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Earthquake Hazard Assessment for Dehradun, Uttarakhand, India, Including a Characteristic Earthquake Recurrence Model for the Himalaya Frontal Fault (HFF)

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Abstract—The seismic hazard has been computed for the city of Dehradun, Uttarakhand, India. The city lies in the Himalayan foothills between two faults: the Main Boundary Thrust (MBT) and the Himalayan Frontal Fault (HFF). The contributions from these two faults have been modelled differently in a probabilistic model. While the MBT has been modelled with a Poissonian earthquake distribution, the HFF has been modelled both with a characteristic earthquake recurrence model and a Poissonian model. The hazard scenarios reveal different patterns depending on the classical approaches and the characteristic models applied, and the obtained results indicate that Dehradun may experience PGA shaking around 2.2 m/s^2 for 225 years return period and around 4.6 m/s^2 for a 2,500 years return period.

Key words: Himalayas, Himalayan frontal fault, PSHA, Dehradun, seismic hazard.

1. Introduction

The Uttarkashi (1991) and Chamoli (1999) earthquakes, and in particular the October 2005 Muzaffarabad, Pakistan, earthquake, enhanced the consciousness about the increasing vulnerability that the growing population in the Himalayan region is confronted with. This is relevant especially in light of several recent destructive earthquakes that had significant long term social and economic impacts. The observation of strong motion and aftershock sequences as well as the investigation of the destruction from these earthquakes provide the disciplines of seismology and earthquake engineering with informative and valuable data, experiences and lessons, and raise a number of important scientific challenges. One major challenge is that the large earthquakes have long recurrence intervals at any specific place, whereas most of the classical probabilistic seismic hazard analysis (PSHA) approaches make use of short term catalogs as a basis for the prediction models. While we believe that technologies such as GPS will prove even more useful in the future, such data is still too scarce in time and spatial coverage to provide convincing evidence of recurrence periods for the large and rare earthquakes.

Himalaya is among the most seismically active regions in the world, and has experienced several earthquake disasters during historical times (Martin and Szeliga 2010). Nevertheless, the Himalayan front is more than 2,000 km long, and the reliable quantitative earthquake catalogs are very limited in time and magnitude coverage (ISC and PDE catalogs are good examples). From a geological perspective the Himalaya collision zone is rich in active faults, and many have been mapped in detail when traceable on the surface (Valdiya, 1986), and particularly well mapped are the Main Boundary Thrust (MBT), the Main Central Thrust (MCT) as well as the Himalayan Frontal Fault (HFF) that is discussed in more detail below. While these faults are well mapped on certain segments, there are large gaps in our understanding as to details of these structures, and attempts to quantify earthquake potentials and recurrence can only be done in an approximate manner. The same incomplete understanding applies even more to the quantification of the seismic potential of regional faults.

Earthquake hazard was first addressed in India by Tandon (1956) in terms of intensity. Later Khattri et al. (1984) computed probabilistic seismic hazard in terms of PGA for the Himalayan region, and Bhatia et al. (1999) calculated the same under the GSHAP

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(global seismic hazard assessment programme). For the region under focus the latest PSHA estimates were computed by MAHAJAN *et al.* (2010) reaching values of 0.3 g for the Garwhal region at a 475 years recurrence interval. While accepting the limitations in our databases we also accept the need for continuously improved seismic hazard estimates.

In the present study the geological and tectonic setup of the region around Dehradun has been revisited and seismotectonic modelling has been carried out as the basis for a new hazard computation. Additionally, modelling of characteristic earthquakes on the Himalayan frontal fault (HFF) (which has possibly been the site of past very large earthquakes) has been included (KUMAR *et al.,* 2006, 2010). Considering the specification of the magnitude-recurrence relation for a source zone being associated with considerable epistemic uncertainties, HFF has been modelled as exponential occurrence as well as characteristic earthquake model with the help of logic tree along with inclusion of other uncertainties at various branches considered in classical PSHA. Seismic hazard for Dehradun, has been estimated using a hybrid PSHA model for the seismogenic features of MBT, MCT and the HFF.

2. Tectonic Setting

The collision between the Indian subcontinent and the Eurasian plate dates back to the Early Tertiary, or about 60 million years ago. After the initial collision, the convergence rates have slowed down, and are presently driving the Indian subcontinent northward into Eurasia (e.g. PRESS and SEIVER,1986). In the northwestern Himalaya region around Dehradun the convergence rate is estimated to be around 15 mm/ year following BANERJEE and BURGMANN (2002).

The seismicity in the whole Himalaya region is driven by the underthrusting of the Indian subcontinent. NARULA (1991) evaluated the seismotectonics of northwest Himalaya and classified them into five seismotectonic domains of discrete deformation styles and seismic behavior namely: the Main Himalayan Seismic Zone, the High Plateau Seismic Zone, the High Himalayan Seismic Zone, the Kashmir Syntaxial Seismic Zone and the Foot Hill Seismic

Zone (Fig. 1). Furthermore NARULA (1992) divided the longitudinal Himalayan Seismic Zone into discrete segments with defined boundaries marked by suggested fundamental faults. These segments are the Kashmir Block, the Chamba Kishtwar Block, the Kangra Block, the Shimla Block, the Garhwal Block and the Kumaoun Block as shown in Fig. 1. This overall interpretation of NARULA (1991, 1992) has been used as a tectonic framework and basis for the zonations defined below.

The study area around Dehradun with more detailed tectonic features is shown in Fig. 2. The study area encompasses two distinct tectonic domains, the Himalayas and the alluvial foredeep (Fig. 2). Towards the northeast the rock sequence of the Himalayan orogenic belt is exposed, while the Quaternary alluvial deposits of the Indo-Gangetic plains cover the southwest.

South of the Indus suture zone is the Main Central Thrust, MCT, which is considered one of the most important continuous tectonic features throughout Himalaya, traceable from east to west, and considered the geological boundary between Higher and Lesser Himalaya. Lesser Himalaya is separated from the frontal Himalaya by the Main Boundary Thrust (MBT). The Siwalik belt occupies the foothill zone with outcrops of Tertiary rocks in several folded and faulted strips (SRIKANTIA and BHARGAVA, 1998). The Himalayan Frontal Fault (HFF) is believed to be continuous and has surface manifestations that are discontinuous at selected places and delineate the southern limit of the frontal Himalaya (KUMAR *et al.,* 2001).

