The Chamoli earthquake, Garhwal Himalaya: Field observations and implications for seismic hazard

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The Chamoli earthquake in the northern part of Uttar Pradesh is an important event from the point of view of seismic hazard and risk assessment in the Himalaya. Tectonically, it is significant due to its location in the 'central seismic gap', a 700-km-long segment between the 1905 Kangra (M 8.6) and the 1934 Bihar (M 8.4) earthquakes. Occurrence of two moderate earthquakes (1991 Uttarkashi and 1999 Chamoli) within a period of nine years naturally raises concern about the seismogenic potential of the region. In this paper we present observations made during the post-earthquake survey around Chamoli, and address some issues regarding the regional seismic hazard.

THE Chamoli earthquake of 29 March 1999 is yet another moderate event of this decade in the Garhwal Himalaya. It occurred at 00:35:13.59 h (local time) near the town of Chamoli in northern India (Figure 1 *a* and *b*). The US Geological Survey (USGS) located the event at 30°49.2′N, 79°28.8′E (m_b 6.3 and M_s 6.6), and the India Meteorological Department (IMD) located it at 30°17.82′N, 79°33.84′E (m_b 6.8 and M_s 6.5; focal depth ~ 15 km). A long aftershock sequence including at least three events of $M > 5$ followed the main event, some of which were located using local and regional stations (Figure 2 *a*). The USGS fault-plane solution indicates a pure thrust mechanism with two nodal planes striking at 282° and 97° (Figure 2 *b*).

The earthquake triggered landslides, blocked several roads, and disturbed electricity and water supply. A maximum intensity of VIII (MSK) has been attributed to this event[1]. Maximum damages occurred in the district of Chamoli where nearly 2600 houses collapsed and over 10,800 were partially damaged, leaving about 100 dead and 400 injured. The quake was also felt at far-off places such as in Kanpur (440 km south-east), Shimla (220 km north-west) and Delhi (280 km south-west). A few buildings in Delhi sustained non-structural damages[1].

The Chamoli event is important from various considerations. One: its location in the 'central seismic gap' (Figure 1 *a*), a segment of the Himalaya that is considered to have the maximum potential for a large earthquake[2,3]. Two: its proximity to the high dam under construction near Tehri, ~ 125 km west of Chamoli. Here, we present some of the observations made in the Chamoli area and discuss the significance of this earthquake in our understanding of the seismic hazard of the region.

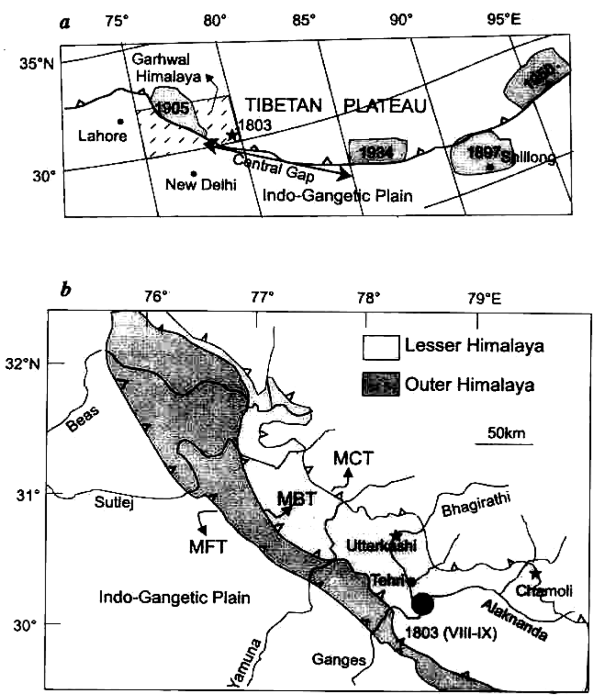

Figure 1. *a*. Sketch map of the Himalaya[11] showing the Himalayan front (solid line). Meizoseismal area of four great earthquakes are shaded in grey. Hatched area is enlarged in Figure 1 *b*; *b*. Simplified geologic map of the north-western India[4]. Locations of the Uttarkashi and Chamoli earthquakes are shown. The region where maximum intensity was observed[18] during the 1803 earthquake is indicated by solid circle. Location of Tehri dam is also shown.

