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# Spatio temporal seismicity variation in earthquakes of Uttaranchal region

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**सार** – भारत मौसम विज्ञान विभाग द्वारा तैयार की गई भूकम्पों की सारणियों का उपयोग करते हुए वर्ष 1981 से 2000 तक की अवधि के आंकड़ों पर आधारित 1991 में उत्तरकाशी और 1999 में चमोली में आए भूकम्पों से पहले भूकम्पनीयता की स्थानिक कालिक भिन्नताओं का अध्ययन किया गया । इस अध्ययन में दो स्थितियों की जाँच की गई । पहले मामले में, क्रमशः उत्तरकाशी और चमोली में आए भूकम्प से पहले के 10 वर्षों की अवधि के दौरान अभिलेखित किए गए सभी भूकम्पों के लिए उन क्षेत्रों के सन्निकट भूकम्पों से अधिकेंद्रित दूरी का पता लगाया गया। दूसरे मामले में, अधिकेंद्रित दूरी का आकलन करने के लिए भारत नेपाल सीमा (जहां पर 1966 और 1980 में भूकम्प आए) के निकट 30.2° उ. अक्षांश और 80.2° पू. देशांतर के निकट स्थित अधिकेंद्र पर विचार किया गया । इसमें दूसरे मामले को शामिल किया गया क्योंकि 1916 (7.5 परिमाण वाला) में धारचूला में आया भूकम्प भूकम्पीय रूप से सक्रिय क्षेत्र रहा है। उत्तरांचल में 1999, 1991 ओर 1980 में आए भूकंपों को भूकंपीय सक्रियता के 6 चरणों में वर्गीकृत किया गया, नामतः (*i*) प्रथम अप्रकट भूकम्प अथवा अंतराल (*ii*) भूकम्पों की अधिक मात्रा (*iii*) द्वितीय अप्रकट भूकम्प अथवा अंतराल (*iv*) पूर्वकम्प (*v*) भूकम्प का बड़ा झटका और (*vi*) भूकम्प के बाद के झटके । तथापि इन चरणों में कुछ भिन्नताएं भी देखी गई है जिन्हें स्रोत यंत्रावली, आइसोसिसमलस, "बी" (गुटेनबर्ग रिक्टर के संबंध), "एच" मानों (ओमोरी का नियम) और प्रभाजी आयामों के माध्यम से बताया गया है। यहां पर यह उल्लेखनीय है कि भूकम्पों की अधिक मात्रा (द्वितीय चरण) की घटना से पूर्व, भूकम्पी पैटर्न से इस क्षेत्र में एम : 6.0 से अधिक अथवा समान परिमाण के बड़े भूकम्प से पूर्व संबद्ध भूकम्प के बाद के झटकों की सक्रियता के क्षीण होने के पश्चात् भूकम्पीय अंतराल (प्रथम चरण) का पता चलता है । हमारा अनुमान है कि इस द्वितीय अंतराल (तृतीय चरण) से उत्तरांचल में विवर्तनिकी की जटिलता की विशेषता का पता चलता है । इस प्रकार गढ़वाल हिमालय के जटिल विवर्तनिक क्षेत्र में भूकम्पीय सक्रियता के छः चरणों वाले सरल कानामोरी के विषम निदर्श को संशोधित किया जा सकता है । "बी" मानों से आकलित किए गए प्रभाजी आयामों द्वारा भूकम्प से पहले भूकम्पीय पैटर्नों की विस्तृत भिन्नता को समझाया गया है ।

**ABSTRACT.** The spatio temporal variations of seismicity preceding Uttarkashi, 1991 and Chamoli, 1999 earthquakes were studied based on the data during the period 1981 to 2000 using the catalogues of earthquakes prepared by the India Meteorological Department. Two scenarios were examined. In one case the epicentral distance from the respective impending earthquakes were worked out for all the earthquakes recorded during a ten years period prior to the earthquake of Uttarkashi and Chamoli respectively. In the other case, the epicenter near latitude 30.2° N and longitude 80.2° E near India Nepal border (where earthquakes of 1966 and 1980 occurred) were considered to compute the epicentral distance. The second case was included because it is a seismically active region where Dharachulla earthquake of 1916 (magnitude 7.5) occurred. The earthquakes of 1999, 1991 and 1980 in Uttaranchal were characterised by six phases of seismic activity namely (*i*) first quiescence or gap, (*ii*) swarm, (*iii*) second quiescence or gap, (*iv*) foreshocks, (*v*) main shock and (*vi*) aftershocks. Some differences among these phases could however, be noticed which were explained through source mechanism, isoseismals, 'b' (Gutenberg Richter's relationship), 'h' values (Omori's law ) and fractal dimension. It is interesting to point out that prior to the occurrence of earthquake swarms (second phase) the seismic pattern exhibits the development of a seismic gap (first phase) after the decay of the aftershock activity associated with a previous large earthquake of magnitude greater than or equal to M: 6.0 in this region. We infer that this second 'gap' (third phase) is a characteristic of the complexity of the tectonics in the Uttaranchal. Thus, the simple Kanamori's asperity model could be modified to consist of six phases of seismic activity in the complex tectonic zone of Garhwal Himalaya. Detailed difference in the seismicity patterns prior to the earthquake were explained by the fractal dimensions estimated from the 'b'values.