To explain the earthquake occurrence and seismotectonics of the Himalayan collision zone, various models have been proposed. Of these, two models, namely, the *Steady-State model* and the *evolutionary model* have been recognized and become important. Both models relate the surface faults to the decollement, but in different ways. The *steady state* model (SEEBER and ARMBRUSTER, 1981) postulates that the MBT and the MCT were formed simultaneously, and that they have ever since continued to remain active as the main deformation faults reaching the surface. The *evolutionary* model (NI and BARAZANGI, 1984) postulates that there has been a progressive shift in the evolution of the faults from north to south. In this
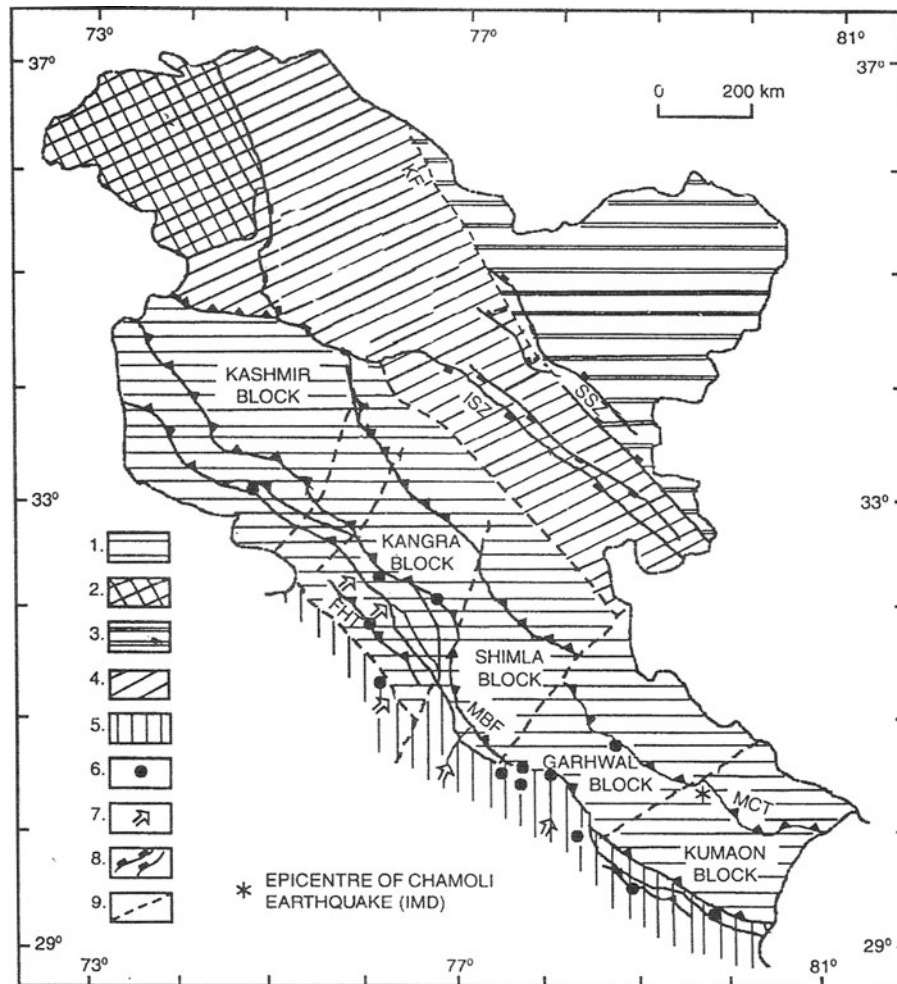
Figure 1
Seismotectonic domains of the NW Himalayan seismic belt. *1* Main Himalayan Seismic Zone (MHSZ); *2* Kashmir Syntaxial Seismic Zone (KSSZ); *3* High Plateau Seismic Zone (HPSZ); *4* High Himalayan Seismic Zone (HHSZ); *5* Foot Hill Seismic zone (FHSZ); *6* Specific location where neotectonic activity has been recorded; *7* Direction of crustal shortening during the Quaternary; *8* Suture Zone; *9* Block boundary based on geological/geophysical/tectonic flux attributes. *SSZ* Shylok Suture Zone; *ISZ* Indus Suture Zone; *KF* Karakoram Fault; *MCT* Main Central Thrust; *MBF* Main Boundary Fault; *FHT* Foot Hill Thrust. (after NARULA *et al*., 2000)

model the main deformation was concentrated on the MCT in the earlier periods and has slowly shifted so that the more recent deformation has been concentrated on the MBT and related faults. In both models it is accepted that the main faults (MBT and MCT) stretch down to the underthrusting decollement and that these faults also give rise to splay faults that are offsprings of the main faults.

The evolutionary model provides for a continuous migration of the activity from north to south, supporting the present day development of a "new" main deformation structure south of the MBT, and this is supported by recent findings (KUMAR *et al.,* 2001; LAVE and AVOUAC, 2000; NARULA, 1991, 1992; NARULA and SHOME, 1992).