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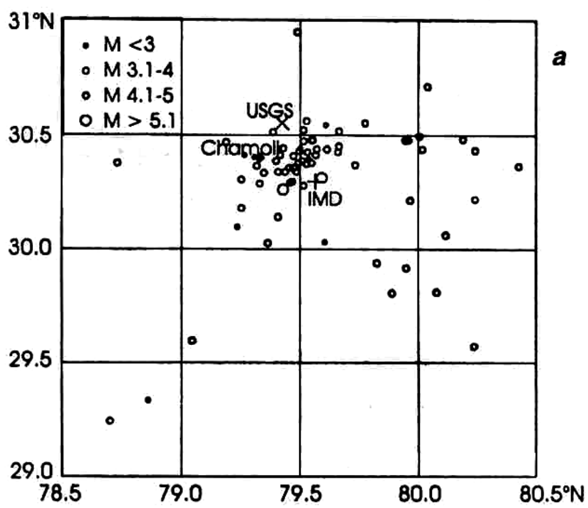
Geologic and tectonic setting

The Himalayan mountain range, an outcome of the compressional processes ensued by the India–Asia collision (70–40 Ma) has been undergoing extensive crustal shortening along the entire 2400-km-long northern edge of the Indian plate. A series of major thrust planes – the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT) – have been formed as a result of these processes[4,5]. In some models, these thrust faults are considered to have evolved progressively, leaving the older ones dormant whereas in others, they are treated as contemporaneous. For example, the evolutionary model[6,7] considers the MCT to be an older thrust plane that was more active in the early phases of the Himalayan orogeny and MBT as a younger one that is more active currently. The steady-state model on the other hand, treats the MCT and the MBT to be contemporaneous and merging at depths with a common detachment surface where the great Himalayan earthquakes are believed to originate[8].

The seismicity of the Himalaya, therefore, needs to be understood in terms of the relative roles of these faults. It has been argued on the basis of focal mechanisms[9] that the MCT is probably aseismic and the current activity is on the MBT. However, Chander[10] noted that the coseismic ground elevation changes observed during the 1905 Kangra earthquake could not be explained by assuming slip on the MBT. The pronounced band of seismicity observed beneath and south of MCT in Kumaun and Nepal[11,12] is another indication of active deformation. The earthquakes recorded during 1984–1986 by a network of stations in the Yamuna and Bhagirathi valleys are also noted to be following a trend of the MCT[13]. The 1991 Uttarkashi earthquake (Figure 1 *b*) is the most recent activity associated with the MCT[14].

Tectonically, the MCT represents a ductile shear zone at depth, comprising a duplex zone with three distinct thrust planes: MCT I, MCT II and MCT III from south to north. Based on the degree of metamorphism, lithostratigraphy and tectonic setting, these thrust planes are also referred to as *Chail* (MCT I, lower thrust), *Jutogh* (MCT II, middle thrust) and *Vaikrita* (MCT III, upper thrust)[15]. Of these, the Chail Thrust (MCT I), the southern-most and the youngest, is believed to have moved during the Uttarkashi earthquake[14]. The Chamoli earthquake appears to be associated with the ongoing deformation along this thrust.



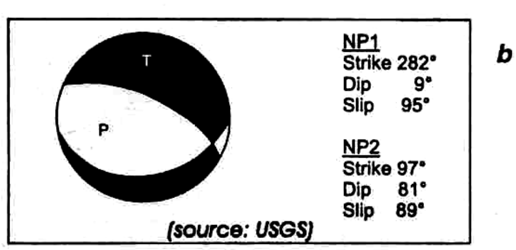


Figure 2. ***a***. Aftershocks until 8 April, as reported by IMD. Main shock locations by IMD and USGS are also indicated; ***b***. Fault plane solution of the main shock (Source: USGS).

An active fold?

The Lesser Himalayan sequence lying between the MCT and the MBT shows stacking of various groups of rocks characterized by south-vergent imbricate thrusts, which were later folded into major scale synforms and antiforms[15]. Geological map of the area indicates presence of an anticlinal structure very close to Chamoli[15]. The whole area, considered as a schuppen zone, is delimited on two sides by almost vertical faults – the E–W trending Alaknanda fault in the south and the NNW–SSE trending Nandaprayag fault in the east[15]. Several parallel faults have been mapped within this schuppen zone and one interpretation is that, these faults demarcate isoclinal anticlines split along the contacts of various litho-units[15].

