Seismological constraints for the 1905 Kangra earthquake and associated hazard in northwest India

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The Kangra earthquake of 1905 occurred when seismological instrumentation with low-gain optical recording seismographs were sparsely located. However, attempts are being made in recent times not only to refine the epicentral data, but even to postulate new earthquakes to explain the secondary meizoseismal area near Dehradun. Careful re-examination and analysis of data reveal that the interpretation given is somewhat misleading as the data provided fit better with a large deeper aftershock of the Kangra earthquake which occurred within a few minutes of the main shock. The meizoseismal area near Dehradun was indeed a site-response effect similar to that during other earthquakes like the Bihar Nepal 1934, Bhuj 2001 and Mexico 1985. Causes for the generation of such meizoseismal areas about 100–500 km away from the epicentre are discussed. It has been highlighted that for earthquake hazard assessment and disaster management, the role of secondary meizoseismal areas should not be ignored.

Keywords: Hazards, Kangra earthquake, secondary meizoseismal area, seismological constraints.

THE great Kangra earthquake of 1905 in Himachal Pradesh took a toll of about 20,000 lives and massive destruction of buildings/houses over a large area in the Himalaya and adjoining plains. At that time only a small number of seismological observatories were operating with low-gain recording analogue instruments at a few places in the world, which included two coastal stations at Bombay and Calcutta, and one at Kodaikanal in India. An observatory in Shimla was established after a few months to record the aftershocks. Thus, the only source of data available for this earthquake is based on sparsely located stations with poor time-keeping of the seismological instruments adding problems in deriving results with the desired precision. The Kangra earthquake, however, generated immense scientific interest due to the development of two high seismic intensity areas separated by about 250 km, one close to epicentre near Kangra–Dharamshala and the other near the Dehradun–Mussoorie area. Although the original work of Middlemiss[1] used Rossi–Forel (RF) scale of seismic intensity to draw isoseismals of main earthquake, attempts have been made to convert them into MSK scale[2–4]. These studies brought out slight differences in intensity, but the two meizoseismal areas near Dharamshala–Kangra and Dehradun–Mussoorie were clearly discernible. Contrary to most of the earlier studies, Hough *et al.*[5,6] surmised that two different earthquakes had occurred within a few minutes with epicentres near Kangra–Dharamshala and Dehradun respectively. According to them, these two earthquakes produced two separate meizoseismal areas.

The objective of this article is twofold; first to re-examine the results of Hough *et al.*[5,6] based on critical evaluation of their seismological observations which led them to postulate a new earthquake near Dehradun. The second is to provide convincing evidence for the development of secondary meizoseismal area Dehradun as a site response due to the great Kangra earthquake of 1905. The plausible causes for its development have been reviewed accordingly. The importance of secondary meizoseismal area in earthquake hazard assessment and disaster management in northwest India and elsewhere has also been discussed. The term 'secondary meizoseismal area' in this article implies a zone of fairly high seismic intensity which may be developed at a distance of about 100–500 km away from the epicentre of the main earthquake.

Tectonic features

The main tectonic features in northwest India[7] are shown in Figure 1. The continued thrusting towards the south resulting from the collision of the Indian and Eurasian plates produced the Main Central Thrust (MCT) and the Main Boundary Thrust (MBT), besides uplifting the Himalaya. The present deformation front is at the foot of the Siwalik hills of India and Nepal marked by Himalayan Frontal Fault (HFF). The sub-Himalaya towards east of the syntaxis is narrower and the basement slope toward the hinter land is steeper than in Pakistan. The Himalayan anticlines are commonly bounded by reverse faults and

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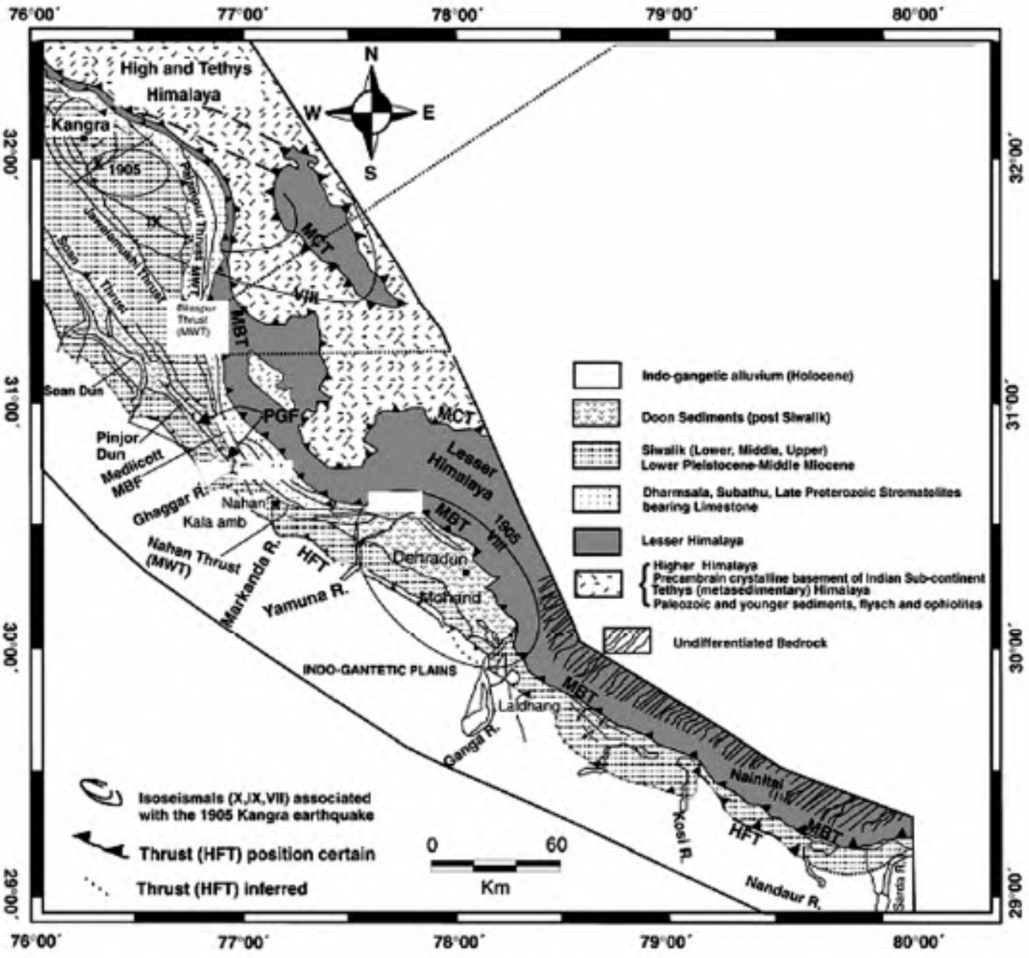