3. *The Himalayan Frontal Fault (HFF)*

The Himalayan Frontal Fault (HFF) has been studied by many workers (e.g. THAKUR, 2004; KUMAR *et al.,* 2006, 2010; MUGNIER *et al.,* 2005; MUGNIER *et al.,* 1999). The plate collision has resulted in three major thrust earthquakes along the Himalaya front
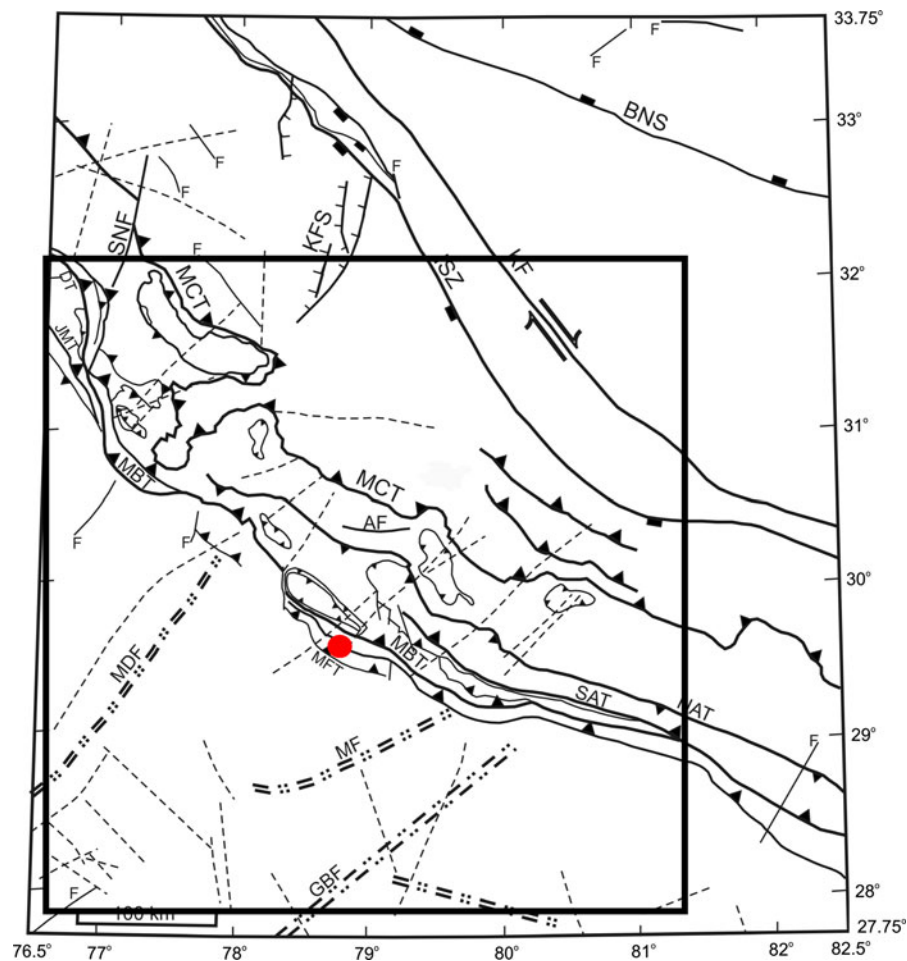
Figure 2

Geological setup around Dehradun (indicated by *dot*). The *inset* shows the area considered for seismotectonic modeling. *BNS* Banggong-Nujiang Suture. *KF* Karakoram Fault, *ISZ* Indus Suture Zone, *KFS* Kaurik Fault Syatem, *MCT* Main Central Thrust, *DT* Drang Thrust, *JMT* Jwala Mukhi Thrust, *AF* Alaknanda Fault, *NAT* North Almora Thrust, *SAT* South Almora Thrust, *RT* Ramgarh Thrust, *MBT* Main Boundary Thrust, *MDF* Mahendragarh Dehradun Fault, *MF* Moradabad Fault, *GBF*-Great Boundary Fault

zone in the previous century: 1905, 1934, and 1950, occurring at different segments of the collision zone. These earthquakes most likely produced surface manifestations; however, surface ruptures that allow a precise definition of the earthquake source fault have not been identified, and the lack of primary surface ruptures has led previous investigators to attribute their occurrence to blind thrusts. The geodetic monitoring shows that interseismic elastic strain is presently accumulating beneath Higher Himalaya (BILHAM *et al.,* 1997; JACKSON and BILHAM, 1994; PANDEY *et al.,* 1995; BANERJEE and BURGMANN, 2002). When combined with the evidence of a developing HFF reported by KUMAR *et al.* (2006), these

observations are consistent with the interpretation that the major historical earthquakes are initiated at a point of localized strain accumulation beneath the Himalayas and propagate southward and upward. This process occurs along a shallow decollement that come to the surface at the southernmost end as the HFF (PANDEY *et al.,* 1995; BRUNE, 1996; BILHAM *et al.,* 1998; LAVE and AVOUAC, 2000; MAHAJAN *et al.,* 2010).

Along the decollement front in northwestern India, terrace deposits exposed 20–30 m above modern river levels are interpreted to have been uplifted by displacements on the underlying Himalayan Frontal Fault (WESNOUSKY *et al.,* 1999). A

radiocarbon dating limits the age of the terraces to $<1{,}665 \pm 215$ years BC ($\leq 3{,}663 \pm 215$ YBP), yielding a vertical uplift rate of $\geq 6.9 \pm 1.8$ mm/year by WESNOUSKY et al. (1999). In combination with published studies constraining the dip of the Himalayan Frontal Fault to about 30°, the observed uplift rate equates to horizontal shortening across the Himalayan Frontal Thrust of $\geq 11.9 \pm 3.1$ mm/year and the slip rate of the Himalayan Frontal Thrust of $\geq 13.8 \pm 3.6$ mm/year. This is very close to previously reported rate estimates (see above). KUMAR et al. (2001) has reported evidence of surface rupturing/deformation earthquakes at six sites covering a distance of ~ 400 km along the strike of the HFF. Trench exposures (KUMAR et al., 2001) across the HFF with radiocarbon dating place limits on the timing of the last surface rupture to be between 1404 to 1422 A.D. The interpretation is consistent with the large co-seismic displacements observable at Rampur Ganda, Lal Dhang, and Ramnagar (see GoogleEarth for locations). At these sites, trench exposures and vertical displacements are interpreted to indicate 18–26 m of coseismic slip during the last earthquake ($\sim 1{,}410$; KUMAR et al., 2001).

In the area around Dehradun, the surface manifestations of the HFF have been identified to the southeast by THAKUR (2004), and the fault has been assumed to be continuous along the foothills where it passes just south of Dehradun. In this scenario Dehradun is located practically just above the fault. Many parts of the HFF have been considered active also by other authors than the previously mentioned: JALOTE and MITHAL (1971); KUMAR and MAHAJAN (2001), KUMAR et al. (2006), KUMAR (2003), Mukhopadhyay and Mishra (2006). On this background it is important to model the HFF activity for the seismic hazard assessment of Dehradun.

4. Seismicity of the Region

The best quality data bases for earthquake information for the study area are from regional catalogs, and in particular the catalogs from ISC and USGS-PDE. The PDE catalog comprises data from 1973 in the spatial window from 20° to 40°N and 58° to 83°E. The portion of this catalog which was studied consisted of earthquake reports having magnitude types of M_b, M_s, M_w and M_w. The ISC database was used in its complete form (i.e. including alternative local solutions for events not reprocessed by ISC). The reason for also using the Harvard catalog as one of our tools is that it frequently contains reports on all three magnitudes (M_b, M_s and M_w) for each of the moment tensor solutions in addition to the location, depth, time, half duration, moment tensor, scalar moment, and double couple solution (strike, dip and slip). From the Harvard database 143 earthquakes were selected from the relevant region, and these were used for deriving inter-magnitude relations, thereby facilitating a catalog with homogeneous magnitudes.