**Key words** – Foreshocks, Main shock, After shock, Uttaranchal.

## 1. Introduction

The spatio-temporal variation of seismicity before earthquakes is studied to understand the physical process leading to an earthquake. The seismicity patterns preceding earthquake also reflect the nature of stress accumulation and their release. The most commonly observed 'seismic quiescence' before several earthquakes

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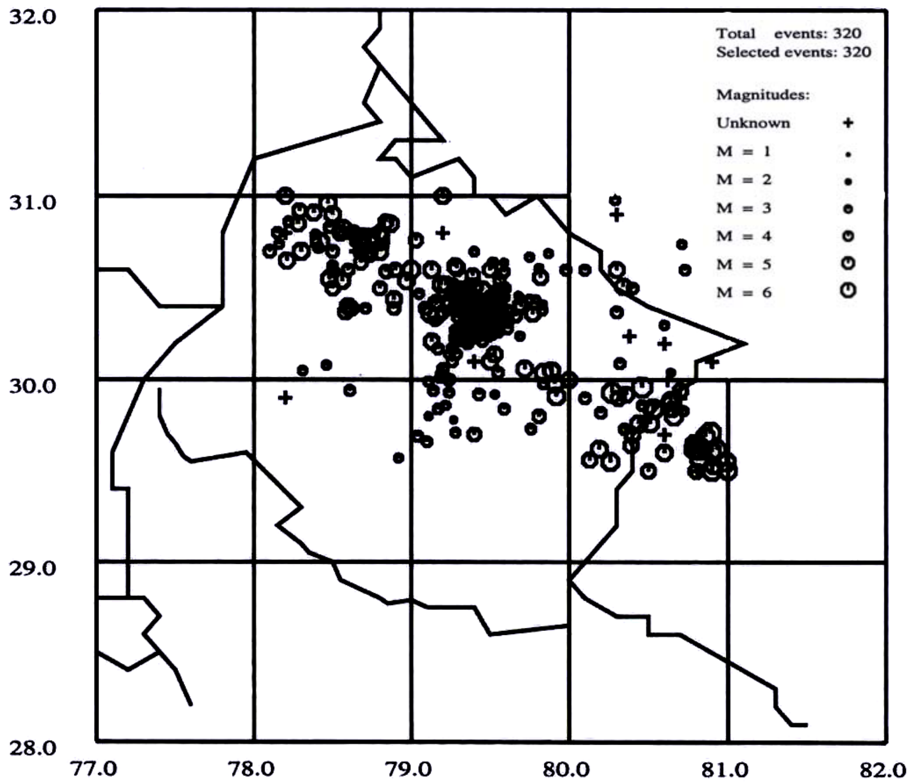


**Fig. 1.** Seismicity in Uttaranchal region for the period 1964 to 2000

in different parts of the world has provided the basis on which a few models of earthquakes have been evolved.

The Uttaranchal state (formerly Hills of west Uttar Pradesh adjoining western Nepal) was affected by two moderate earthquakes in less than 10 years causing huge loss of life and property. The Uttarkashi earthquake of 1991 and the Chamoli earthquake of 1999 had their epicentres barely 65 km apart. In the Indian region, the patterns of earthquake occurrence has been studied by several workers in different sectors of the Himalaya (Srivastava *et al.* 1987, Srivastava and Gautam 1987, Chatterjee *et al.* 1990, Srivastava and Rao 1991, Bhattacharya and Srivastava 1992). Near the India-Nepal-Tibet trijunction, the seismicity patterns were found to be slightly different before the earthquakes of 1966 and 1980 which had the same magnitude of 6.0 and occurred at the same place (Srivastava and Gautam 1987). This could be attributed to non-linearity in the stress build up near continent-continent collision type of Indian Eurasian plate boundary. Keeping in view the occurrence of recent earthquakes of 1991 and 1999 in almost similar tectonic set up, we have examined their precursory seismicity patterns and synthesized the results with those of 1966 and 1980 earthquakes.

Two approaches were adopted to work out the seismicity patterns. In the first methodology, the epicentral distances of all the earthquakes in the grid bounded by latitudes 29.0° N to 32.0° N and longitude 78.0° E to 81.0° E from the respective epicenters of Uttarkashi and Chamoli earthquakes were worked out. In the second method, the epicentral distances of all the earthquakes in the same grid were computed from Latitude 30.2° N, Longitude 80.2° E near Dharachulla, where earthquakes of 1916, 1966 and 1980 occurred and is a more probable zone far recurrence of a damaging earthquake keeping in view the past history of earthquakes. The methodology adopted in this paper provides an insight into the differences in the pattern of seismicity from operational angle wherein we need to fix the epicenter of an impending earthquake in a more probable earthquake zone for routine monitoring.