Figure 1. Geology and tectonics of Himachal Pradesh (after Kumar and Mahajan[7]).

these cut the Precambrian basement. Significant features in northwest Himalaya are marked as Janauri–Jawalamukhi transect between the Beas and Sutlej rivers, and the Mohand structure at Dehradun between the Yamuna and Ganga tears.

Focal mechanism solutions have been worked out for a few earthquakes in northwest Himalaya by various workers[8,9]. These solutions were generally based on Jeffreys–Bullen (1938) or Herrins (1981) velocity models. Most of these results brought out thrusting as the predominant mechanism in northwest India. However, data from a local network of stations in northwest India using local crustal velocity model constrained the nodal planes more accurately. One of the important results was that the two earthquakes of 1974 and 1978 near Dharamshala brought out a NNE striking strike slip fault[10]. CMT solution for another earthquake (location lat. 31.28°N, long. 78.13°E, focal depth 10 km with M_w 5.1 on 19 February 1977) about 100 km south of Kangra, showed thrust faulting with the two nodal planes having strike 346°, dip 37° and slip angle –118° and another with strike 199°, dip 58° and slip angle –71°. Subsequently, the earthquake of 26 April 1986 (magnitude 5.6) from the same region showed thrusting with both nodal planes almost oriented along MBT fault[11]. Further east, the Kinnaur earthquake of January 1975 showed normal faulting and the nodal planes did not coincide with the north-south oriented Karnik fault[12]. Towards west, two earthquakes in 1980 near Kathua, Jammu were also thrust mechanism[13] and these were corroborated by Bhattacharya and Kayal[14]. In spite of more than a century after the occurrence of the great Kangra earthquake, this source region remains active, while another active region lies near the Kaurik fault.

The detailed geology and tectonics of Dehradun[15] is given in Figure 2. Dehradun valley is bounded in the north by MBT making the main front and in the south by the rising Mohand anticline. This anticline is cut in the south by the foothill (locally called Mohand) thrust. The foothill thrust is terminated in the west and east by the Yamuna and Dhal Khand tear faults respectively. Doon valley is mostly underlined by piedmont fan deposits which are locally called Doon gravel. The hilltop surface consists of thick boulders and gravel beds. The piedmont surfaces divided as the Middle Doon Surface and the Lower Doon Surface comprise of less consolidated and

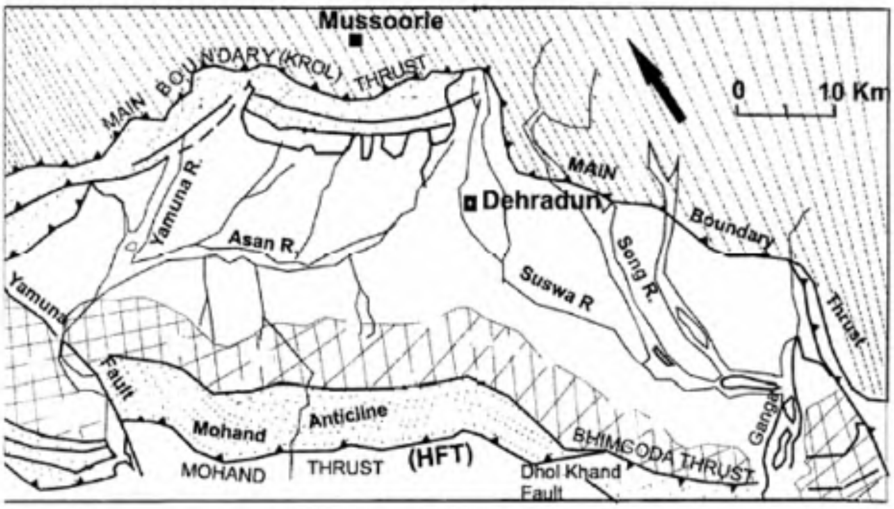

Figure 2. Geology and tectonics of Dehradun (after Thakur[15]).

weathered ground beds. The piedmont terrace (Lower Doon Surface) covers mostly the central and southern part of the Doon valley. It consists of alluvial fan deposits of the major tributaries of the Ganga and Yamuna rivers. Detailed bed-rock profiles in Dehradun city have been studied by Indian Institute of Technology, Roorkee in collaboration with institutions in Norway based on SASW survey, and Mahajan[16] and Mahajan *et al.*[17] for several sites using H/V spectral ratio and MASW methods. These studies were directed to generate V_s profiles and spectral acceleration at different locations in the city. Similar studies using microearthquakes were also undertaken by Kandpal *et al.*[18].

Isoseismal maps due to the 1905 Kangra earthquake

Figure 3 *a* and *b* shows the isoseismal maps by Molnar[2] and Joshi *et al.*[4] using MSK intensity scale. Comparison of these maps shows that delineation of seismic intensity lower than VI is broadly comparable, but the maximum intensity in MSK scale was X, i.e. one intensity lower than that shown by Middlemiss[1] in RF scale. All these isoseismal areas show a primary zone near Kangra–Dharamshala and a secondary zone near Dehradun–Mussoorie.

We compare here the development of secondary meizoseismal areas for other great earthquakes.