4.1. The Historical Earthquakes

KUMAR et al. (2010) reported that the historical earthquakes attributed to slip on the HFF are the 1505 central Himalayan earthquake ($M_w \sim 8.2$), the 1555 Kashmir earthquake ($M_w \sim 7.6$), the 1803 Kumaon-Garhwal earthquake ($M_w \sim 7.5$), the 1833 Nepal earthquake ($M_w \sim 7.3$), the 1905 Kangra earthquake ($M_w \sim 7.8$), the 1934 Bihar-Nepal earthquake ($M_w \sim 8.1$), and the 1950 Assam earthquake ($M_w \sim 8.4$) (AMBRASEYS and BILHAM, 2000; AMBRASEYS and JACKSON, 2003; AMBRASEYS and DOUGLAS, 2004; BILHAM, 1995; BILHAM, 2004; BILHAM and AMBRASEYS, 2005; MARTIN and SZELIGA, 2010). The largest historical earthquakes are found in the regions where the instrumental catalogs also show high activity; however, additionally, the historical records indicate significant seismic activity also along structures in the lowlands, south of the Himalaya rise. The historically largest was the 4 April 1905, Kangra earthquake, (magnitude estimate is subject to debate; see below) which occurred northwest of Dehradun in the Kangra block (Fig. 1; THAKUR et al., 2000). There are even indicators that this earthquake took place on the Himalaya Frontal Fault (HFF) rather than on the Main Boundary Thrust (KUMAR et al., 2006). The Kangra earthquake with Ms = 7.8, (AMBRASEYS and BILHAM, 2000) took place in the northwest Himalaya, west of Dehradun, and was the first of a few devastating twentieth century earthquakes in northern India. This earthquake is believed to have triggered a magnitude

$M_w = 7.0$ earthquake 40 km below Dehradun that occurred in the coda of the mainshock (HOUGH et al., 2005). The size of the Kangra earthquake has been important for the estimation of the largest credible earthquake (M_{max}) that might occur in the western Himalaya. Regrettably, the largest historical earthquakes do not have a sufficiently precise location to be assigned to any particular fault or structure, and even for the Kangra earthquake it is remains uncertain if it ruptured the Himalayan Frontal Fault (HFF) since no continuous surface rupture has been identified (AMBRASEYS and BILHAM, 2000; KUMAR and MAHAJAN, 2001; KUMAR et al., 2001; Bilham et al., 2001). Since the present work is focussed on Dehradun, we note that the Kangra earthquake caused particularly high damage in the Dehradun region (which was at the time a small city).

No large historical earthquakes seem to have been closer to Dehradun than the Kangra earthquake (MARTIN and SZELIGA, 2010). To the northwest of Dehradun (in the Kashmir region) large earthquakes occurred in 1501, 1555 and 1885 (BILHAM, 2004), and a significant earthquake took place in 1803 east of Dehradun (MARTIN and SZELIGA, 2010). These reports may indicate a longer recurrence period for the largest earthquakes on the Garhwal segment.

4.2. Recent Large Earthquakes

The Uttarkashi earthquake of 19 October 1991 ($M = 6.6$) affected parts of Uttakashi and nearby areas, but was also strongly felt in Dehradun at some 60 km distance. It took a toll of 769 lives, injured several thousand people and caused partial to severe damage to about 100,000 houses. Displaced rocks and failure of terraced slopes were observed within an area of 440 sq. km.

On 29 March 1999 at 00:35 local time, an earthquake of magnitude of 6.8 hit the northwestern part of India (known as the Chamoli earthquake). The maximum impact of this earthquake was felt in the hill districts of Chamoli, Rudraprayag and Tehri in the Garhwal region of Uttarakhan some 90 km from Dehradun. The earthquake claimed more than 100 lives, left several hundred people injured and about 6,000 houses severely damaged. Electricity, water supply and communication facilities suffered extensive damage, especially in the Chamoli town, Gopeshwar. Ground cracks and openings were reported to have developed at several places. Both of the two reverse faulting earthquakes (Uttarkashi and Chamoli) reported surface ruptures; however, not in a continuous sense (SHARMA and DUBEY, 2000).

5. Analysis of Instrumentally Recorded Seismicity

One of the first issues to be solved was to establish an earthquake catalog with a homogeneous magnitude. Magnitude conversion formulas were derived for the region with basis in the Harvard catalog (see above), and Fig. 3 shows the regressions established, which were used for converting all magnitudes in the ISC and PDE catalogs to M_w.
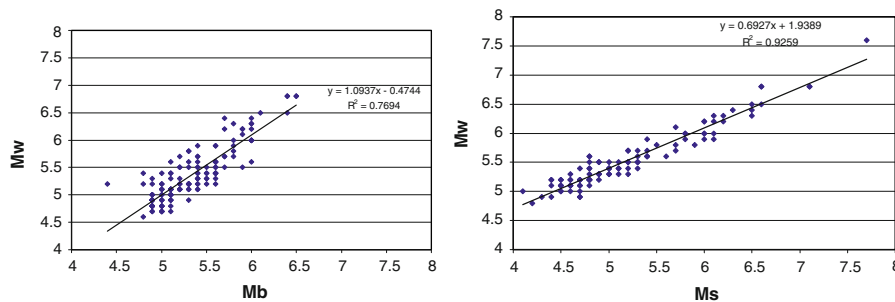