During the post-earthquake investigations, we observed some signatures of recent deformation, associated with the anticline mapped near Chamoli. A sharp contact of MCT I with recent/sub-recent deposits was located on the southern flanks of this anticline. Thick deposit of colluvium (boulders and pebbles intercalated with coarse sand) occurs at the foot of the steeper limb of the fold (Figure 3). The colluvium may have been remobilized on an incipient slope due to the development of the growing fold. Such surficial features have been associated with fault propagation folds[16]. We interpret the contact near Chamoli to be the surface expression of an active fold. The tight compressional folding in the Berinag quartzite and the stretching lineation in mylonitic quartzite observed at these localities are suggestive of the intense shortening along this contact.

The above observations are significant because the contact of the thrust plane occurs very close to the epicentral zone of the Chamoli earthquake. Although the models for many earthquakes including the Uttarkashi event suggest the rupture along MCT I[14], geological evidences for active faulting in this region are sparse. From this point, the above observations from the epicentral region of the Chamoli earthquake may provide certain clues to identify active faults/folds in the Himalaya. The present data by themselves are insufficient to suggest the nature of the ongoing deformation in this region, but they provide pointers for selecting sites for palaeoseismological and related investigations.

Historic and current seismicity

Although four great earthquakes ($M > 8$) have occurred along the Himalayan front during the last 100 years, the Garhwal region is not known to have experienced a magnitude 8 or larger earthquake in the recorded history[13]. Historic and recent seismicity of the Kumaun–Garhwal region (Figure 4) suggests the occurrence of at least three earthquakes of $M > 7$ in this region. The largest historic earthquake reported from this region occurred on 1 September 1803 (ref. 17). Several villages were reported to have been buried by rockfalls and landslides caused by this earthquake[18]. The Badrinath temple located ~ 40 km north of Chamoli was severely damaged in this earthquake. The epicentre based on the maximum intensities is located ~ 100 km west of Chamoli[18].

We examined two temples (7th–12th century AD) at Gopeshwar and Makkumath, both of which have been reconstructed at least once in the past. Inscriptions on stones, supported by historic data testify that the damages to these temples caused by the 1803 event were substantial and that the smaller structures around the main shrine were totally destroyed. It should be noted that the temples at Gopeshwar and Makkumath suffered only minor vertical cracks during the 1999 earthquake, in spite of their locations in the meizoseismal area, possibly because the 1803 event was much larger. Based on the extent of affected areas, it has been suggested that the 1803 event is a much larger earthquake on the detachment surface[8].

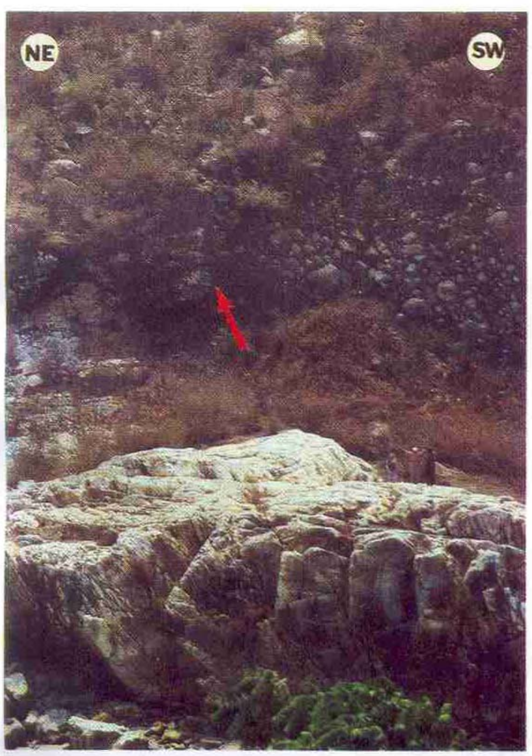


Figure 3. Contact zone of the Berinag quartzite (north-eastern side) and the colluvium of pebbly sediments (south-western side) developed on a growing anticlinal fold. This section is exposed on the banks of the Alaknanda river near the Chamoli town. Whitish rock (Berinag quartzite) in the foreground forms part of the uplifted terrace (~ 1.5 m from the present river bed).