(i) The epicentre (lat. 26.5°N, long. 86.5°E, *M* 8.3) of the great Bihar Nepal earthquake of January 1934 lay below the alluvium slightly to the north of towns of Darbhanga and Muzaffarpur. Three secondary meizoseismal areas were observed; the largest being an elongated track aligned approximately 128 km long, WNW–ESE from Motihari to Madhubani through Sita Marhi; the second at Monghyr, south of Ganga river and the third around Kathmandu valley in Nepal, similar to Dehradun valley in the case of Kangra earthquake. The maximum intensity[19] in these meizoseismal areas was X.

(ii) The Bhuj earthquake (epicentre 23.40°N, 70.28°E, *M* 7.8) of January 2001 caused a primary meizoseismal area near Bachhau with the maximum intensity of X in an elliptical area aligned N75°E–S75°W. The secondary meizoseismal area was developed near Mehsana, Ahmedabad[19], with maximum intensity of VII–VIII at a distance of about 250 km. Another meizoseismal area was also observed near Surat at a distance of 350 km away from main earthquake.

(iii) The great Mexican earthquake of September 1985 (*M* 8.5) occurred near the plate boundary of Cocos, South American plate boundary. This earthquake caused the worst disaster in Mexico City, located about 350 km away from the epicentre[20]. The maximum intensity in this secondary isoseismal area was assessed as IX. Such an extensive damage was attributed to the largest spectral acceleration, largest duration and occurrence of two shallow-focus events within an interval of 27 s, besides efficient generation of surface waves (0.2–1 Hz) towards Mexico city[21].

(iv) Smaller earthquakes of magnitude slightly less than *M* 7 also produced secondary meizoseismal areas.

- The *M* 6.8 earthquake in Bihar Nepal region in August 1988 was located at lat. 26.75°N and long. 86.62°E, with a focal depth of 57 km. Maximum intensity of IX was estimated in the primary meizoseismal area in north Bihar (Geological Survey of India)[19], whereas it was reported as VIII in Kathmandu valley (USGS) at a distance of about 100–150 km away from the secondary meizoseismal area.
- The Uttarkashi earthquake in Uttarakhand (epicentre 30.75°N, 78.85°E, *M* 6.6, focal depth 12 km) occurred

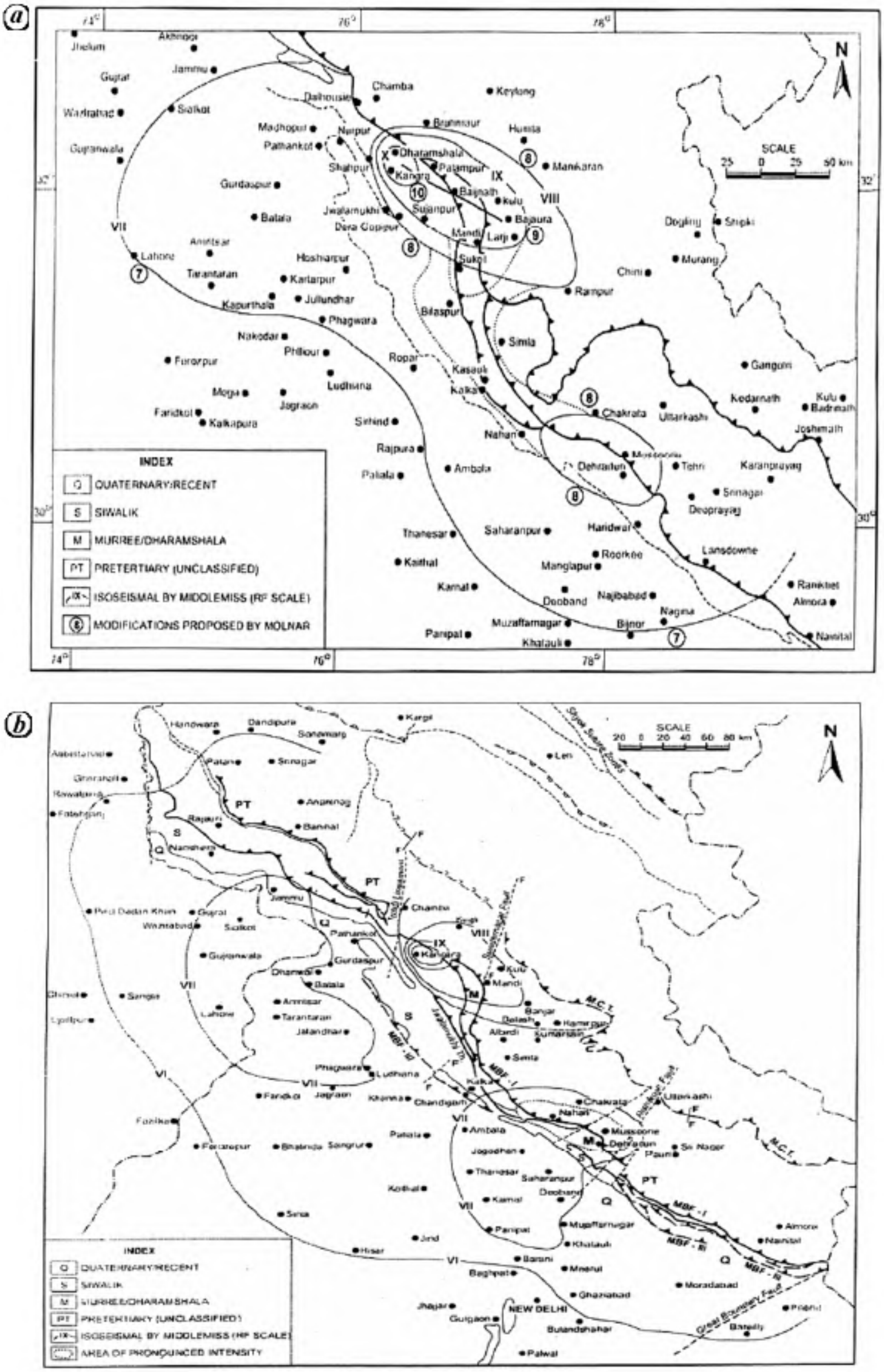

Figure 3. ***a***, Higher isoseismals of Kangra earthquake by Middlemiss[1] and proposed modifications by Molnar[2]. ***b***, Revised isoseismals on MSK scale of the 1905 Kangra earthquake[4].