Figure 3
Conversion of (left) body-wave magnitude (mb) into moment magnitude (M_w), and (right) surface-wave magnitude (M_s) into moment magnitude (M_w) based on the Harvard catalog
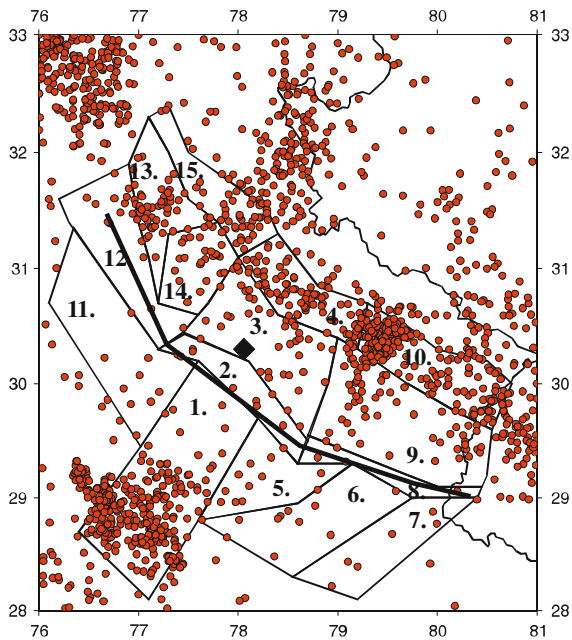
Figure 4
Earthquakes in the NORSAR catalog (largely ISC) and the zones defined for the hazard computation. *Black diamond* indicates the location of Dehradun. The *solid line* shows the HFF considered as characteristic model in the present analysis
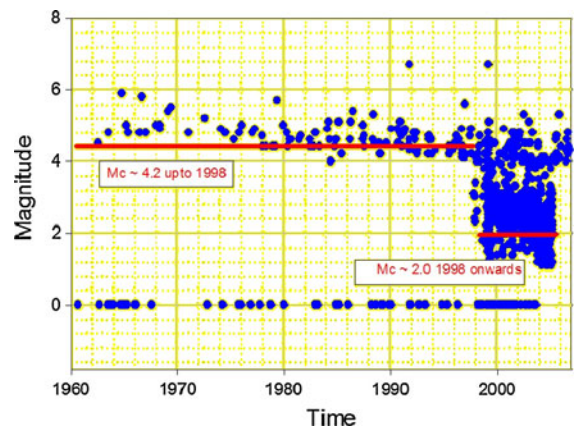

Figure 5
The magnitude versus time plot for the catalog used to estimate the magnitude completeness thresholds. Only data from the region comprising all the zones were included. Magnitudes shown as 0 are those events for which no magnitude could be assigned/reported

5.1. Seismogenic Source Zonation

The spatial earthquake distribution was analyzed in detail and balanced with the geology of the region. As a result of this analysis the region was divided into 15 genuine source zone regions as shown in Fig. 4, and following the PSHA methodology, the activity model parameters were established through data regressions for each region and groups of the defined zones (guided by the regional tectonics).

5.2. De-clustering of the Catalog

The seismicity reported for a region contains the earthquakes (small and large) including possible foreshocks and aftershocks. The PSHA methodology requires that foreshocks and aftershocks, being dependent on the main event, should be removed from the catalog before carrying out any statistical and probabilistic analysis. To separate the dependent from the independent seismicity, the earthquake catalog has been de-clustered. The de-cluster algorithm used is based on HABERMANN (1987), and the "look-ahead time" was assumed to be between 1 and

10 days, and for the distance out to 10 km from the main event. The declustering analysis identified 17 earthquake clusters with a total of 84 events (out of 977), and these were removed prior to the continued analysis.

5.3. Catalog Completeness

The magnitude homogenized catalog was tested for completeness thresholds. The threshold magnitudes were determined for various time periods and only events above the completeness thresholds were included in the Gutenberg-Richter analysis. There are various methods described in the literature for completeness checks (the oldest possibly by STEPP, 1973), and for the present analysis the preferred method of visual inspection of magnitude-time plots was applied as shown in Fig. 5. Although the data after 1998 may be assumed complete up to magnitude 2.0 (see Fig. 5), the cutoff magnitude was estimated as 4.2 for the analysis for the data after 1960. The data before 1960 had so high completeness threshold that it could not be used in any sensible regressions.

5.4. Recurrence Parameters

Following the completeness analysis, we computed the Gutenberg-Richter parameters a and b for data from 1960 and magnitudes larger or equal to 4.2.

The b value was fixed to 0.87 for the whole region (for which it could be determined with confidence), and the corresponding global a value was found as 4.21 normalized to per year, indicating the recurrence period of a magnitude 4.8 earthquake or larger to be around 1 year for the sum of all sub-areas. While there are certainly variations in the b-value from region to region, our data does not permit individual and robust estimations, and the global value was therefore also used on the subzones.

The recurrence parameters were estimated for each of the 15 subzones, and normalized to the global values. The process could partly be conducted through formal regressions on the data; however, in some areas the data was too scarce, and for these zones judgment estimates based on the seismotectonic potentials and geology were used. Furthermore, the 15 subzones were tectonically grouped in order to improve the stability of the recurrence parameters, and the recurrence parameters were estimated for four main groups: (1) the foreland zones, (2) the HFF zones, (3) the MBT zones and (4) the MCT zones. For each group a more stable a-value could be computed, and the area-normalized values were then distributed on each of the sub-zones to obtain a more realistic activity value for the computation model. It should be noted that this has led to a significant activity potential on the MBT zones which are modeled by relatively narrow zones.

Based on the geological findings as detailed above, it was decided to *additionally* model the HFF as a fault source. The data in the instrumental catalog did not allow for proper regressions to this side, and a model using characteristic recurrence was found more appropriate in this situation. The characteristic earthquake hypothesis went through several stages of development. Initially it was proposed by SCHWARTZ and COPPERSMITH (1984). Fitting of a characteristic model to this seismogenic source requires validating the used model based on available earthquake size distribution and the reasonable prediction in future. WESNOUSKY et al. (1999) reported several great (M ∼ 8) historical earthquakes which, due to lack of evident surface ruptures have been attributed to blind thrusts while trench exposures. KUMAR et al. (2001, 2010) investigated trenches across the HFF, and radiocarbon dating placed limits

on the timing of the last surface rupture to be between 1404 to 1422 A.D. Considering the presence of HFF all along the Himalayas and with regular interval of occurrence of earthquakes (MARTIN and SZELIGA, 2010; KUMAR et al., 2010), a characteristic model is possibly appropriate to be used for the seismic hazard assessment. Using the CRISIS software (ORDAZ et al., 2003), the exceedance rate for characteristic recurrence is given by

$$\lambda(m) = \lambda_0 \frac{\phi\left(\frac{M_u - EM}{s}\right) - \phi\left(\frac{M - EM}{s}\right)}{\phi\left(\frac{M_u - EM}{s}\right) - \phi\left(\frac{M_0 - EM}{s}\right)}, M_o \le M \le M_u \tag{1}$$

