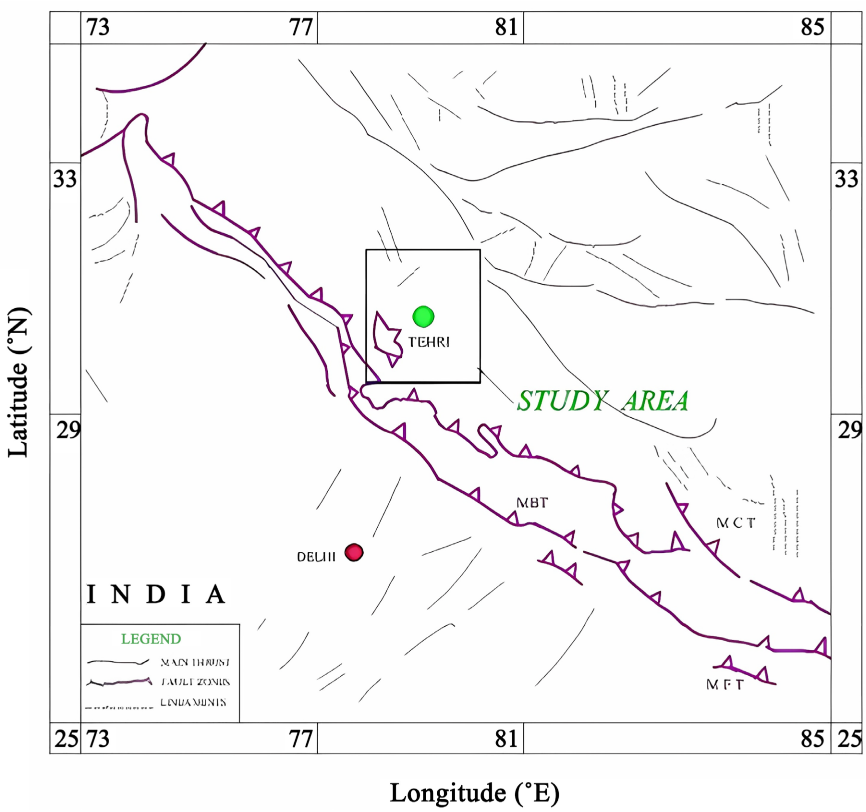


Figure 1. A map showing the study area, fault lines, and lineaments.

A proper understanding of the seismicity of a region and its meaningful interpretation requires a comprehensive and reliable database. Such a database is helpful to study the spatial distribution of events to a region's tectonic features and to undertake various investigations for pattern recognition. Given this, the present paper aims to prepare a PC-based seismicity database for Tehri and its vicinity to study the spatiotemporal variations of seismicity and associated phenomena. An attempt has also been made to identify precursory swarm and anomalous seismicity rate changes based on the cumulative number of earthquake occurrences as a function of time (CNET).

2. Study Area and Data

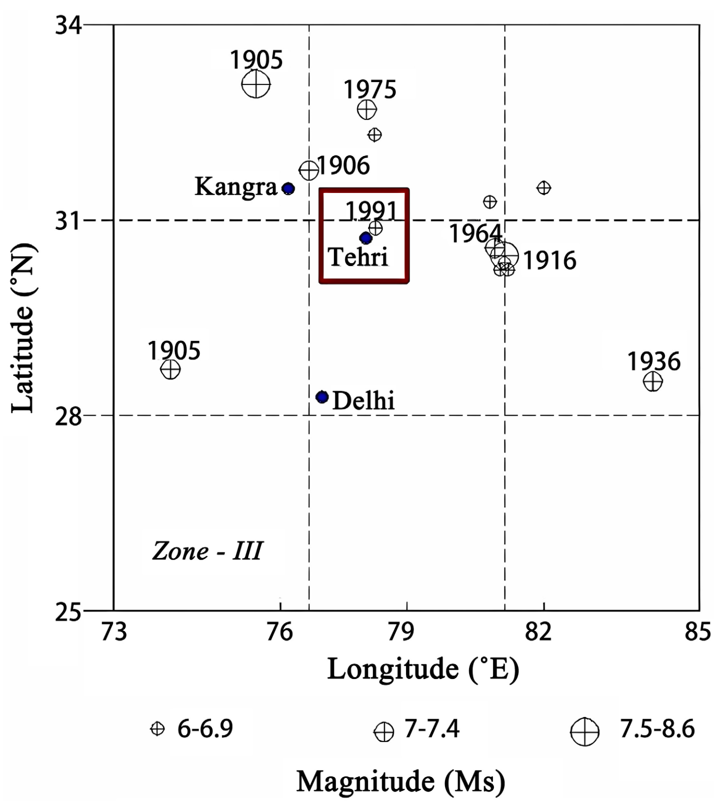
A seismicity database for the region bounded by 25˚N - 40˚N and 65˚E - 85˚E has been prepared with the help of a compatible personal computer system using a standard database management package [23] [24]. The whole region (25˚N - 40˚N and 65˚E - 85˚E) has been divided into three zones based on seismic activity (Singh and Raghavan, 1991a, b), namely Zone I, Zone II and Zone III. The seismicity of Zone II and Zone III (a part of the Himalayan region) are comparable to each other. In contrast, Zone I is extremely active since it includes the Hindukush and Tien Shan regions [25]. The pertinent literature and available earthquake catalogues (Catalogues of International Seismological Summary (ISS); Preliminary determinations of Epicentres (POE) of USGS); [26]-[35] have been critically examined to prepare a comprehensive database. A total of 6105 events from November 1, 1853, to March 31, 1989, have been incorporated in the database.