close to MCT on 20 October 1991. The primary meizoseismal area[18] had maximum intensity of IX MM. Narula *et al.*[22] reported an anomalous high, i.e. secondary meizoseismal area with intensity V near Delhi at an epicentral distance of 250 km. This was attributed to lithological accentuation caused by the deep floodplain of the Yamuna. Srivastava[23], after comparing the Mexico earthquake vis-à-vis the great Indian earthquake had surmised earlier that in the event of a great earthquake occurring in central Himalaya, a large secondary meizoseismal area would develop near Delhi and the adjoining Indo-Gangetic Plains.

- It may be noted that the field effects of the Bihar Nepal earthquake (1988) were similar to great earthquake of 1934, with two meizoseismal areas at the same places separated by about 150 km. However, due to lower seismic intensity of the 1988 earthquake, the damage was confined to smaller areas compared to that of the 1934 earthquake.

On going through the historical catalogues[24], it is interesting to note that a great earthquake was reported to have occurred in Mathura on 1 September 1803 and another in the Garhwal Himalaya. The former caused extensive damage at Mathura and the latter heavy landslides, rockfall and major damage to Badrinath temple. It is also mentioned that due to the former, the top floor of Kutub Minar in Delhi fell down. These and many other field reports have been examined in detail by Rajendran and Rajendran[25], who surmised that there was only one earthquake in 1803 with its epicentre near Srinagar in Garhwal, Kumaun Himalaya. It was possibly associated with a subsidiary thrust of MCT. They estimated the magnitude of this earthquake as M_w 7.7. Recently, Szeliga *et al.*[26] re-evaluated the magnitude as 7.3 and estimated its location 9 km south of the 1991 Uttarkashi earthquake. Their inferences are open to question because the extent of damage and liquefaction features do not support lower magnitude. Also, the epicentre cannot be located accurate to 9 km for a historical earthquake. Damage to tall structures like the Kutub Minar occurred due to the generation of longer-period seismic waves from a distant earthquake in Uttarakhand, similar to that from the great Mexico earthquake of 1985. Damage in the Delhi–Mathura region was attributed to the amplification of seismic energy due to thick alluvium beneath these towns in the Gangetic plains. If we compare the isoseismal pattern of this earthquake with more recent Uttarkashi earthquake of 1991, we find a well-marked similarity confirming the development of a secondary meizoseismal area close to Delhi.

Another strong earthquake occurred in Nepal on 26 August 1833. The epicentre of this earthquake was northeast of Kathmandu[27]. Its magnitude was assessed between 7.5 and 7.9. The isoseismal map prepared by Bilham[27] shows only one meizoseismal area in Nepal. However, the intensity IX in Bihar plains encompasses Monghyr, Muzaffarpur and Purnea districts, which clearly form a secondary meizoseismal area. The localized high intensity in this region was attributed to the amplification of surface waves in the water-saturated sediments as they approach the southward shelving bed rock south of the Gangetic plains. Similarly, the lake deposits of the Kathmandu valley were presumably responsible for localized high intensities and rapid variations in intensity, similar to that of August 1988 earthquake.

Local seismological network

During the 1960s, the Bhakra Beas Management Board (BBMB) approached the India Meteorological Department (IMD) to operate a ten-station network at Dalhousie, Nurpur, Mukerian, Dharamshala, Pong, Jawalamukhi, Kulu, Sundernagar, Shimla and Ghagghar. The network was equipped with short-period (1 s), three-component Hagiwara electromagnetic seismographs. Timing precision was maintained using radio signals. The recording was done on a film which was analysed by a high-speed film reader. A similar request by the Salal Hydroelectric Project enabled IMD to operate three more stations at Jyotipuram, Rampur and Udhampur from early 1980. The seismological stations under the national network of IMD are located at Srinagar, Jammu, Thein Dam, Bhakra, Kalpa and Dehradun. The BBMB network was gradually reduced to six stations after 1993–1994. From 2002, the stations under the Salal Hydroelectric Project were also closed. Thus, the accuracy in the epicentral determination was best during 1965–1992.

Figure 4 shows a plot of epicentres during 1964–1974 and 1981–1985 based on earthquakes detected by the local network[28]. Similar distribution of epicentres is noted for other periods as well. It may be noted[29] that between Dharamshala and Kinnaur regions, there is a gap in seismicity marked A. Seismic activity is very high near the Dharamshala–Kangra region. It is relatively absent near the Kulu–Shimla–Sundernagar region close to MBT. High seismic activity is again noted near Kinnaur region, particularly after the 1975 earthquake. whose aftershocks have continued for a long time. The implications of gap in seismicity bring out an anomalous zone between Dharamshala and Kinnaur regions, which could have profound influence on seismic wave propagation across this zone.

Kangra earthquake: seismological constraints

Several studies pertaining to the great Kangra earthquake have brought out the following points.

(i) The exact epicentre could not be determined due to lack of seismological data, but considering the damage in the Kangra–Dharamshala region, the best estimate could be rounded to 32.5°N, 76.5°E.

(ii) The magnitude of the earthquake has been determined as M_s 8 on surface magnitude scale[30]. Using empirical intensity, focal depth and magnitude relations Joshi *et al.*[4], by assuming focal depth varying from 10 to 32 km, found magnitude to be 7.0 compared to magnitude 8 from instrumental data. It is obvious that due to inherent errors in empirical relations, their application to determine magnitude is hardly justified, particularly when the focal depth cannot be reliably determined due to lack of seismological observations. Also, comparison with the damage pattern of M 7 earthquakes like Kinnaur (1975), Bihar Nepal (1988) and several others[31] rules out its magnitude as 7 as inferred by Joshi *et al.*[4] and as 7.3 by Szeliga *et al.*[26]. Prior to this, Ambraseys and Douglas[3] tried to determine the moment magnitude for this earthquake and refined its magnitude as M_w 7.8. This is also open to errors due to determination of the spectrum from low-gain analogue seismograms, digitization process and poor azimuthal control. In view of this, the magnitude of the earthquake for hazard analysis (even in moment magnitude scale) may be adopted as 8.0.