where $\phi(.)$ is the standard normal cumulative function, M_0 and M_u are the minimum and maximum characteristic magnitudes, respectively, and EM and s are the parameters defining distribution of M. EM can be interpreted as the expected value of the characteristic earthquake and s as its standard deviation. λ_0 is the exceedance rate of magnitude M_0. The probability density of the magnitude is then estimated using truncated Gaussian distribution. In addition, a slip-predictable behavior can be modeled assuming that EM grows with time elapsed since the last characteristic event. The HFF in the present study is modelled as a fault line with characteristic recurrence behaviour. HFF is seen to generate repeatedly the maximum earthquakes in a narrow magnitude range (of course, throughout the Himalayas, NARULA et al., 2000) with a much higher occurrence rate than that predicted by the recurrence relationship for smaller magnitude which has given rise to the concept of characteristic earthquakes (WESNOUSKY et al., 1983; SCHWARTZ and COPPERSMITH, 1984). Based on the past seismicity in the whole Himalayas where the HFF has been sporadically active to generate moderate to great earthquakes, the minimum magnitude and the maximum magnitude limits are assumed to be 7 and 8 respectively albeit much larger magnitudes have been reported but with much larger return periods (KUMAR et al., 2010). These limits have been assumed based on the part of the HFF in this region as described by NARULA (1992), ACHARYA and NARULA (1998), NARULA et al. (2000) and NARULA and SHOME (1992) where the limits of the seismogenic sources are based on both transversal and longitudinal block

segmentation. The activity of the HFF model fault has been added to the area zone contributions, and the authors recognize that this is more of a test of its influence than based on undisputed facts on the activity level of the HFF. The available earthquake catalogs rapidly loose reliability when going back in time, and the recent activity predicts longer recurrence intervals than can be deduced from the historical catalog of the large earthquakes. The median inter-event time has been considered as 200 years. It is noted that this recurrence is in concordance with the geological findings, but as stated above it cannot be substantiated by the seismological catalogs. The HFF is shown as a line source with characteristic model in Fig. 5.

Table 1 summarizes the earthquake activity model used in the present computation. All the contributions from the individual area sources have been scaled such that the accumulated activity match the activity obtained through the overall regression.

6. Ground Motion Models

It is well known from many earlier studies that the uncertainties in wave attenuation models contribute significantly to the absolute hazard level and to the

Table 1

Seismic activity model parameters used in the computation

Zone	λ (activity rate for $M = 5.0$)	β	σ_b	M_{max}	σ_{Mmax}
1	0.102	2	0.2	6.5	0.3
2	0.0222	2	0.2	8	0.3
3	0.0489	2	0.2	8	0.3
4	0.0786	2	0.2	8	0.3
5	0.0259	2	0.2	6	0.3
6	0.0371	2	0.2	7.5	0.3
7	0.0206	2	0.2	7.5	0.3
8	0.0141	2	0.2	8	0.3
9	0.0686	2	0.2	8	0.3
10	0.0973	2	0.2	8	0.3
11	0.0356	2	0.2	6	0.3
12	0.0526	2	0.2	8	0.3
13	0.0256	2	0.2	8	0.3
14	0.0219	2	0.2	8	0.3
15	0.0723	2	0.2	8	0.3

HFF fault source	Median inter-event time (years)	σ_M	M_{min}	M_{max}
16	200	0.3	7	8

total uncertainty in the seismic hazard estimates (e.g. AKKAR and BOMMER 2007a, b). The scatter is nearly as important as the mean with respect to contribution to the total hazard, since in general the PSHA integrate directly over the distribution described by the scatter (sigma value) in the ground motion model. Spectral ground motion prediction models relevant for the tectonics of the Himalaya region were considered, and since well founded prediction relations based on Himalayan data are still missing it was necessary to look to regions with some tectonic *similarity*. Seven prediction relations were considered initially (from DOUGLAS, 2004):

- The AMBRASEYS *et al.* (2005) model is based on 595 horizontal records from shallow earthquakes Europe and the Middle East from $M_w \geq 5.0$ and for a distance range from 0 to 100 km, based on data from compressional tectonics.

- Another model considered was the SADIGH *et al.* (1997) which was developed for California. The relevance in the Himalaya context is that this region also exhibits significant strike-slip deformation even when the main mechanism is thrust. The other reason for evaluating SADIGH *et al.* (1997) is that it has a rather high attenuation that may also be relevant for the Himalaya region.

- Based on 41 hard rock records and 25 soil records with distances greater than 50 km, SHARMA (1998) developed a model for the Himalayas for PGA only. This relation is revised for spectral attenuation in SHARMA and BUNGUM (2006).

- SHARMA *et al.* (2009) used the data from Himalayas and Zagros region to predict the spectral accelerations in the Himalayas.

- JAIN *et al.* (2000) proposed a PGA relation based on the Himalayan data combining SMA and SRR (a simple three frequency maximum acceleration measurement device) data. The lowest period is 0.4 s. Data from magnitude 5.5–7.0 and distance range 0–322 km was considered.

- KHADEMI (2002) proposed an attenuation relationship for PGA only using Iranian data based on 160 horizontal records in the magnitude range 3.4–7.4 in the distance range from 0 to 180 km.

- AKKAR and BOMMER (2007a) provides spectral ground motion prediction based on 532 strong

motion records which largely overlap with the AMBRASEYS et al. (2005) dataset. The regressions were conducted on ground velocity rather than the more commonly used acceleration.