## 2. Seismo-tectonics of the region

The Uttarkashi (1991) and Chamoli (1999) earthquakes occurred in Uttaranchal in the lower Himalaya in the collision zones of Indian and Eurasian plates. Table 1, shows the epicentral parameters of the Uttarkashi and the Chamoli earthquakes. The Kumaon and

**TABLE 1**

**Epicental parameters of Uttarkashi (1991) and Chamoli (1999) earthquakes**

| S. No. | Date | Origin Time (GMT) | Epicentre | | Focal Depth (km) | Magnitude | | | | Maximum Intensity | Remarks (Source of Epicentre) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | (°N) | (°E) | | ML | MB | MS | MW | | |
| 1 | 19 Oct 1991 | 21h 23m 16.4s | 30.75 | 78.86 | 12 | | 6.6 | | | More than | IMD USGS |
| | | 21h 23m 14.3s | 30.78 | 78.77 | 10 | | 6.5 | 7.0 | 6.6 | VIII MM | |
| 2 | 28 Mar 1999 | 19h 05m 13.4s | 30.41 | 79.42 | 21 | 6.8 | | 6.3 | | VIII MM | IMD USGS |
| | | 19h 05m 10.0s | 30.55 | 79.42 | 15 | | 6.4 | 6.6 | 6.4 | | |

Garhwal Himalaya have been effected by a number of damaging earthquakes in the past. In the region bounded by Latitude 29.0° N to 31.0° N and Longitude 78.0° E to 81.0° E, 24 events of magnitude >5.5 have been recorded in the last hundred years. The seismicity of the region for the period 1964 to 2000 is shown in Fig. 1. It may be noted that the seismic activity is more marked near the India Nepal border where the largest earthquake of magnitude 7.5 occurred in Dharchulla in 1916. The main tectonic feature is the Main Central Thrust (MCT) which separates the higher grade Vaikrita rocks above from the low grade metamorphics of the Lesser Himalayan formation. Active faults have also been identified along Main Bounbary Fault (MBT). In the adjoining Nepal also, active faults have been identified along the MCT in north-west Nepal and some major geological faults in the lower Himalayas. They are oriented NW-SE, dipping towards the north. In the whole Kumaon region several transverse lineaments have been identified. The meizoseismal area of Uttarkashi and Chamoli earthquakes is also oriented parallel to MCT. But the meizoseismal area of 1980 earthquake near Indo-Nepal border based on the field surveys by the Geological Survey of India suggests the movements to have occurred on north-north-easterly lineament parallel to Moradabad fault. The aftershock surveys do not define the fault planes uniquely possibly due to activation of both the MCT and tear faults. The field observations for the 1966 earthquake near Indo-Nepal border were not undertaken.

## 3. Data and analysis

For an earthquake of magnitude 6, a period of six to ten years appears to be adequate to understand the different phases of the precursory seismicity pattern namely background seismicity, preparatory process, anomalous seismicity or seismic gap followed by seismicity increase or foreshock (if any) prior to an earthquake (Srivastava *et al*. 1987, Srivastava and Gautam 1987, Chatterjee *et al*. 1990, Srivastava and Rao 1991, Bhattacharya and Srivastava 1992, Gupta and Singh 1986). Therefore, this study is based on the data from the catalogue prepared by the India Meteorological Department (IMD) for the years 1981 to 1991 and from 1992 to 2000 in a grid bounded by Latitudes 29.0° N to 32.0° N and Longitude 78.0° E to 81.0° E for the respective Uttarkashi (1991) and Chamoli (1999) earthquakes. It may be noted that this grid includes MCT and several lineaments. The epicentral distances within 300 km of all the reported earthquakes in the catalogue were computed from each of the impending epicenters (including one hypothetical source at Latitude 30.2° N and Longitude 80.2° E) which have been plotted separately as shown in Figs. 2 (a&b) and Figs. 3 (a&b). For delineating the seismicity pattern, the important criteria of the uniformity in the detection capability of earthquakes in the region was kept in view.

## 4. Results

Generally, seismicity pattern follows five different phases of stress build up through precursory swarm (I), seismic quiescence (II), foreshocks (III), resulting in main shock (IV) and aftershocks (V). Since the fault are hetrogeneous, the regions of increased strength, generally called asperties show a gradual stress concentration. This stress concentration followed by failure of the asperity is manifested through the seismicity pattern. This is called the 'Asperity Model' proposed by Kanamori (1981), who examined such patterns prior to earthquakes in different parts of the world. He found that there are significant variations from one region to other or even from one earthquake to the other. This inference is also supported from the occurrence of two earthquakes (1973 and 1980) in the Koyna and Nepal-India border region (1966 and 1980) which had same magnitude, similar focal depth and a localised source in the respective region.

The different phases have been marked as I, II, III, IV, V and VI in Fig. 2(a) and Fig. 2(b) for quiescence,