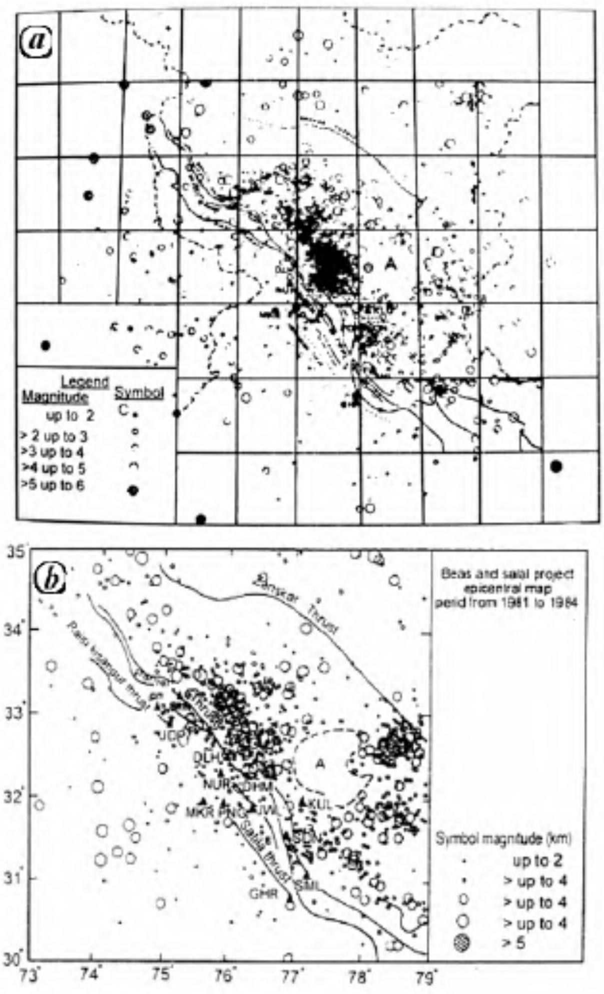

Figure 4. ***a***, Microseismicity in Himachal Pradesh and 'gap in seismicity' marked 'A'[27,28]: (***a***) 1965–1974 and (***b***) 1981–1984.

(iii) Crustal studies[28] suggest the thickness of granite layers in this region to be 24.5 km. According to the steady-state model proposed by Seeber and Armbruster[32], most of the earthquakes occur above the plane of detachment in the focal depth range of 10–25 km. Thus the focal depth of the main earthquake may be adopted for hazard analysis to vary from 15 to 25 km, implying that its focus lies in the granitic layer.

(iv) The length of the fault rupture was 100–150 km based on the intensity distribution at Kangra, but if the secondary meizoseismal area at Dehradun is included[33], the fault rupture is about 250 km. Molnar and Pandey[34] also mentioned both these possibilities and also suggested the possibility of two separate areas encompassed by the VIII MM isoseismals for a total length of about 200 km of the Himalaya front. It is more reasonable to consider 100–150 km only as the fault rupture, because the secondary meizoseismal area near Dehradun is only a site effect which cannot be included in fault rupture. It is possible that longer rupture length as expected for a magnitude 8 earthquake was inhibited by the anomalous zone characterized by the gap in seismicity on the east[28] and by Salt range in Pakistan[32] on the west. In this connection, Bilham[27] also reported that the 1905 Kangra earthquake was unique in that its intensity VIII area was anomalously small from a great earthquake. However, the explanation proposed was that the Kangra earthquake may have been a slow earthquake. Looking into the Leipiz seismogram, it is clear that no features of a slow earthquake are discernible.

(v) The mechanism of the main earthquake is thrust faulting[1]. Seeber *et al.*[35] surmised that the Kangra earthquake occurred on a blind thrust at the top of basement. However, Krishnaswamy *et al.*[36] stated that aseismic slip was not observed on the MBT or any other thrust. He suggested that the earthquake slip occurred on buried portions of Satlita and Kalagarh thrusts, located southwest of the MBT.

(vi) The aftershocks of the Kangra earthquake were spread over a large area, which continued for many years and showed a tendency to migrate southeast. However, their epicentres could not be determined due to lack of data. The decay in aftershocks appeared to follow Omori's law, as inferred from the Omori seismograph installed after a few months at Shimla.

Results and discussion

The above results suggest that for great earthquakes (M 7 or more), there is a higher probability of occurrence of secondary meizoseismal area in specified zones. However, the maximum intensity in such areas is generally one or two units less compared to the primary meizoseismal area. The reason for their development is attributed to site response and focusing of seismic waves due to multiple reflections or presence of low-velocity layers. In some situations standing waves may be set up through reflections across a valley causing pockets of high intensity. Drake[37] using a finite element model, showed that Love and Rayleigh waves propagating into a semi-infinite valley are greatly amplified at certain periods despite the absence of a reflecting boundary. The periods of large amplifications may correspond to other lowest resonant periods of shear waves propagating vertically into the relatively soft alluvium layer at the surface. At a distance of almost 200 km, Lg waves whose velocity depends upon shear waves in the underlying soft layer, are greatly amplified. Considerable structural damage in secondary meizoseismal area occurs when resonance is caused by multiple reflections between the free surface and any discontinuity which gives rise to a pronounced change in shear wave velocity. More important phenomena giving rise to resonance occur when body waves propagating through the valley sediments and surface waves propagating across the valley reinforce. Zhu *et al.*[38] found that the effect of topography and sedimentary layer produces complex interference of seismic waves. The Dehradun region being covered by fan deposits – a product of weathering, erosion and deposition over long periods of time – is a preferred zone of high amplification for seismic waves due to the existence of faults on all the four sides; MBF and MFF towards the north and south respectively, and Yamuna and Dhalkhand tear faults on other two sides of the valley.