The Khademi relation is based on data from a presumably compressional regime (not specified regions in Iran), but demonstrates unexpected low attenuation. This calls for caution. The SHARMA (1998), Jain et al. (2000) and SHARMA and BUNGUM (2006) relations have the advantage of being developed from Himalayan data, but the SHARMA and BUNGUM (2006) (which replaced SHARMA, 1998) has, in tests, been demonstrated to be inadequate due to very high magnitude scaling, and the JAIN et al. (2000) relation is largely based on data from SRR (Seismic Response Recorder) sensors, which are low cost (low precision) sensors. Furthermore, the sources are not confined to the Himalayan region. This leaves us essentially with the AMBRASEYS et al. (2005) relation. This relation is based on a large and qualitatively secured dataset. Figure 6 shows the PGA ground motion prediction for various magnitudes. AMBRASEYS et al. (2005) analyzed the scatter in the data relative to the predictions, and could state that they along with other authors found an increasing scatter with decreasing magnitude. Spectral acceleration predictions for two magnitudes (6.0 and 7.5) and two distances (4 and 32 km) from AMBRASEYS et al. (2005) are shown in Fig. 7. AHMED (2008) shows the comparison of Chamoli earthquake strong
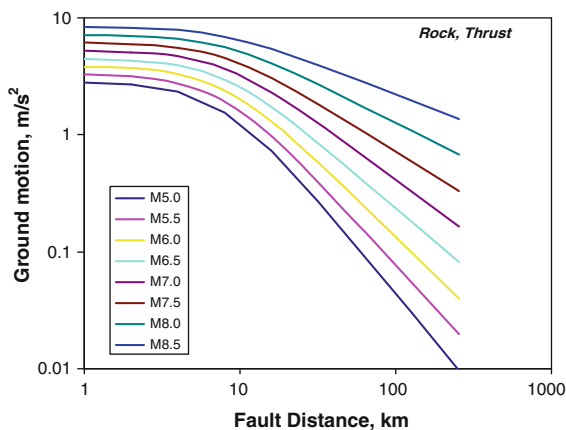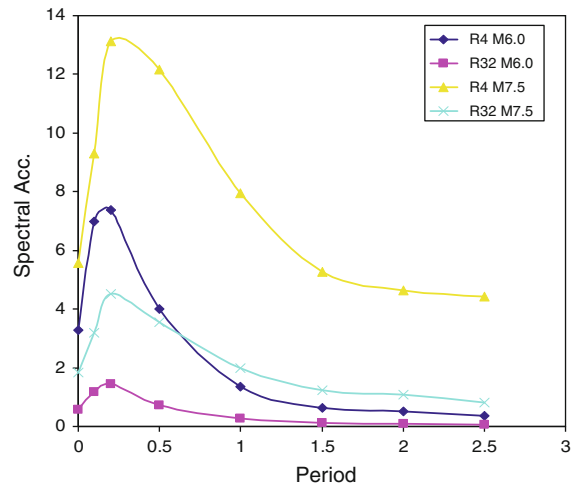

Figure 7

Spectral acceleration predictions for two magnitudes (6.0 and 7.5) and two distances (4 and 32 km) from AMBRASEYS et al. (2005)

motion data with the attenuation relationship given by SADIGH et al. (1997) and observed its closeness for the Himalayan region. Following a review also of the Sadigh relation it was finally decided to use a hybrid attenuation relation in which we combined SADIGH et al. (1997), AMBRASEYS et al. (2005) and SHARMA et al. (2009) with equal weight on each relation.

7. Seismic Hazard Results

The seismic hazard assessment has been carried out in two steps. In the first (and basic) approach the 15 source zones of Table 1 were used exclusively. In the second approach hazard was estimated by adding the HFF modelled as a line source with characteristic earthquake occurrence (ORDAZ et al., 2003 modelling). The characteristic occurrence was set to a $M = 7.5$ with a medium recurrence interval of 200 years. While the uncertainty of this recurrence and magnitude is recognized it was conducted to study the effect on the hazard for Dehradun. A most useful way of presenting the result is in terms of hazard and intensity maps for different return periods, i.e., for 50, 100 and 500 years, relating estimated ground motion to annual exceedance probabilities.

The results are presented in terms of peak ground acceleration (PGA) and equal probability spectra. All results were computed by using a logic tree model

Figure 6

PGA predictions for a suite of magnitudes for AMBRASEYS et al. (2005)

with the combined AMBRASEYS *et al.* (2005), SADIGH *et al.* (1997) and SHARMA *et al.* (2009) ground motion models, and all ground motions are hard rock-free field values. For any given site the local soil condition (type and thickness) will modify the ground motions predicted herein. The hazard was computed for a 5 km grid covering the city of Dehradun, Uttarakhand.

The seismic hazard thus estimated for bedrock outcrop sites in Dehradun is depicted in Fig. 8

comparing the mean values for seismic hazard with and without considering the HFF for two return periods, i.e., 475 and 2,500 years and for two frequencies (PGA and 1 Hz). Figure 8 shows the influence of the HFF fault model through the increased seismic hazard towards the south as one approach closer to the supposed HFF surface expression. To look into more details for the trend changes due to vicinity of the two main features namely MBT and HFF to Dehradun a profile (marked
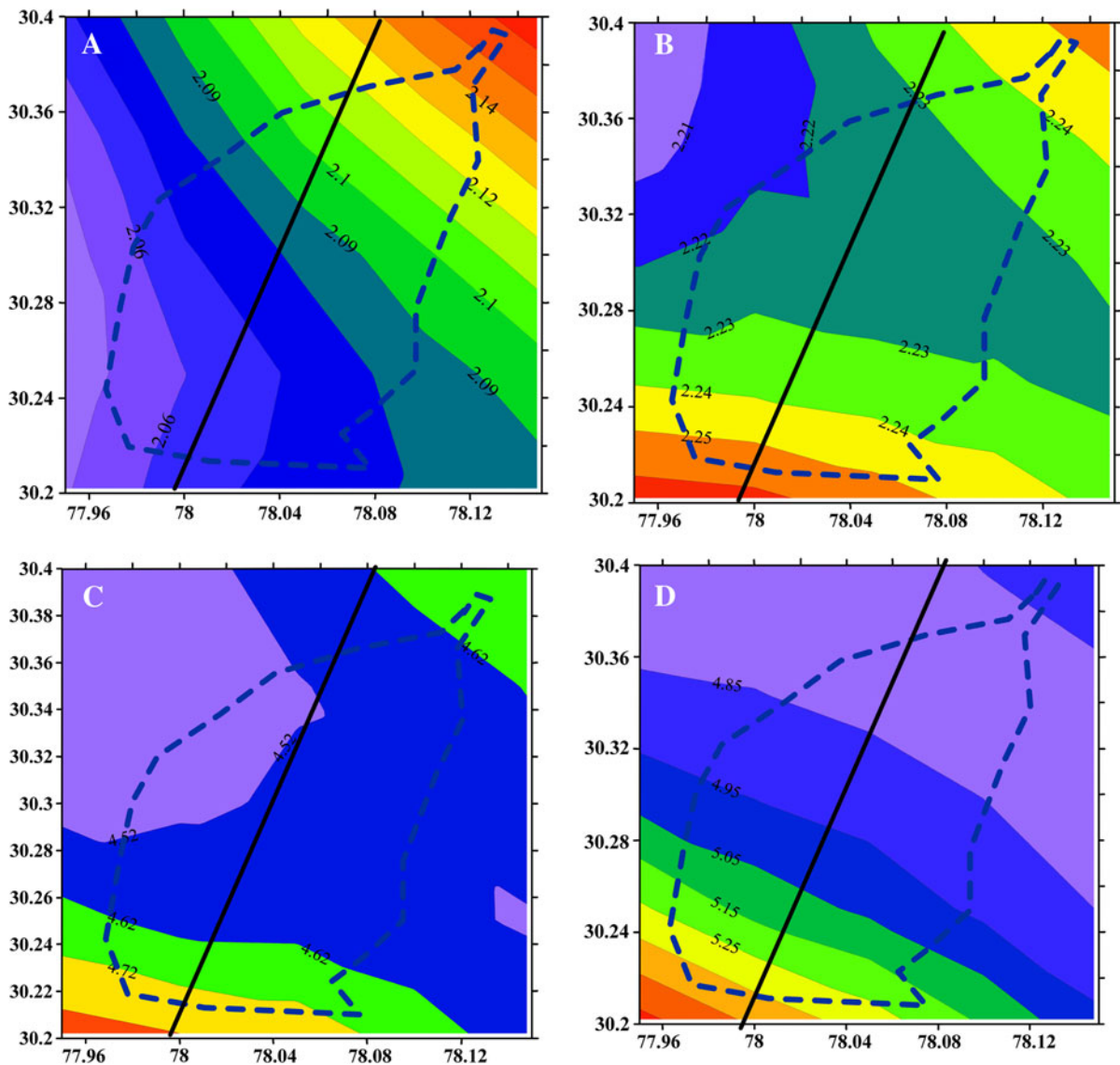