Before 1853, the reporting of epicentral location and magnitude were highly inconsistent [36]. Since the location of the events is of critical importance for seismological investigations, only those events are listed for which epicentral locations are available. The database has been critically scrutinised, and duplicates (the same events reported in different sources) have been eliminated. For the first time, a seismicity database of part of the Indian region has been compiled in computer format using a PC system that is supposed to be the most reliable and accurate since it is free from apparent errors often observed in the existing catalogues. The existing catalogues have minimal application in their present form since they are not prepared in computer format or arranged systematically [23] [24].

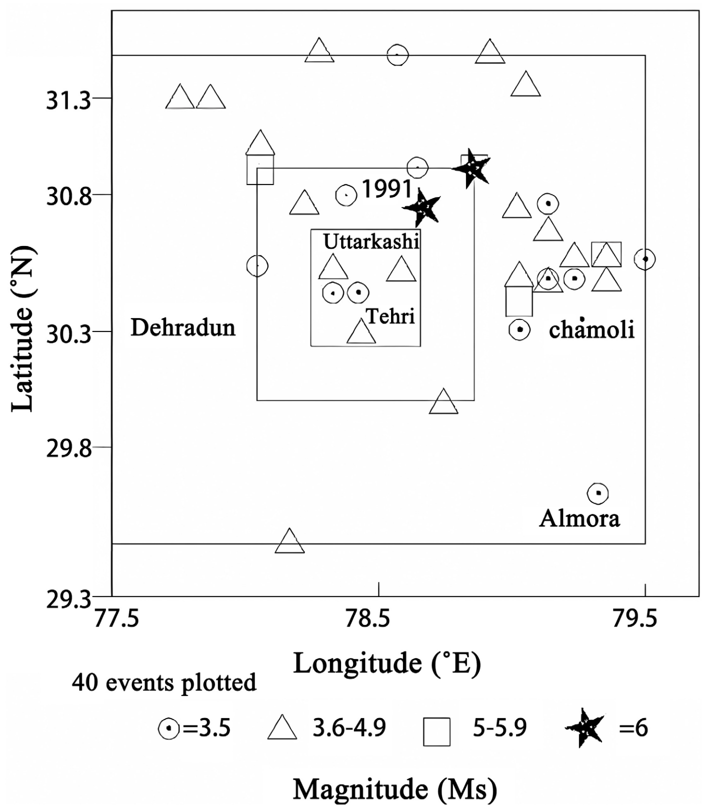
Tehri area is approximately centrally located in Zone III, where 543 events have been reported from November 1, 1853, to March 31, 1989 (**Figure 1**). During the entire period, the Himalayan Frontal Arc (Zone experienced 5 large earthquakes of $M \geq 7$ till 1962 and medium-sized earthquakes of $mb \geq 6$ (**Table 1**) from 1963 to March 31, 1989 (**Figure 2(a)**). The great Kangra earthquake of April 4, 1905, of $M = 8.6$, occurred in this region about 400 km northwest of Tehri. The recent seismic activity due to medium-sized earthquakes in the area seems to be clustered in the north and east of Tehri. The database record shows no major earthquake has been reported in the Tehri area during the last 17.5 years [37]. The only recent destructive earthquake of October 20, 1901 (IST) occurred at Uttarkashi, about 40 km northeast of Tehri (**Figure 2(a)**).