It may be mentioned that during the Bhuj 2001 earthquake, the damage at Ahmedabad in the secondary meizoseismal area was attributed to higher ground acceleration compared to neighbouring places. Strong motion observations were available in a site at Ahmedabad from this zone. The highest level of ground motion (peak ground acceleration) from this zone was 0.11 g in the longitudinal component, whose predominant frequency was between 2 and 4 Hz. Saikia *et al.*[39] noted that motions recorded at Ahmedabad were relatively large compared to ground motions estimated from empirical attenuation relations. They inferred that seismic waves must have propagated through several local basins with low-velocity materials and may have amplified the ground motions. Pseudo spectral accelerations estimated from SRRs revealed that the level at Ahmedabad was 225 cm/s^2, which is high compared to two other nearby sites (outside the secondary meizoseismal area) at Anand and Cambay with much lesser values of 60 and 40 cm/s^2 respectively. It is, therefore, inferred that attenuation relations of peak ground acceleration with distance may hold good from the epicentre till the periphery of the secondary meizoseismal area, after which they break down due to large accelerations developed locally.

A question is raised as to why secondary meizoseismal areas develop in specific directions from the earthquake source. For example, in the case of the 1803 earthquake in Garhwal, Kumaun Himalaya, the secondary meizoseismal area developed from Delhi to Mathura, but not towards Dehradun. Similar field effects were again observed during the Uttarkashi earthquake of 1991. On the other hand, the secondary meizoseismal area from the 1905 Kangra earthquake, developed near Dehradun and not over the Indo-Gangetic alluvium at similar distance. The secondary meizoseismal areas during the 1934 and 1988 earthquakes occurred at the same place near Kathmandu, but the extent of damage and loss of life was commensurate with their magnitudes. Due to non-availability of strong motion data for primary and secondary meizoseismal areas for the same earthquake in the Indian region, a quantitative explanation cannot be given. Nevertheless Singh *et al.*[21], based on similar data from near and far field, have shown why there was extensive and large damage towards Mexico City at a distance of about 250–300 km away, which we refer to as secondary meizoseismal area. They computed the Fourier amplitude ratio (A) of the main earthquake (19 September 1985, $M_s = 8.1$) and the large aftershock (21 September 1985, $M_s = 7.6$) from data in and near Mexico City. The wave paths for these two events to a given station may pass through slightly different crustal structures. Therefore, the ratio A_{19}/A_{21} should reflect the source spectrum ratio and any differences in the focal mechanism, directions, path and depth of energy release of the two shocks. Also, nonlinear behaviour of clay at high strains positively identified an anomalously large radiation for $0.2 \leq + \leq 0.5$ Hz in and near Mexico City, compared to the sites along the coast at similar distances during the September 1985 earthquake. It was found that this ratio increases from about 3.5 at 0.5 Hz to about 10 at 0.2 Hz. The increase was neither seen in the coastal data (near the epicentral zone) nor in the teleseismic broadband GDSN P-wave spectra. It was not predicted by w–z or Gusev scaling laws. This increase in frequency of less than 0.5 Hz is attributed to a special path and or a depth of energy release effect for the 19 September earthquake. The damage to Mexico City is mostly related to 0.5 Hz energy. Ground motion at lake bed sites in Mexico City with $f = 0.25$ Hz was amplified 75 times with respect to hard rock and coastal sites at equal distances from the source.

Hough *et al.*[5,6] have postulated that another earthquake was triggered within a few minutes near Dehradun with M 7–7.5 and focal depth ranging from 30 to 50 km, southeast of Dehradun close to 29.0°N, 78.7°E (± 0.5°). They attributed this earthquake to have occurred within the Indian plate in a different tectonic set-up similar to the 1988 earthquake. This is not substantiated due to following reasons:

(i) The occurrence of another earthquake of M 7–7.5 could have caused much more damage SE of Dehradun at Haridwar, Saharanpur and Roorkee regions, where the depth of alluvium increases markedly from the foothills to the plains. Consequently, the intensity in these areas should have been at least VIII, but these places have been placed in zone VII only in all the isoseismal maps[1–4]. In this connection, it is also interesting to note that Middlemiss[1] reported hardly any damage in Haridwar.

(ii) From MASW experiments, 1D or 2D profiles were generated up to a depth of 30–40 m. They show that shear wave velocity, V_s is higher in the northern part of Dehradun city (about 200–700 m/s) compared to its south and southwestern parts (180–400 m/s)[16–18]. If the postulated earthquake[5,6] would have actually occurred, it would have caused major destruction in the southern part of the city (where shear wave velocity is less), in addition to other places shown in zone VII in isoseismal maps.

(iii) The predicted intensity from the 1905 Kangra earthquake using rupture models is full of assumptions and empirical conversion from peak ground acceleration to intensity[5,6]. The difference between the predicted and actual intensity is largest towards east near Dehradun, implying the limitations of the model (Figure 5). Nevertheless, it does show two meizoseismal areas which could result by assuming modelling parameters, particularly the source time functions of only one earthquake.

(iv) The analogy of the postulated earthquake with the Bihar Nepal earthquake of August 1988 is misleading. Although its magnitude was much less (6.8) than the great Bihar Nepal earthquake of 1934, it also produced two meizoseismal areas – one in Bihar and the other in Nepal near Kathmandu. Thus, this earthquake is an analogue of the Bihar–Nepal earthquake (1934) and not of the postulated Dehradun earthquake. It is inappropriate to compare a postulated earthquake with the August 1988 earthquake on the basis of uncertain focal depth, when the generation of two meizoseismal areas due to the August 1988 earthquake is actually an observed feature based on the damage reported.