Intensity of shaking, site effects and coseismic processes

The area affected by the Chamoli earthquake lies in seismic zone V (IS:1893–1984), implying a potential for shaking intensity of IX (and above) on the Modified Mercalli scale. Our survey indicates that the maximum intensity of the 1999 event was only VIII (Figure 5). Intensity showed rather abrupt changes from one location to another, probably due to the local site conditions. For instance, the intensity of shaking at Upper Birahi located

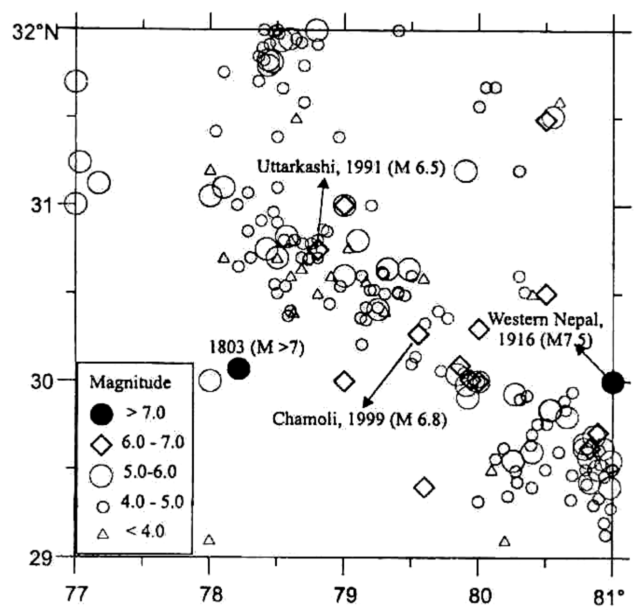


Figure 4. Historic and recent seismicity data (1803–1988) in the Kumaun and Garhwal regions (Source: IMD, 1988).

on the river terrace was VIII, whereas it was only VI at Lower Birahi located on the hard rock (Figure 5). Similarly, Lower and Upper Chamoli showed intensity VIII whereas Gopeshwar, located 2 km away on the hill slope, showed intensity V. Higher intensity observed at Makkumath, located on the river terrace, ~ 15 km north-west of Chamoli, is another example of site amplification.

Ground cracks developed at several places as part of slope failure, causing threat to the settlements. Well-developed ground cracks trending roughly in the east–west direction and showing lateral movement of up to ~ 12 cm were observed at Gopeshwar, Chamoli and Bairagna (Figure 6). Attempts to make trenches across the ground fissures at Telecom Hill in Gopeshwar were unsuccessful since these were bottomed on the rubble and boulders at shallow depths (~ 1 m), which form a part of the debris. In one of these trenches, a poorly defined thrust plane was detected, but its growth and overburden followed a complex pattern. Although the trench sections did not reveal fault planes convincingly, the fissures which had cut through concrete steps and well-consolidated debris could be traced for nearly 1 km. Orientation of these ground fissures, although discontinuous, conforms to the trend of the MCT and also to one of the nodal planes (282°) inferred from the focal mechanism (Figures 2 and 4). The predominance of east–west oriented fissures, particularly those developed in the well-consolidated debris, may be manifestation of a blind thrust.

The earthquake was also associated with marked changes in groundwater discharge. In many groundwater springs, flow increased by as much as ten times, surpassing even the post-monsoon discharge. Flow decreased and the water turned muddy, in one spring near village Bairagna, a possible indication of fluidization and remobilization of fine sediments.

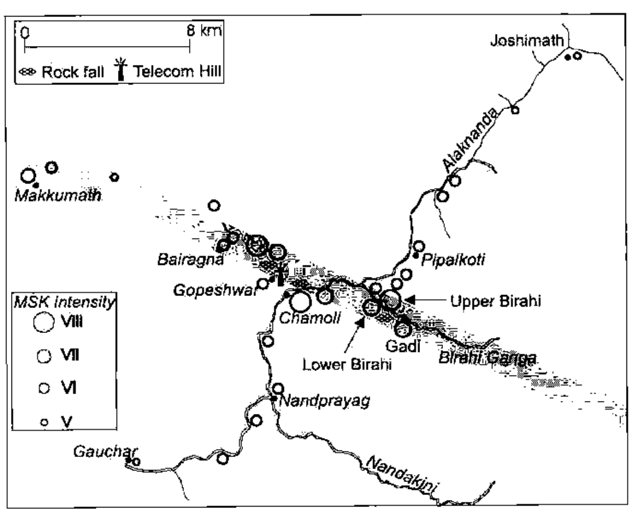


Figure 5. Intensity of shaking observed at various locations around Chamoli. Shaded portion shows the trend of the fault as per the fault plane solution which is consistent with the damage distribution.