Table 1. Significant earthquakes occurred in Zone III (Part of the Himalayan Frontal Arc) from November 1, 1853 to 1991.

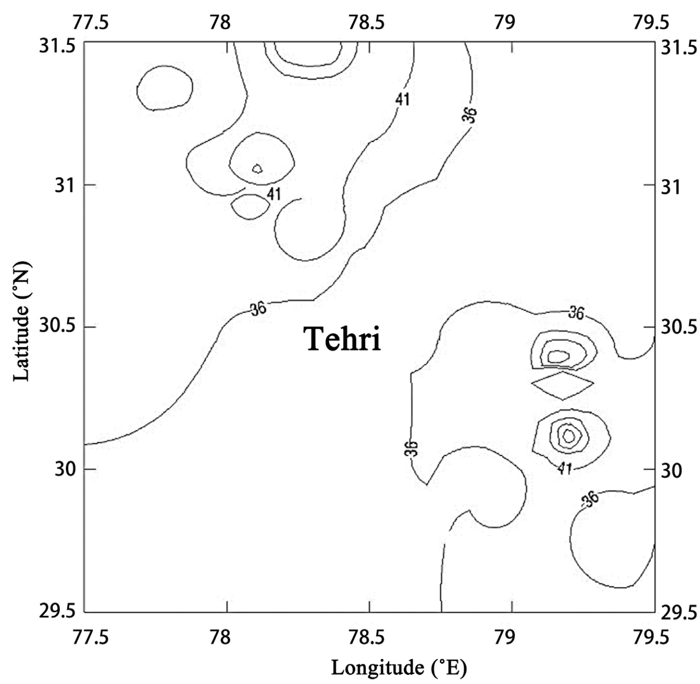
Date	Time			location		Focal Depth	Magnitude			Source
mm/dd/yy	hr.	Min.	Sec.	Lat (˚N)	Lon (˚E)	(km)	mb	Ms	OM	
04/04/1905	00	50		33	76	25			8.6	G-R
09/26/1905	01	26	09.0	29	74	60			7.1	BDA
02/28//1906				32	77				7.0	TS.
08/28/1916	06	39	29.0	30	81	60			7.7	BDA
05/27/1964	00	46	02.8	30.1	80.7				7.0	G-R
09/26/1964	00	46	02.8	30.1	80.7	50	6.2			PDE
03/06/1966	02	15	57.2	31.5	80.5	50	6		6.5	PDE
06/27/1966	10	41	07.8	29.6	80.9	6			5.75	USE
06/27/1966	10	59	14.1	29.7	81.0	13	6			PDE
01/19/1975	08	02	02.5	32.5	78.4	33	6.2	6.8	6.8	PDE
01/19/1975	08	12	08.1	32.0	78.5	33	6.1	6.5	6.6	PDE
07/29/1980	14	58	40.8	29.6	81.1	18	6.1	6.5	6.6	PDE
01/23/1982	17	37	30.3	31.7	82.2	33	6	6.5	6.6	PDE
10/19/1991	21	23	15.5	30.7	78.8	6.5	7.1			PDE



(a)



(b)



(c)

Figure 2. A map showing (a) Major earthquakes that occurred in Zone III from 1853 to December 17, 1991, and (b) Spatial distribution of earthquakes in the Tehri area from 1902 to March 31, 1989 (c) Contour map of focal depths of events in Tehri area, considering database from 1963 to March 31, 1989.