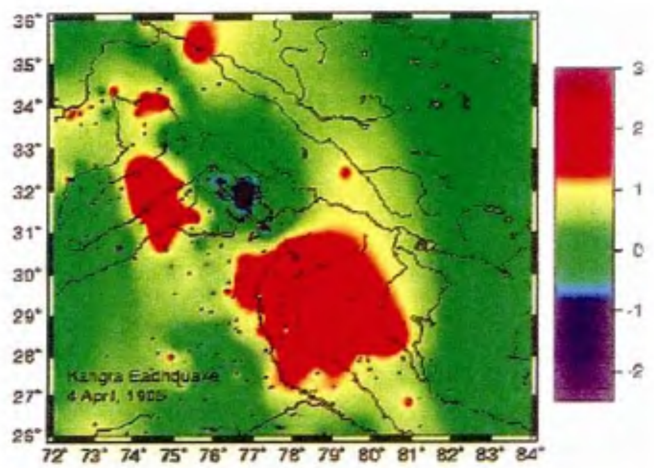

Figure 5. Residual intensity (observed minus predicted) from the 1905 Kangra earthquake[5,6]. Scale bar (right) indicates value of MSK residual.

(v) Hough *et al.*[5,6] considered that first SmS arrivals at Leipzig seismograms and 7 min thereafter apparent SmS group ahead of surface waves with larger sS-S time are indicative of a postulated deeper second event. This is a misinterpretation of instrumental data. After a great earthquake, aftershocks start occurring within minutes of the main shock. These aftershocks show marked spatial, temporal and focal depth variation. Thus, the second event on the Leipiz seismogram of the Kangra earthquake was a large aftershock with larger focal depth (= 30 km), which was triggered on the downdip extension of the same fault that caused the main earthquake.

(vi) Hough *et al.*[5,6] found that at Colaba, Mumbai about 1500 km away, two distinct *P*-wave arrivals were noted in Weichert seismograms, while 7 min difference between two *S*-waves was observed at Leipzig. The two *P*-wave arrivals at Colaba were clearly due to two earthquakes within a minute – one relating to the mainshock and the other its aftershock large enough to be recorded. At Leipzig, since *P*-waves were not discernible, epicentral distance could not be computed. The two *S*-wave movements could either be associated with the main shock and its large aftershock, or two large aftershocks of comparable magnitude from the Kangra region. These *S*-movements could not be connected with those of the *P*-waves recorded at Colaba. It is inferred that there were four different movements of *P*- and *S*-waves, which possibly resulted from four different earthquakes (main shock, three large aftershocks).

(vii) It is well known from reflection studies that Moho shows wide variation in depth as well as sharpness in different places. The depth of Moho in Kangra–Dharamshala and central Himalayan foothills has been found as 45 and 49 km respectively, based on earthquake data using crustal velocity model[27]. The reflection of *S* phase if found to be equally sharp to be recorded on a seismogram as reported by Hough *et al.*[5], would suggest that the two earthquakes have originated from the same focal zone and not at two distant places like Dharamshala and SE of Dehradun.

(viii) Hough *et al.*[5,6] inferred that the pattern of circular isoseismals as drawn by them is indicative of triggered earthquake near Dehradun. This inference is questionable since except these workers, other studies have reported elliptical isoseismals near Dehradun in conformity to the trend of HFF. If an earthquake would have happened southeast of Dehradun as postulated, the isoseismals could alternately be oriented N/NE in conformity with the Rishikesh fault or Delhi–Haridwar ridge. It is well known that only with point source and azimuthal symmetry of medium can we get circular isoseismals, but not with fault dislocation. It is obvious that the isoseismals drawn as circular were biased. Also, triggered earthquakes need not necessarily have circular isoseismals.

(ix) Mahajan[16] classified Dehradun in two soil classes, i.e. class D (180–360 m/s) and class C (360–760 m/s) according to NEHRP classification (1997). Some of the areas on the southwestern side of the fan deposits had average shear wave velocities less than 180 m/s and were classified as soil class E. In the Kutch seismic zone, where extensive damage occurred due to the great Bhuj earthquake of 2001, Mandal *et al.*[40] also inferred the presence of soil classes C and D in the Kutch region, which is almost similar to Dehradun region. In other words, the site effect at Dehradun is equally conducive for seismic wave amplification causing damage.

(x) Rajput *et al.*[41] reviewed the process of stress distribution at different scales and summarized five processes which are responsible for fault interaction with the nearby stress field. They computed Coulomb stress changes and discussed triggering of aftershocks of earthquakes. A close network of temporary stations set up around epicentres of the earthquakes of Killari (1993), Jabalpur (1997), Chamoli (1999) and Bhuj (2001) showed that the aftershocks of these earthquakes remained confined near the focal zone and none of them triggered an aftershock about 250–300 km away. Thus the deeper aftershock of the Kangra earthquake which occurred within a few minutes could be inferred to have been caused by dynamic stress change.

It may, therefore, be concluded that the secondary meizoseismal area near Dehradun is only a site effect similar to the Bihar–Nepal (1934), Bhuj (2001), Mexico (1985) and other earthquakes. It appears to be risky to postulate an earthquake giving its epicentre, magnitude and even its focal depth based on a single seismogram about 3500 km away from the epicentre, when even the *P*-wave onset cannot be read. The interpretational anomaly can be dispensed with by fitting the meagre dataset based on sS-S time interval cited by Hough *et al.*[5,6] with a large deeper aftershock of the great Kangra earthquake, which appears to have occurred within a few minutes after the main shock in the same tectonic set-up.

We can synthesize seismological characteristics of the earthquakes which developed secondary meizoseismal area.

(i) The threshold magnitude for secondary meizoseismal area in the Indian region has been found to be 6.8.
(ii) The focal depth of the earthquakes should be shallow (15–60 km).
(iii) Major earthquakes in intra-plate or inter-plate settings are equally conducive to generate secondary meizoseismal area.
(iv) Secondary meizoseismal areas tend to develop at the same place, if a major earthquake recurs.
(v) Longer duration of shaking.
(vi) Focusing of seismic energy in specified frequency bands.
(vii) Larger peak ground acceleration on soft sediments compared to hard rock (similar to primary meizoseismal area).
(viii) Under similar conditions in primary and secondary meizoseismal areas, possibility of soil liquefaction at a relatively lower threshold magnitude of the earthquake due to longer shaking of the ground.