Response of structures

The building stock in the affected area consists primarily of rural dwellings, urban houses and a few modern constructions. Load-bearing random rubble stone masonry in mud mortar forms the predominant wall system. Brick or concrete block masonry in cement mortar is used in many newer constructions. The roofing system is usually thatch, tin sheets, slate tiles, or reinforced concrete (RC) slabs. Many recent constructions are in RC frames, with masonry infill walls. In general, most of these are non-engineered with no formal involvement of engineers in design or construction. In this session we briefly discuss the performance of common types of buildings in these areas.

Traditional stone dwellings

The traditional dwellings in the area are usually made up of one or two storeys with a rather low storey height (~ 1.65 m). The walls are about 0.45–0.60 m thick and are made of random rubbles or slate wafers. The former type of walls has two separate layers, the outer and inner wythes, the intervening space being filled with stone

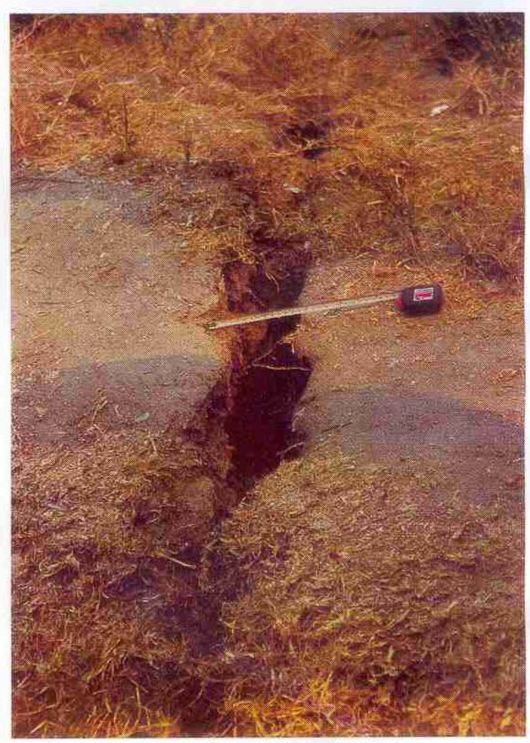


Figure 6. Ground fissure at Telecom Hill near Gopeshwar.

rubble. In the latter type, dressed stones and slate wafers are stacked tightly using very little or no mud mortar. Most dwellings have wood rafter roof supported directly on the walls. Many old constructions and a few new buildings have wood rafter roof supported on vertical wooden posts. Some of the new constructions use RC roof directly resting on the walls.

Houses described above performed poorly, as expected, and most deaths and injuries were caused by the collapse of such constructions. Among these types of constructions, those with masonry walls in slate wafers performed better than those in random rubble masonry, probably due to better interlocking in the latter. The most common damage pattern was the separation of wythes following which the walls tended to buckle (Figure 7).

Brick masonry buildings and buildings with lintel bands

In general, buildings with burnt brick masonry in mud or cement mortar performed much better than the traditional stone masonry buildings. Numerous recent constructions in stone as well as brick/concrete block masonry are provided with a RC lintel band. Often rooms are provided with a RC shelf of about half metre width, projecting from the wall at the lintel level, serving the dual purpose of a storage slab and a lintel band. Most houses with lintel bands performed very well (Figure 8).

Reinforced concrete frame buildings

Many RC frame buildings (up to four storeys) with brick masonry infill walls characterized by simple and regular configuration, performed well even though most of these were not formally designed, and certainly not for seismic loads. The common form of damage included separation cracks at the interface of the RC frame and infill panels, and cracking of infill material.

Implications for the high dam at Tehri

Construction of the 260 m high rockfill dam at Tehri, located between the MCT and the MBT (Figure 1) has remained controversial since its inception. The environmental issues associated with the dam as well as the seismic design parameters have remained active topics of discussion[19–24]. Occurrence of another earthquake in its vicinity is likely to enliven this debate. In this context, it may be useful to review some of these issues.