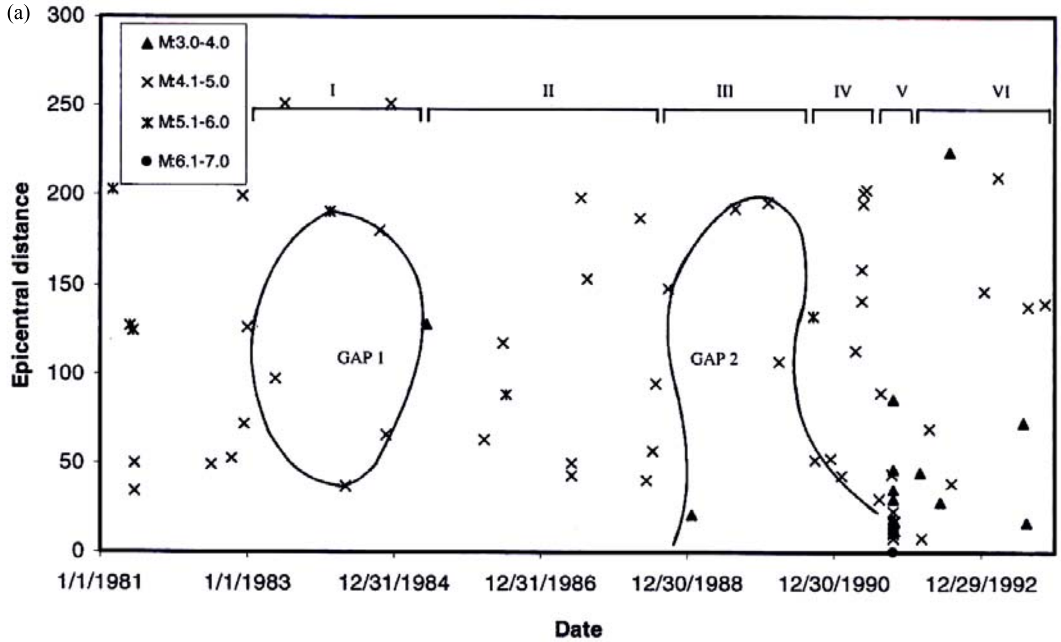


**Fig. 2(a).** Seismic activity for the period 1981 to 1993 from the epicentre of Uttarkashi earthquake of October 1991

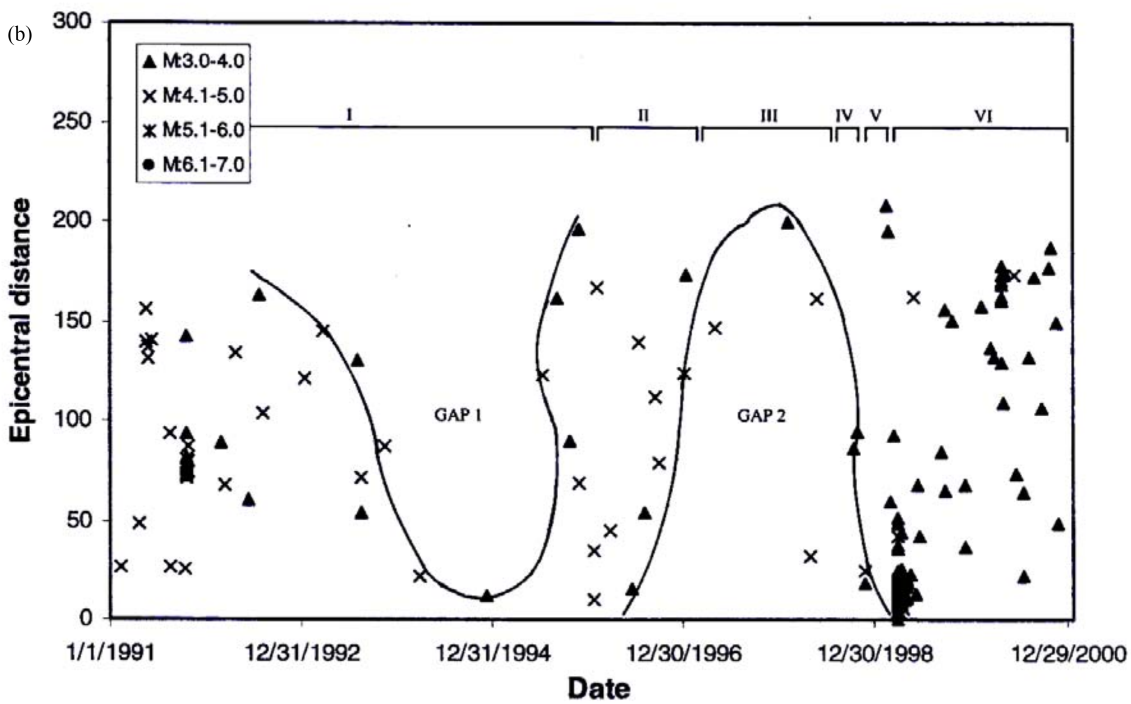


**Fig. 2(b).** Seismic activity for the period 1991 to 2000 from the epicentre of Chamoli earthquake of March 1999

(a)