2.1. Extraction of Seismicity Data

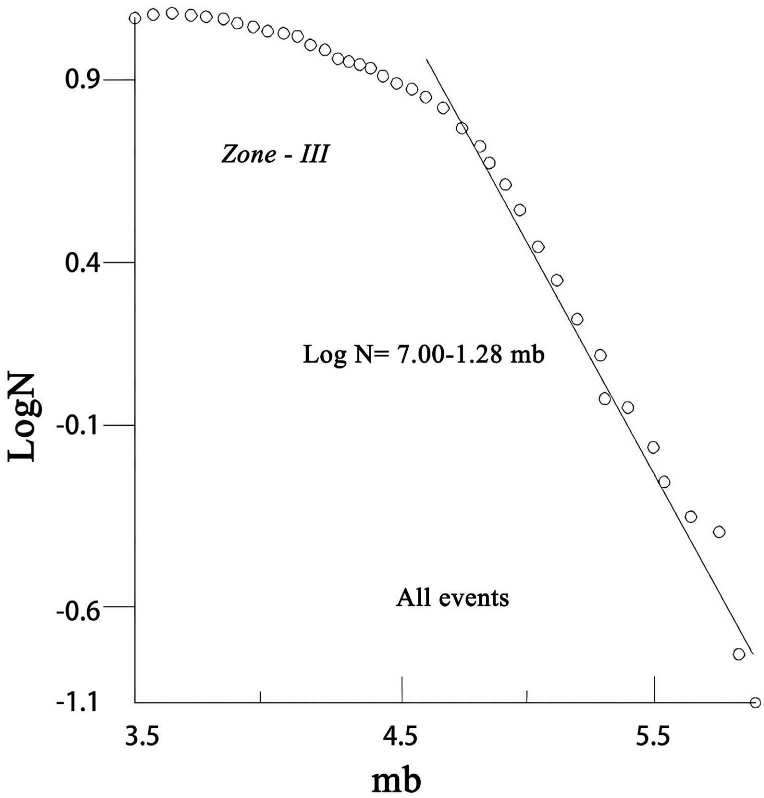
A grid-wise search has been made using the above database to extract the study area's seismicity data, considering Tehri (30.5˚N and 78.5˚E) as the central point. A repeated search has been targeted at Tehri using three different grid sizes, namely 2˚ × 2˚ (29.5˚N ≤ latitude ≤ 31.5˚N & 77.5˚E ≤ longitude ≤ 79.5˚E), 1˚ × 1˚ (30˚N ≤ latitude ≤ 31˚N & 78˚E ≤ longitude ≤ 79˚E) and 0.5˚ × 0.5˚ (30.25˚N ≤ latitude ≤ 30.75˚N & 78.25˚ ≤ longitude ≤ 78.75˚E) as shown in Figure 2(b) similar to [38]-[41]. A total of 39, 14 and 5 events were located in the above grids. The magnitude of events reported before 1963 is listed as other magnitude (OM), whereas it is the body wave magnitude for the events since 1963. The total events in the study area are listed in Table 2, and the epicentres are plotted in Figure 2(b) in three grids. Figure 2(c) presents the contour of focal depths for earthquake events between 1963 and March 31, 1989.

Table 2. Seismicity database for the Tehri area, Northern India (From 01/01/1902 to 31/03/1989).

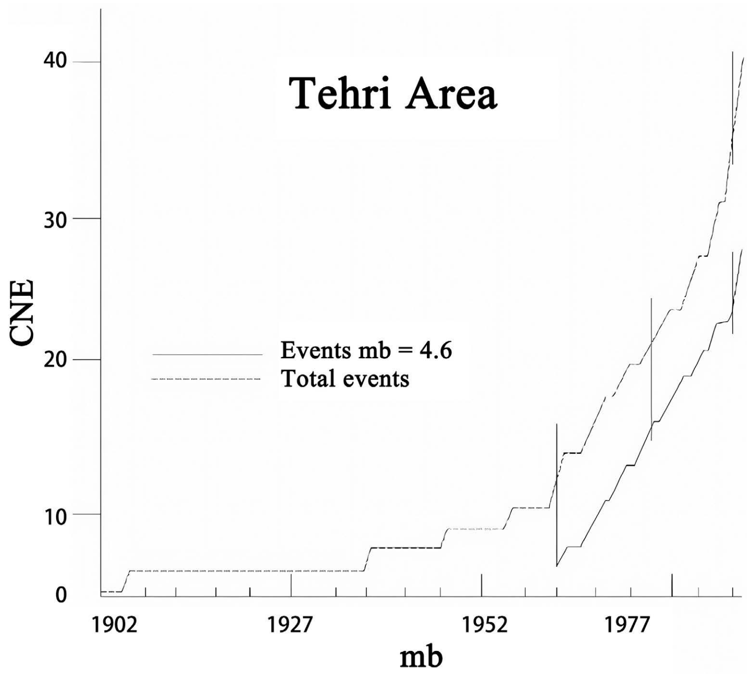
Date	Time			Location		Focal depth	Magnitude			Source
mm/dd/yy	hr	mn	sec	Lat (˚N)	Lon (˚E)	Km	Mb	Ms	OM	
06/16/1902	01	23	43	31	79				6.0	BKG
06/13/1906				31	79				5.7	TS
10/20/1937	01	23	43.0	31	78.0				5.5	G-R
05/05/1948				30.5	78.5					ISS
06/27/1955	13	45	10.0	31.5	78.5					PDE
07/14/1962	15	58	53.7	30.4	79.5	40				PDE
08/29/1962	11	30	39.3	30.9	78.4	36				PDE
07/14/1963	14	48	28.4	30.3	78.5	33	4.8			PDE
11/27/1963	21	10	39.9	30.8	79.1	33	5.1			PDE
10/19/1964	02	15	58.1	31.4	79.0	33	4.8			PDE
01/02/1967	22	17	56.3	30.6	79.3	25	4.8			PDE
01/05/1968	06	42	44.7	30.4	79.1	7	5.4			PDE
06/22/1969	01	33	24.1	30.6	79.4	19	5.4			PDE
01/30/1971	20	15	40.8	30.5	79.1	56	4.6			PDE
02/24/1974	21	32	08.8	30.9	78.1	45	4.7			PDE
07/07/1974	20	56	49.7	30.6	78.7	33	4.9			PDE
08/23/1975	03	08	56.3	30.6	79.5	33	4.0			PDE
11/06/1975	00	11	33.9	29.5	78.1	33	4.9			PDE
01/28/1977	03	08	54.1	31.5	78.3	55	4.7			PDE
04/20/1977	04	21	9.4	30.5	79.4	33	4.8	4.3		PDE
01/07/1978	07	23	20.5	30.6	79.4	33	4.7			PDE