Although no great earthquakes have been reported from the vicinity of the dam during the historic past, the Uttarkashi and the Chamoli events have occurred during a span of nine years, within a radius of ~ 125 km from Tehri (Figure 1 *b*). As mentioned earlier, the largest historic earthquake in this region is the 1803 event of $M > 7$. Maximum intensity based on historic reports[18] indicates that the source of this earthquake may be within a distance of 50 km from the dam. Aside from current and historical activity, this region is believed to have undergone several movements in the recent geological past, as expressed by the morphological features like deep incision of rivers and development of river terraces[24]. The

Figure 7. Collapse of one of the wythes in a traditional house in slate wafer masonry.

Figure 8. Two-storey house at Pipalkoti showing no damage. The ground storey is in slate wafer masonry, upper storey in concrete block masonry has been added later. Both storeys have RC lintel band.

WNW–ESE trending Srinagar Thrust is a prominent structure reported to be passing through the vicinity of the dam[24]. Data on slip rates or fault offsets in trenches are not available, placing major limitations on the evaluation of recurrence rate of earthquakes in this region. However, probability for an earthquake during the projected life of the dam is considered to be high[21,25].

Effect of impoundment of a large reservoir leading to the possibility of reservoir-induced seismicity (RIS) is another concern. Proximity to an active thrust and geological conditions favourable for infiltration of water into the deep fault zones may favour weakening of faults, leading to failure[20]. Gupta and Rajendran[26] suggested that the water load might tend to stabilize the thrust faults in the immediate vicinity of the Himalayan reservoirs, making them less prone to seismicity, although the delayed effect of pore pressure diffusion may be significant during later periods. Mathematical simulation for the load-induced changes at Tehri has also suggested a postponement of the next earthquake[27], but later studies suggest that the delay may be short-lived[28]. Thus, the studies so far indicate that water-induced weakening of the faults may remain as a point of concern in the long-term life of the dam.

Another important issue is the possibility of landslips, earthquake-induced or otherwise. A large chunk of land falling into the river could generate large waves that could breach the dam or could cause an overflow. Instances of landslips that caused enormous floods in the Indus River in Pakistan are reported[19]. The landslips and rockfalls that followed a moderate earthquake at Chamoli (that too during a dry season) underline the serious threat posed by these processes and an urgent need to identify landslide prone regions, from the point of seismic hazard associated with high dams in the Himalaya.

Need for a database

A major issue of contention regarding the Tehri dam has been the choice of peak ground acceleration (PGA). Preliminary design of the dam was carried out by pseudo-static analysis for a design seismic coefficient of 0.12 g. Subsequently, dynamic analyses were carried out for earthquake motions with effective peak ground acceleration (EPGA) of 0.25 g, which was considered inadequate by many workers[19,21,22]. Specialists from Russia have also been involved in the evaluation of the seismic hazard at the dam site and checking the dam's safety. After considering a number of postulated earthquake scenarios, their evaluation of dam safety was based on two worst ground motions: a M 6.5 earthquake on Srinagar fault with PGA of 0.5 g at Tehri site, and a M 8.0 event on the MBF with PGA of 0.4 g (ref. 29). At the time the dam was designed, strong motion records were not available for this region, and the characteristics of strong motion records obtained elsewhere were used to develop the design spectrum. Data on stress drop, attenuation characteristics and site amplification have also been very limited, for a proper evaluation of the seismic hazard in the Tehri region. In this context, the earthquake at Chamoli is significant as it provides a useful set of data.

Summary

The Chamoli earthquake gives further credence to the view that the frontal parts of the MCT are still active and capable of generating moderate/large earthquakes. From this point, more studies in the epicentral region may be useful in identifying and characterizing the active faults in the region. Our studies indicate that it may be possible to identify sites showing tell-tale signatures of active tectonism in these areas, in order to quantify the slip rate. A moot point is whether the faults in Chamoli and Uttarkashi are multiple segments of a single structure, and if an earlier earthquake occurred in 1803 and had ruptured both these segments, resulting in a larger stress drop. If we assume this as the real scenario, it is likely that the large and moderate earthquakes in the Garhwal–Kumaun region follow a different rate of recurrence.

Our studies suggest that the historic temples in the area, which are among the oldest surviving structures, can be used as archives of preserved evidences of past earthquakes in the region. A systematic study of these temples may be useful to reconstruct part of the earthquake history of these regions. The 1803 earthquake appears to be a larger event ($M > 7$), which seems to have affected a wider area, in comparison to the Uttarkashi and Chamoli earthquakes.