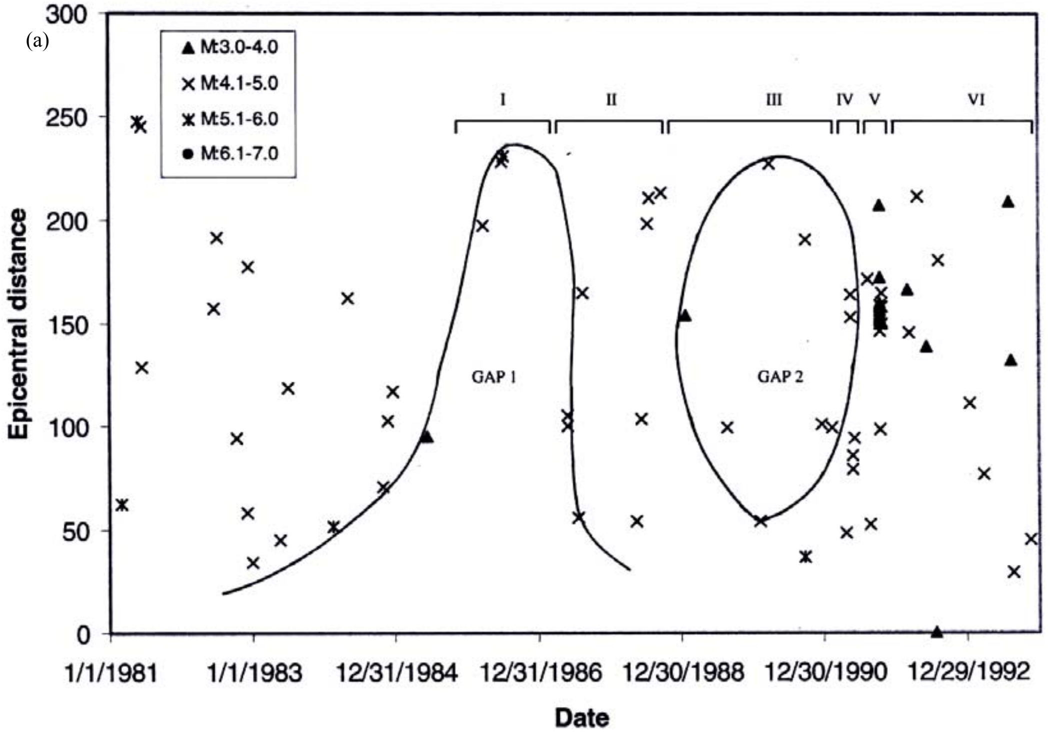


**Fig. 3(a).** Seismic activity for the period 1981 to 1993 from the epicentre of assumed source

(b)