Continued

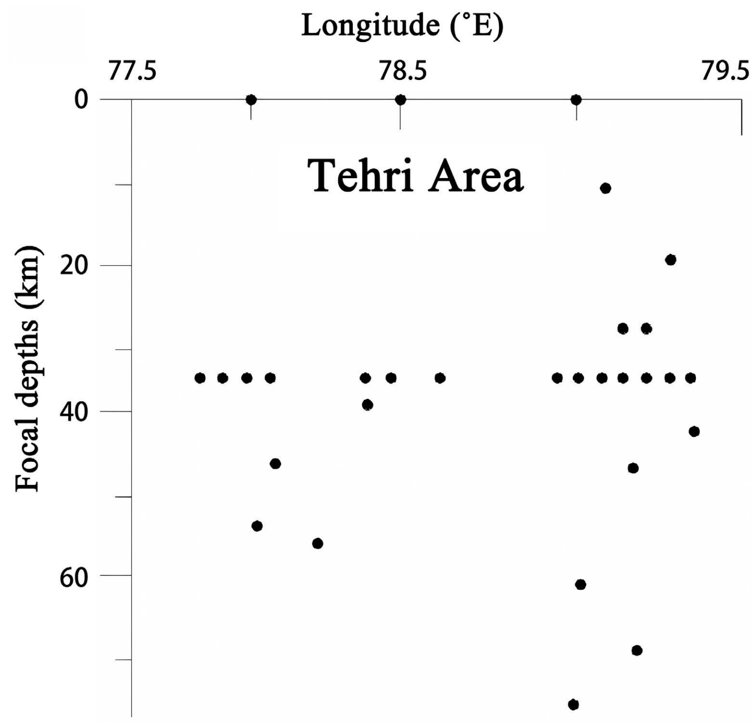
12/28/1979	01	59	18.8	30.6	78.4	33	5.0		PDE
06/19/1981	10	41	44.4	30.5	79.2	64	4.4		PDE
08/10/1981	10	58	24.6	31.3	77.9	33	4.6		PDE
10/16/1982	02	22	56.7	30.3	79.1	71	4.5		PDE
12/14/1982	23	57	32.7	31.5	78.9	33	4.6		PDE
03/23/1984	00	34	8.7	30.0	78.9	33	5.1		PDE
05/03/1984	13	17	58.1	30.5	78.4	33	4.5		PDE
11/26/1984	03	35	37.7	30.5	79.3	33	4.5		PDE
12/15/1984	10	54	10.5	31.3	77.8	33	4.7		PDE
06/14/1985	17	19	05.9	29.8	79.3	33	3.9		PDE
03/28/1986	18	05	46.7	30.8	79.2	33	4.2		PDE
07/16/1986	22	03	10.7	31.0	78.0	33	5.6	5.2	PDE
06/06/1987	03	14	24.4	30.6	79.3	33	4.7		PDE
06/06/1987	11	02	41.5	30.5	79.2	44	4.9		PDE
07/18/1987	16	29	18.8	31.1	78.0	54	4.7		PDE
06/09/1988	12	11	49.8	30.7	79.2	25	4.8		PDE
12/26/1988	11	11	11.0	30.6	78.0	33	4.2		PDE
01/27/1989	11	03	30.7	31.0	78.7	33	3.7		PDE