It may be noted that the lesser magnitude earthquakes of Uttarkashi (1991) and Bihar Nepal (1988) are the analogues of major earthquakes of 1803 and 1934 respectively, which produced two meizoseismal areas – one close to the epicentre and the other about 150–250 km away. Extending the analogy, if a great earthquake recurs in the Kangra–Dharamshala region, the secondary meizoseismal area would again develop near the Dehradun–Mussoorie region. Molnar and Pandey[34] concluded, 'In evaluating earthquake hazard, it seems reasonable to assume that only the segment approximately 100 km in length surrounding Kangra rupture in 1905 but also to consider the possibility the entire zone 200 km in length'. In effect, therefore, they have considered the importance of secondary meizoseismal area. However, if the less convincing evidence about the postulated earthquake near Dehradun by Hough *et al.*[5,6] is considered, there is no role for a secondary meizoseismal area in hazard assessment, which is contrary to the observations during the Bihar Nepal (1934), Bhuj (2001), Mexico (1985) and several other earthquakes. It may, however, be noted that the presence of active faults/lineaments close to secondary meizoseismal areas should be given due weightage, which may cause local earthquakes of damaging intensity producing near-field effects[42,43]. For example, NCR Delhi will typically experience effects from central Himalayan earthquake (*M* 7–8) as well as due to local earthquakes (*M* 6.0–6.5).

Isoseismal maps and strong motion observations are important for disaster management and earthquake hazard assessment respectively. Based on extensive seismic intensity data of Indian earthquakes, Szeliga *et al.*[26] found that the attenuation of intensity for Himalayan events was comparable to intensity attenuation in California, whereas intensity attenuation of cratonic events was higher than intensity attenuation reported for central/eastern North America. They inferred that except for the nonlinearity associated with ground motion at sediment sites, the equations derived appear to be appropriate for characterization of peak ground acceleration for large and small earthquakes. The implicit failure of such simple relations in secondary meizoseismal areas is obvious from their statements, 'A simple uniform adjustment of intensity observations to correct for amplifications is not possible'. They also made interesting observations which are of direct relevance to earthquake hazard assessment for secondary meizoseismal areas, 'Where higher mode surface wave trains develop and propagate the continent crust, the highest amplitude shaking typically has a long duration. It is thus reasonable that a prolonged Lg wave train with a given peak acceleration will produce a higher intensity observation than with ground motions with the same peak acceleration and a much shorter duration. Shaking duration will clearly be a potential factor for structural damage'.

Based on strong motion data, Kumar *et al.*[44] found that attenuation characteristics of the observed peak acceleration as a function of distance and magnitude for Dharamshala (1986) and Uttarkashi earthquake (1991) were different. In the Dharamshala area, the attenuation rate was higher, as was also observed during the Kangra earthquake. In this region, a thick Neogne Siwalik sedimentary lid forms the upper crustal layers which are relatively less consolidated and also contain gravel and boulder beds that promote attenuation of waves by scattering. On the other hand, Uttarkashi lies in the Lesser Himalaya, where the upper layers are composed of the Palaeozoic meta-sedimentary rock. The attenuation rate is accordingly lower due to consolidated and hard nature of the rocks.

Khattri[45] and Singh *et al.*[46] estimated A_{max} (peak ground acceleration) and V_{max} (peak ground velocity) from a hypothetical earthquake of M 8.5 in the central gap of the Himalaya. The values A_{max} and V_{max} at soft sites in Delhi were predicted[46] between 174 and 218 gal as well as 17 to 36/s cm respectively, which were in agreement with those of Khattri[45]. For these studies, strong motion data from the Uttarkashi (1981) and Chamoli (1999) earthquakes were used, which included three sets of observations from Delhi for the Chamoli earthquake. It may however be noted that no secondary meizoseismal area was clearly discernible around Delhi during the Chamoli earthquake (1999) and the data may not be representative. Singh *et al.*[46], therefore, suggested recording earthquakes simultaneously at many representative sites in the Delhi area and carrying out a microzonation of the city.

Under the programmes of Ministry of Earth Sciences, microzoning studies have been initiated at several cities in the country, but our interest at present is confined to the results obtained at Dehradun, NCT Delhi and Ahmedabad, which are the main cities located in the three secondary meizoseismal areas. Kandpal *et al.*[18] reported maximum amplification in the southwest part of the Dehradun urban complex. The first-level microzonation map of NCT Delhi has been prepared by the Earthquake Risk Evaluation Centre, IMD. Shukla *et al.*[47] divided NCT Delhi into nine units. The lowest hazard zone was found in Ridge ambience of exposed rock and the highest hazard in newer alluvium proximal to Yamuna River due to liquefaction potential. Rastogi *et al.*[48] summarized microzoning results for Gujarat[40]. It was found by the Geological Survey of India that areas of low shear velocity in Ahmedabad were associated with higher amplification, but larger damage occurred elsewhere. It is therefore surmised that detailed studies for microzoning are called for.

Conclusion

1. Seismological constraints rule out the postulation of a magnitude 7–7.5 deeper focus earthquake near Dehradun, as inferred by Hough *et al.*[5,6].
2. The meagre seismological data quoted by Hough *et al.*[5,6] fit better with the large aftershock of the great Kangra earthquake that occurred within about 7 min.
3. The secondary meizoseismal area near Dehradun is a site response similar to the Bihar Nepal earthquake of 1934, Bhuj earthquake (2001), Mexico (1985) and several other earthquakes.
4. For earthquake hazard assessment and disaster management, due attention needs to be given to secondary meizoseismal areas (where because of distance, the influence of surface wave generated on tall structures and longer duration of shaking assume an important role).

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