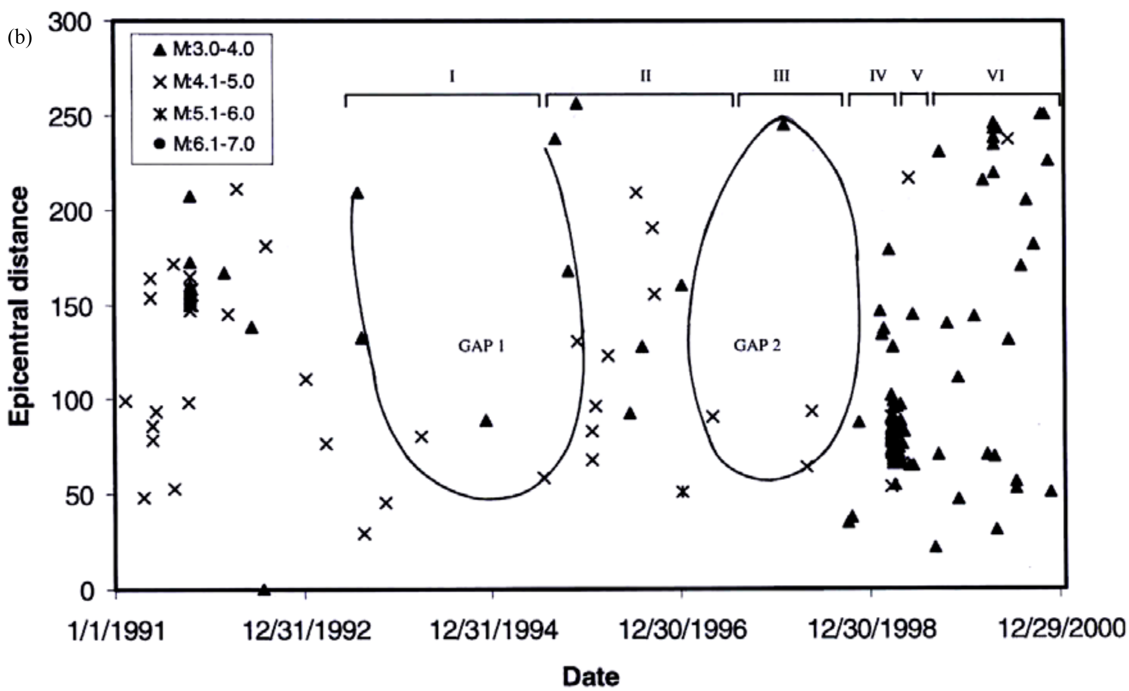


**Fig. 3(b).** Seismic activity for the period 1991 to 2000 from the epicentre of assumed source

**TABLE 2**

**Regional and aftershock values of ‘b’ and other parameters in Uttaranchal**

| S. No. | Station/area | Magnitude | ‘b’ Value | h | Aftershock area | Stress drop | Asperity size (fractal size) | Orientation of isoseismals | Reference |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Chamoli (1999) | 6.8 (ML)<br>6.3 (MS) | 0.54 | 0.69 | 500 km$^2$<br>(30×17) | | 1.1 | E-W | IMD Report (2000)<br>Gupta *et al*. (2001) |
| 2 | Uttarkashi<br>(1991) | 6.5 (MB)<br>7.0 (MS) | 0.95<br>1.23 | 0.87 | 1200 km$^2$<br>(30×40) | 10 bars | 1.9 | NW-SE | Kayal *et al.* (1995) |
| 3 | Nepal-India Border | | | | | | | | Srivastava and Kamble (1972) |
| (a) | (Dharachulla 1980) | 6.1 | 0.86 | | | | 1.7 | NNE-SSW | |
| (b) | (Dharachulla 1966) | 6.0 | 0.51 | 1.28 | 600 km$^2$ | | 1.0 | | |
| 4 | 29.00-31.50° N<br>79.00-81.50° E | | 0.88 | | | | | | Srivastava (1973)<br>Regional Value |
| 5 | 29.00-31.00° N<br>79.00-82.00° E | | 0.60 to 0.81 | | | | | | Srivastava and Dattatrayam (1986) Regional Value |
| 6 | 26.00-34.00° N<br>76.00-85.00° E | | 0.52 to 0.83 | | | | | | Teotia *et al*. (1991) Regional value |

swarm, quiescence (gap), foreshocks, main shock and aftershocks for the earthquakes of Uttarkashi (1991) and Chamoli (1999) in Uttaranchal. These figures represent the first scenario in which the impending earthquake has been assumed as the actual epicenter of Uttarkashi and Chamoli earthquakes, while Fig. 3(a) and Fig. 3(b) show the second scenario by assuming the future earthquake (30.2° N, 80.2° E) to occur near India-Nepal-Tibet border trijunction.

Fig. 2(a) shows the spatio temporal variations of seismicity preceding Uttarkashi earthquake. It may be noted that there was a decline of the aftershock activity due to Dharchulla earthquake of July, 1980 after the year 1982. A well marked ‘seismic quiescence’ developed during the years 1983 to 1985 (Phase I). The seismic activity started increasing during mid 1986 to December 1989 which was essentially of swarm type (Phase II). Thereafter seismicity decreased, receding away to a distance of about 200 km, showing a seismic gap (Phase III). There was some spurt of seismic activity in 1991 (Phase IV). The largest foreshocks of magnitude 4.5 and 2.7 occurred during four hours preceding the main earthquake (Phase V) of 20 October 1991 in early morning. Thereafter, aftershock activity (Phase VI) continued which decreased following the usual Omori’s law. The largest aftershocks had a magnitude of 4.8 which occurred within an hour. The aftershock ‘b’ value in Gutenberg Richter frequency magnitude relationship was large as compared to regional values. The decay of the aftershocks was relatively slower (Table 2) and spread over an area of about 1200 km$^2$. Fig. 3(a) shows the second scenario which also exhibit almost similar seismicity pattern. However, the seismic gap in the second scenario was noted about 60 km away from the impending earthquake implying the occurrence of an earthquake at some distance from the assumed epicenter as compared to Fig. 2(a). The earthquake of Uttarkashi, however occurred at about 140 km away from the assumed source.

Fig. 2(b) shows the seismicity pattern preceding the Chamoli earthquake of March, 1999 including the aftershock activity of Uttarkashi earthquake of 1991. A well marked seismic gap formed from mid 1993 to 1995 end (Phase I). Thereafter, swarm type activity occurred (Phase II). Another ‘seismic gap’ was observed during 1996 to 1997 (Phase III). Foreshock activity became discernible (Phase IV) prior to the main earthquake (Phase V) with the largest foreshock of magnitude in February, 1999. However, comparison with the Uttarkashi earthquake shows that the foreshock activity was less marked. Thereafter the aftershock activity (Phase VI) was characterized by a low ‘b’ value and slower decay rate (Omori’s law). The aftershock area was also much less as compared to that of Uttarkashi earthquake. The aftershocks of Chamoli shock are more numerous due to their monitoring by deployment of several portable seismographs in epicentral region. Similar pattern of seismicity in six phases was observed [Fig. 3(b)] by assuming the epicenter of impending earthquake near Dharachulla. In this case also, the gap (Phase III) appeared about 50 km away from the assumed epicenter similar to that of Uttarkashi earthquake. The Chamoli earthquake,