(a)



(b)



(c)

Figure 3. (a) Estimation of a- and b-values for Zone III and for the Tehri area on considering database from 1963 to 1988 (b) Cumulative Number of Events as Function of Time (CNET) curve for the Tehri area for two schemes: (1) Total events from 1902 to 1988; (2) Events with mb ≥ 4.6 from 1963 to 1988. The vertical slashes indicate the time for a change of seismicity rates (c) Focal depth distribution with longitude in the Tehri area (Text for details). The focal depths for five events, which are considered to be 0, are not available and are shown along the x-axis.

2.2. Data Completeness and b-Value

The seismicity database of Zone III from 1963 to 1988 has been used to estimate the location and detection capabilities of earthquake occurrences using frequency-magnitude relations (logN = a − bM) [22] [42]. In the present case, a linear relation between the logarithm of cumulative earthquake frequency and magnitude has been established as logN = 7.0 − 1.3 mb. **Figure 3(a)** indicates that the database is complete for events with mb = 4.6 in Zone III, which is also valid for the Tehri area. Thus, the a & b values for the Tehri area are estimated to be 7.0 & 1.3, respectively, considering the database for mb ≥ 4.6 [43]-[45].

2.3. Revisiting Tehri Seismicity beyond March 1989

During a period of 135 years (from November 1, 1853, to March 31, 1989), only 39 events have been reported in the Tehri area (**Table 2**). It is evident from the data furnished in Table 2 that the detection and location capabilities in the region were so poor before 1902 that no shock was reported. Details of earthquake occurrences are available only from June 16, 1902. The spatial distribution of events in the three respective grids in various magnitude ranges is shown in **Figure 2(b)**. The ratio of seismicity in the three grids from inside to outside is 1:2.8:7.0, whereas it is 1:1.8:5 for the areas uncommon in each grid, respectively. The area's seismicity is diffused and concentrated primarily in the east, north, and northwest-southeastern direction of Tehri [46]-[49]. The overall seismic activity within the innermost grid, centred around Tehri, is notably lower in comparison to the seismic activity observed in the eastern portion of the outermost grid (**Figure 2(b)**). Of the total events during the entire period, the magnitude of the largest earthquake in the close vicinity of the Tehri area is mb = 5, which occurred about 18 km northwest of it. There is no activity beyond 25 km in the southwest and west and 80 km in the northeast of Tehri. However, 40% and 18% of the total seismic activity are concentrated beyond 60 km to the east and northwest of Tehri, respectively. The seismicity in the eastern part of the outermost grid is separated by an east-west gap of about 40 km from the active area of the easternmost boundary of the Tehri area. A few scattered events have been reported in the south.

On the other hand, there is a relatively subdued level of activity in the northern direction, occurring at two points along an east-west axis, with distances of approximately 50 and 100 kilometres between them, and they are divided by a 50-kilometer-wide seismic gap. Most seismic events (63%) in the Tehri vicinity register magnitudes falling within the range of 4.0 to 5.1. Significant seismic activity is observed beyond 60 kilometres to the northwest and east of Tehri.

It is well established that tectonic earthquakes occur invariably in association with a region's weak zones/fault systems. Using this fact, tectonic features can be accurately mapped if seismicity is monitored with the help of a seismic network consisting of dense seismic stations. Based on the spatial distribution of events of the Tehri area (**Figure 2(b)**), the tectonic features may be visualised as (1) It is the most active. A complex tectonic feature is situated east of Tehri at about 60 km.

Its prominent trend is approximately N-S; certain E-W trending small-scale features are also present. It is located between latitude 30˚N - 30.8˚N & longitude 79.1˚E - 79.5˚E. (2) Moderately active feature trending NW-SE and passes through Tehri and is located between latitude 30.3˚N - 31.3˚N & longitudes 77.8˚E - 78.8˚E. The largest earthquake of July 16, 1986, of mb = 5.6, occurred in association with this zone. (3) This feature seems to be connected in the east and west with features (1) & (2) respectively. It is a considerably narrow feature trending between latitude 30.9˚N - 31.1˚N & longitude 78.0˚E - 79.0 ˚E and situated about 50 km north of Tehri. The earthquakes of 1902 & 1906 of magnitude M = 6 & 5.7, respectively (**Table 2**) are associated with this feature. (4) This northernmost E-W trending isolated feature is also considerably narrow, about 100 km north of Tehri and confined between latitudes 31.3˚N - 31.5˚N & 78.3˚E - 79.1˚E.