From an engineering point of view, damages due to the Chamoli earthquake clearly demonstrated that codal provisions for masonry houses are quite effective. While the traditional stone houses failed as expected, constructions with lintel bands performed well. Settlements developed on alluvial terraces, although far separated, suffered severe damages, while the intervening regions on relatively harder rocks suffered little or no damage. Site-amplification could be one of the probable reasons for wider damages during the 1991 earthquake at Uttarkashi, which is situated on extensive river terraces. The Chamoli earthquake provides a whole set of new data, including new ground motion data to study the seismic attenuation and site amplification characteristics, for better hazard assessment and mitigation.

1. Jain, S. K., Murty, C. V. R., Arlekar, J., Rajendran, C. P., Rajendran, K. and Sinha, R., Special Report, Earthquake Engineering Research Institute (EERI), California, 1999, vol. 33, pp. 1–8.
2. Khattri, K. N. and Tyagi, A. K, *Tectonophysics*, 1993, **96**, 281–297.
3. Bilham, R., *Curr. Sci.*, 1995, **69**, 101–127.

4. Gansser, A., *Geology of the Himalayas*, Interscience, New York, 1964, p. 289.
5. Molnar, P. and Chen, W. P., in *Mountain Building Processes* (ed. Hsu, K. J.), Academic Press, New York, 1982.
6. Le Fort, P., *Am. J. Sci.*, 1975, **275**, 1–44.
7. Molnar, P., Chen, W. P., Fitch, T. J., Tapponier, P., Warsi, W. E. K. and Wu, F. T., *Editions C.N.R.S.*, 1977, **268**, 269–294.
8. Seeber, L. and Armbrustc., J., in *Earthquake Prediction: An International Review*, Maurice Ewing Series 4, AGU, Washington, DC, 1981, pp. 259–277.
9. Ni, J. and Barazangi, M., *J. Geophys. Res.*, 1984, **89**, 1147–1163.
10. Chander, R., *Tectonophysics*, 1988, **149**, 289–298.
11. Yeats, R. S. and Thakkur, V. C., *Curr. Sci.*, 1998, **74**, 230–233.
12. Pandey, M. R., Tandukar, R. P., Avouac, J. P., Lave, J. and Massot, J. P., *Geophys. Res. Lett.*, 1995, 751–754.
13. Khattri, K. N., Chander, R., Gaur, V. K., Sarkar, I. C. and Kumar, S., *Proc. Indian Acad. Sci.* (*Earth Planet Sci.*), 1989, **98**, 91–109.
14. Cotton, F., Campillo, M., Deschamps, A. and Rastogi, B. K., *Tectonophysics*, 1996, **258**, 35–51.
15. Valdiya, K. S., *Geology of Kumaun Lesser Himalaya*, Wadia Institute of Himalayan Geology, Dehra Dun, 1980, p. 291.
16. Powers, P. M., Lillie, R. J. and Yeats, R. S., *Bull. Geol. Soc. Am.*, 1998, **110**, 1010–1027.
17. Ballore, M., *Mem. Geol. Surv. India, Calcutta*, 1904, **35**, 153–194.
18. Smith, R. B., *J. Asiatic Soc. Bengal*, 1843, **12**, 1029–1056.
19. Pearce, F., *New Sci.*, 1991, **26**, 37–41.
20. Valdiya, K. S., *Curr. Sci.*, 1992, **61**, 801–803.
21. Brune, J. N., *Tectonophysics*, 1993, **218**, 281–286.
22. Iyengar, R. N., *Curr. Sci.*, 1993, **65**, 384–392.
23. Chander, R. and Kalpna, *Curr. Sci.*, 1996, **70**, 291–299.
24. Valdiya, K. S., *High Dams in the Himalaya*, PAHAR, Nanital, 1993, p. 40.
25. Chander, R., *J. Struct. Geol.*, 1992, **14**, 621–623.
26. Gupta, H. K. and Rajendran, K., *Bull. Seismol. Soc. Am.*, 1986, **76**, 205–215.
27. Chander, R. and Kalpna, *Curr. Sci.*, 1996, **70**, 291–299.
28. Chander, R., Kalpna and Gahalaut, V. K., *Curr. Sci.*, 1996, **70**, 873.
29. Thatte, C. D., *Indian Geotech. J.*, 1992, **22**, 1–41.

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