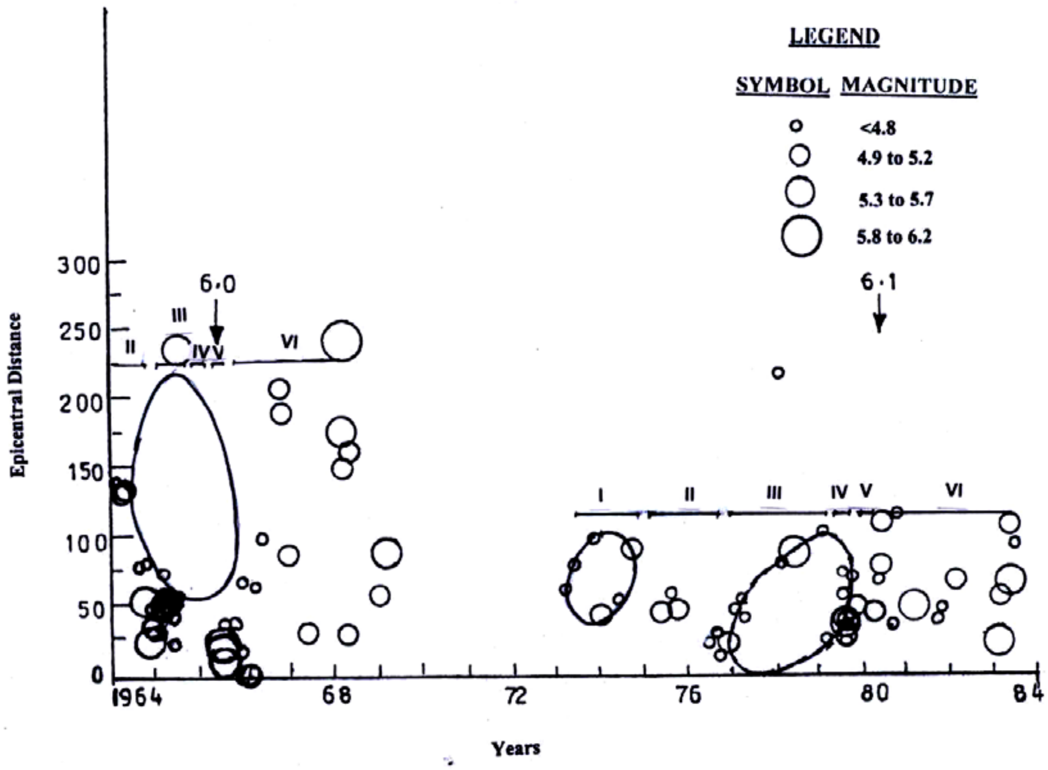


**Fig. 4.** Seismicity pattern preceding the earthquakes of 1966 and 1980 near India – Nepal border for the period 1964 to 1984 based on L.S.C. data

however, occurred at about 80 km away from the assumed source.

Seismicity pattern before 1966 and 1980 earthquakes which occurred near Dharachulla had shown marked quiescence preceding these earthquakes (Srivastava and Gautam 1987) but it may be interesting to re-examine the seismicity pattern for the sake of comparison with the recent earthquakes (Fig. 4). In view of reliability in the epicentral parameters after the establishment of WWSNN stations, data was included form 1964 onwards. Thus, the earthquakes of 1966 had only two years observations instead of about 8 to 10 years available for the earthquake of 1980, 1991 and 1999. In view of this limitation, all the precursory phases of seismic activity may not be discernible for 1966 earthquake. Swarms may be noted from 1964 to 1965 (Phase II). Almost simultaneously, seismic quiescence started developing (Phase III). There were no significant foreshocks and phase IV was poorly defined prior to main earthquake (Phase V). Phase VI for aftershocks was well marked which continued for almost two years. This is one of the few cases where another earthquake of the same magnitude 6.0 as the main shock occurred within 20 minutes which may be called a doublet. Such doublets are attributed to the existence of relatively large, isolated high stress (asperity) zone on the fault. Due to failure of these discrete zones, stress concentrations are rapidly transmitted to the adjacent asperity leading to a second major failure resulting in doublet behavior. The aftershock 'b' value was low and almost comparable to the regional value. However, the aftershocks showed a rapid decay as compared to Uttarkashi and Chamoli earthquakes. There was hardly any seismic activity during the years 1969 to 1973 which showed quiescence (Phase I). Thereafter swarms were noted within 75 km of the epicenter of 1980 earthquake (Phase II) which continued for almost four years. Seismic quiescence (Phase III) was well marked till the occurrence of the main earthquake. However, there was a strong foreshock (Phase IV) of magnitude 5.7 about two hours before the main earthquake (Phase V). Thereafter, aftershock activity continued till 1984 (Phase VI). The value of 'b' from the aftershocks was higher than that of 1966 sequence. Thus, monitoring seismicity pattern from a more frequent source of earthquakes near Dharchulla, enable us to infer that the possibility of occurrence of an earthquake about 50 to 100 km away from the assumed epicenter on the basis of the development of a 'seismic quiescence'. In this case of seismicity pattern prior to the occurrence of an earthquake (1966, 1980) in this region, the seismic gap extended from the impending source.

It may therefore, be inferred that the earthquake sequences in Uttaranchal are generally characterized by six phases namely, first quiescence or gap, swarms, second quiescence or gap, foreshocks, main shock and aftershocks. Thus, the model proposed by Kanamori (1981) needs to be modified into six phases of seismic activity in the Uttaranchal region instead of five phases. The first quiescence is attributed to the nature of asperity wherein after the cessation of aftershock activity of a previous earthquake, accumulation of stresses take place because of complex tectonics. Thereafter, the pattern of seismicity broadly conforms to the dilatancy models.

## 5. Discussion

Gahalaut (1994) considered a much larger block bounded by latitude 30.0° N to 38.0° N and longitude 75.0° E to 83.0° E based on C. N. Algorithm defined by function 'K' (temporal variation of seismicity). He found that when the value of K is 2 or more, the possibility of earthquake increases. This study suggested the occurrence of a strong earthquake anywhere over a very large area with different well defined tectonic blocks like Tibet (normal faulting) and Himalayan plate boundary (thrust faulting with some strike movement). On the other hand, the seismicity pattern in the present study was delineated from a much smaller grid size of almost similar tectonic set up, reducing the location of an impending earthquake to a small area which is important from the point of view of hazard assessment.