Focal depth for events is available from 1963 onwards. **Figure 2(c)** and **Figure 3(c)** indicate a contour map of focal depths and distribution of focal depths with longitudes, respectively. The earthquakes of the Tehri area are of shallow focus, and the maximum concentration is between 25 - 36 km depth (**Figure 3(c)**). The focal depth of 907 events is less than 45 km. Minimum (7 km) and maximum (71 km) focal depths are reported east of Tehri. Events of normal focal depths (33 km) have been reported near Tehri. The contour map (**Figure 2(c)**) indicates that the events with focal depths less than 36 km are located in a stretch with a minimum width of 60 km elongated in the northeast—southwestern direction, which widens rapidly at the northeast and southwest ends. Deeper focal depths are located northwest and east of Tehri. No event has been reported in the east of longitude 77.8˚E (**Figure 3(c)**).

2.4. Updated Tehri Seismicity beyond March 1989

The PC-based seismicity database is available till March 1, 1989 only. The USGS data were analysed to get an idea of recent seismicity from April 1, 1989. The pattern of earthquake occurrences from April 1, 1989, is similar to what prevailed before, *i.e.*, no notable change was observed till October 1, 1991. However, an earthquake of mb = 6.5 (**Table 1**) occurred on October 20, 1991, due to which at least 200 people were reported to be killed, primarily in Uttarkashi aid Chamoli areas. It is stated that more than 1800 people were injured, and 18,000 buildings were destroyed. Its epicentre was estimated at 30.7˚N and 78.8˚E, 60 km northeast of Tehri (**Figure 2(a)**, **Figure 2(b)**). Numerous aftershocks followed this earthquake. From 1991 onwards, there have been only 7 instances of seismic activity with mb ≥ 4.5: 29/03/1999 (mb = 5.4), 31/03/1999 (mb = 5.2), 07/04/1999 (mb = 4.9), 07/04/1999 (mb = 4.6), 14/04/1999 (mb = 5.2), 18/04/1999 (mb = 4.8), 27/05/2003 (mb = 4.7). No seismicity with mb ≥ 4.5 has been recorded after 2003. Hence, we believe that a study on recent seismicity is not required. Additionally, there have not been any major earthquakes in the area since 1991. Therefore, studying the latest seismicity will not result in any notable change in our analysis.

3. Temporal Variation of Seismicity

The database is subjected to identify precursory swarm and seismicity rate changes associated with medium size earthquakes. Such investigations on a regional basis in the Himalayas have been carried out by [50]-[52]. [24] reported that medium to large-magnitude earthquakes are preceded by precursory swarm and seismicity rate changes. The basis of these investigations is the Cumulative Number of Earthquake occurrences as a Function of Time (CNET) curves, which, in the present case, have been obtained for two schemes: (1) Total database since 1902 and (2) database for mb ≥ 4.6 since 1967. Since 1963, the database has been considered for detailed studies only since the same is not complete before 1963.

Three medium size earthquakes (mb = 5.4, 5.4 & 5.6) have occurred in the Tehri area since 1963 (**Table 2**). Swarms are events that occur quickly in an area spread over a period and followed by a quiescence before the occurrence of mainshocks. Also, in a particular area if there are a series of small earthquake in a short duration, but none of the events is a principal event, then the series of earthquakes are considered as a swarm. On analysis of the database for the two schemes mentioned above, it was found that none of these medium-sized earthquakes in the Tehri area were preceded by swarm-like activity (**Figure 3(b)**).

The changes in the seismicity rate of a particular strange period may show an increasing or decreasing trend as compared to rates of preceding periods. Properly assessing dependent and independent events in the database is necessary to differentiate accurate rates caused by earthquake processes in the earth's interior from those associated with detection changes. In the present case, total events and events that complete the database (mb ≥ 4.6) have been considered. It is presumed that the dependent events (swarm. foreshocks, clusters, aftershocks, etc.) are not present, especially on considering the database for events with mb ≥ 4.6 since

The region is moderately active. The CNET curve shown in **Figure 3(b)** cannot be interpreted accurately before 1963 since the database is incomplete due to poor location and detection capabilities that prevailed during the period. The CNET curves pertaining to total events and events with mb ≥ 4.6 show a similar pattern of continuous increasing trend. Three anomalous periods can be identified on careful examination of the CNET curve of total events from 1963 to 1988: 1963 to 1973, 1974 to 1985 and 1986 to 1988, during which the seismicity rates deviated in the ratio 1:2.2:4.5 respectively. This indicates that the continuous increase of the seismicity rates in successive anomalous periods may largely be attributed to the detection changes (**Figure 3(b)**).