A closer look at the seismicity pattern preceding the earthquakes in 1966, 1980, 1991 and 1999 showed significant differences in the size of the quiescence area, the temporal variations in the phases I, II, III, IV and the aftershock activity even for the earthquakes of the same magnitude at the same place (1966 & 1980). The different parameters examined are given in Table 2. The regional values of 'b' by different workers in the grids of different sizes are also given for the sake of comparison. It is well known that fractal structures in time, space and magnitude are observed in the seismicity of earthquakes. The 'b-value' in Gutenberg Richter frequency magnitude relationship is equivalent to fractal relationship between the number of earthquakes and the characteristic size of the rupture. The Omori's constant 'p' from the aftershocks of an earthquake is also suggestive of the fractal geometry (Turcotte, 1992).

The ratio of quiescence area was of the order of 1.11 in case of Chamoli and India-Nepal Border earthquake in 1980 while the corresponding ratio of the magnitudes of these earthquakes was of order of 1.13 showing a close relationship. This suggests that larger the quiescence area, the larger may be the magnitude of the impending earthquake. Similar results were obtained in case of 1968 and 1978 earthquakes of Himachal Pradesh (Srivastava *et al*. 1987). However in case of Uttarkashi earthquake the quiescence area was comparatively less. This may be attributed to the complexity in tectonic features of the region.

We have considered the fractal dimension as twice the value of 'b' (Turcotte 1992). Teotia *et al*. (1999) have also shown a positive correlation between 'b' value and fractal dimension.. Both Chamoli (1999) and Dharachulla (1966) earthquakes had deeper focal depth with almost same fractal dimension and occurred close to the MCT. Their focal mechanism also showed predominantly thrust faulting although due to the non-availability of nearby P wave observations, one of the nodal planes remained poorly defined in both the cases. Isoseismals were oriented east west from the Chamoli earthquake but no field survey was undertaken for the 1966 earthquake. Although the focal mechanism of 1980 earthquake (which was better estimated) showed NW-SE nodal planes and thrust faulting, the field survey by the Geological Survey of India suggested the meizo-seismal area as NNE-SSW oriented suggesting its association with a lineament almost parallel to the Moradabad thrust. Keeping in view that the fault plane solutions of these earthquakes was based on worldwide averaged travel times and may change by using the local crustal velocity model, study of 1968 and 1978 earthquakes in the Himanchal Pradesh brought into focus the role of lineament instead of main boundary fault (Srivastava *et al*. 1987). We infer that the differences in the pattern of seismicity between the 1966 and 1980 earthquakes are attributed to the shallower focal depth of the later shock, the north-north-easterly lineament *vis-à-vis* MCT, the decay constant in Omori's law of aftershocks and mode of generation of foreshocks. The fractal dimension of 1966 earthquake was much smaller than that of 1980 earthquake implying that a larger asperity at a shallower depth was involved in the later case. This was corroborated by the isoseismal pattern of the 1980 earthquake, whose isoseismal area was oriented in NNE direction (Narula and Shome, 1992) implying slippage of rocks along lineaments instead of WNWly oriented thrust fault.

It may be noted that amongst all the four earthquakes, the Uttarkashi earthquake had the shallowest focal depth of 12 km, NW-SE oriented isoseismals as well as one of the fault planes (thrust type) with a very shallow dip of 5° in NE direction in conformity with MCT (Memoir 30, GSI, 1995), well marked foreshock activity and the largest fractal dimension. The largest magnitude of the main earthquake, aftershock area and highest meizoseismal intensity (close to IX) further corroborate the involvement of the largest asperity as the causative factor for its differences in the seismicity pattern. It is of interest to note that no significant difference could be noted in the corner frequency, source radius or stress drop between the foreshock and aftershocks of comparable magnitude for Uttarkashi earthquake using the short period portable digital seismograph at Delhi. The deployment of broadband seismographs may resolve the problem. Further studies may also throw light on the tectonics of this region through seismic tomography. Also, more detailed fractal nature of the seismicity pattern would require very large micro-earthquake data. It may however, be summarized that a larger fractal dimension could be associated with a larger magnitude of an impending earthquake (Table 2).

It may be noted that one of the limitation of the present study pertains to the time of occurrence of main earthquake *vis-à-vis* the time required to develop the quiescence area. Although, these stages are precursory as found in this study but due to availability of only four cases, a statistical relationship between them can not be worked out at present.

## 6. Conclusions

The above study has brought out the following interesting results:

(*i*) Except, 1966 earthquake for which data is limited the other three earthquakes in Uttaranchal in 1980, 1991 and 1999 showed six phases in the pattern of seismicity namely, first quiescence or gap, swarms, second quiescence or gap, foreshocks, main shock and aftershocks in contrast to the five phases reported earlier. This is attributed to the complex tectonics of Uttaranchal region.

(*ii*) Greater insight into the difference in the seismicity pattern could be found from the fractal dimensions estimated from the 'b' value deduced from the aftershocks data.

(*iii*) The size of the quiescence area is proportional to the magnitude of earthquake as inferred from the fractal dimension of aftershocks.

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