On the other hand, three anomalous periods can also be identified by carefully examining the CNET curve obtained for the events with mb ≥ 4.6 (**Figure 3(b)**): 1963-1973, 1974-1985 & 1986-1988. The seismicity rates in these periods are 0.5, 0.9 & 1.7 events/year, respectively. The CNET curve (**Figure 3(b)**) shows a uniform gradient till 1985, which may be largely due to detection changes. However, there is a two-fold increase in the seismicity rate from 1986 compared to the preceding anomalous period due to a sharp change in the gradient of the CNET curve

(Figure 3(b)). This change is conspicuous and may be considered a real one caused by the earthquake processes in the earth's interior. When the present database is analysed in addition to data reported by USGS for the period from April 1, 1989, to October 1, 1991, it was observed that the Uttarkashi earthquake of October 20, 1991, was not preceded by a precursory swarm. However, the two-fold increase in seismicity rate change from 1986 may be considered as precursory to the Uttarkashi earthquake. The validity of this change may be obtained only if the present data have been available on a wide range of magnitude.

4. Discussion and Conclusion

We acknowledge the constraints of the database, which are restricted to events with a magnitude of mb ≥ 4.6 only, and recognize the inherent error associated with estimating focal depths. This has limited the mapping of the extent of four main tectonic features, even considering total events. Despite these limitations and the number of observation points, the focal depth contour map (Figure 2(c)) seems very reasonable, separating normal focal depth areas (less than 36 km) from the regions where considerably deeper events have been reported.

The identification of seismic precursors is constrained due to the lack of lower-magnitude events. The area has not had much seismic activity for the past 135 years since November 1, 1853. It was observed that none of the medium-sized earthquakes of the Tehri area were found to be associated with the precursory swarm. However, seismicity rate changes obtained from the CNET curve for the total events indicated a continuously increasing trend, which is interpreted mainly due to detection changes (Figure 3(b)). At the same time, an increase in real rate change has been observed from 1986 on considering events for mb ≥ 4.6 (Figure 3(b)). The changes in the seismicity rate indicate only the probability of occurrence of future major earthquakes in a region under consideration. Hence, it isn't easy to estimate the occurrence time and magnitude and to pinpoint the location with the help of this precursor. The Tehri area has been moderately active, and no event of M ≥ 6 occurred from 1902 to March 31, 1989 (Table 2). Hence, it can be said that if this rate change is real, then the associated mainshock magnitude would be of moderate size. This has been inferred based on past seismicity reported in the area. The spatial distribution of events (Figure 2(b)) indicates that the more significant events in the area are located northeast of Tehri.

The main conclusions of the present investigations are:

The seismicity database of the Tehri area from 1963 to 1988 is complete for the events with mb = 4.6 only.

Based on the spatial distribution of events, four main moderately/active tectonic features responsible for the Tehri area's seismicity have been delineated. General seismicity in the Tehri area is considerably low, particularly near it. Seismic activity is mainly confined in the areas beyond 60 km east and northwest of Tehri. These two tectonic features are separated by a well-defined north-south trending gap of about 40 km wide (east-west), where no event has been reported

(**Figure 2(b)**). However, the spatial distribution of earthquakes may not correlate directly with the number of events or encompass all earthquakes in the database.

Earthquakes in the Tehri area are of shallow focus, with a maximum concentration of 25 - 36 km. The magnitude of the majority of events ranges from 4.1 to 5.0. The events with focal depths (less than 36 km) are confined in a stretch oriented along the northeast-southwest where Tehri is centrally located.

None of the medium size earthquakes in the Tehri area are preceded by precursory swarms. However, a signature of a 2-fold increase in real seismicity rate change has been observed from 1986 on considering events for mb ≥ 4.6 from 1963 to 1988. The earthquake associated with this rate change would be of moderate size, which has been envisaged based on the pattern of earthquake occurrences in the past. The seismicity rate change observed from 1986 may be considered a possible precursor to the recent Uttarkashi earthquake of October 20, 1991 (IST).

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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