Figure 8
Mean PGA values for Dehradun (boundaries of the city shown as *dashed lines*) for a 225 years return period without HFF **b** 225 years return period with HFF, **c** 2,500 years return period without HFF and **d** 2,500 years return period with HFF
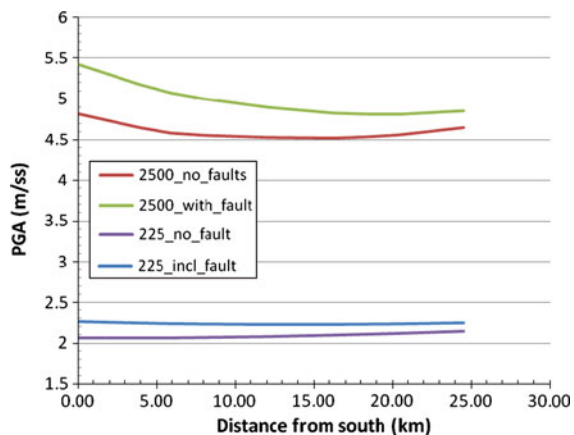
Figure 9

Peak ground acceleration (PGA) profiles across Dehradun city showing the change in the trend for 225 and 2,500 years return periods considering two cases namely with and without the effect of HFF. Profiles are indicated in Fig. 8

in Fig. 8) has been prepared and the PGA values have been plotted in Fig. 9. Figures 8 and 9 (PGA) reveals the influence of HFF. To further analyse the situation mean values of spectra acceleration at 1 s were explored in a similar manner. Figure 10 shows the variation of spectral acceleration at 1 s, and similarly, the trend was plotted on the same profile line as shown in Fig. 11. In this case (1 s) the trend across the profile is low; however, a more 10% static increase of hazard with the HFF line model is found, as also expected. The final result in the form of response spectra for Dehradun has been shown in Fig. 12. All hazard results are provided for bedrock outcrop sites.

Since probabilistic seismic hazard analysis results are based on the summation of contributions from all sources (area sources and fault sources and nearby as well as far away sources) it is often difficult to understand the source of the main contributions. Disaggregation of the results provide a means of understanding the main sources of the computed hazard.

Figure 13 shows the disaggregation for PGA using AMBRASEYS et al. (2005) at two different ground motion levels, depicting how the lower ground motion is mainly a result of nearby intermediate magnitude earthquakes, contrary to the high ground motion which is primarily a result of large magnitude earthquakes occurring at somewhat greater distances.

Figure 14 shows the same disaggregation for 1 s spectral period again using AMBRASEYS et al. (2005). It is there clearly seen how the long spectral periods are directly related to large magnitude earthquakes, and are hardly influenced by earthquakes with magnitudes lower than 7.0. Furthermore, the distant earthquakes become more important at these periods.

8. Comparison with Other Studies

Being a high seismic activity region with a lot of development activities going on, seismic hazard assessment has been carried out by several workers in this area (SHARMA, 2003; MAHAJAN et al., 2002, 2010; SHARMA and DIMRI, 2003; BHATIA et al., 1999). SHARMA (2003) and MAHAJAN et al., (2002, 2010) applied the classical probabilistic seismic hazard approach with Poissonian modelling of the seismogenic sources in the region. BHATIA et al. (1999) reported the seismic hazard assessment for the Indian region under the global seismic hazard assessment program (GSHAP program). The regional hazard around Dehradun in terms of PGA at a 475 year return period (corresponding to 10% exceedance probability in 50 years) as computed through the GSHAP initiative range between 0.1 to 0.3 g for the Garhwal Himalaya region with MBT and MCT governing the pattern of the seismic hazard contours. The resolution do not allow for retrieving the Dehradun hazard results from GSHAP.

Two other regional studies have also been conducted: SHARMA and DIMRI (2003) reported around 0.35 g PGA for 20% exceedance probability in 50 years (225 years return period) for the Dehradun area. MAHAJAN et al. (2010) has estimated the probabilistic seismic hazard for the northern Indian region, and the PGA for the approximate Dehradun location was estimated to be about 0.3 g for 10% exceedance in 50 years. The present results seem clearly lower than the results from SHARMA and DIMRI (2003) and possibly well in line with MAHAJAN et al. (2010).

In all the studies reported above the Poissonian modeling was assumed and applied in a classical PSHA methodology, and it is interesting to observe that even when the present study applies a hybrid
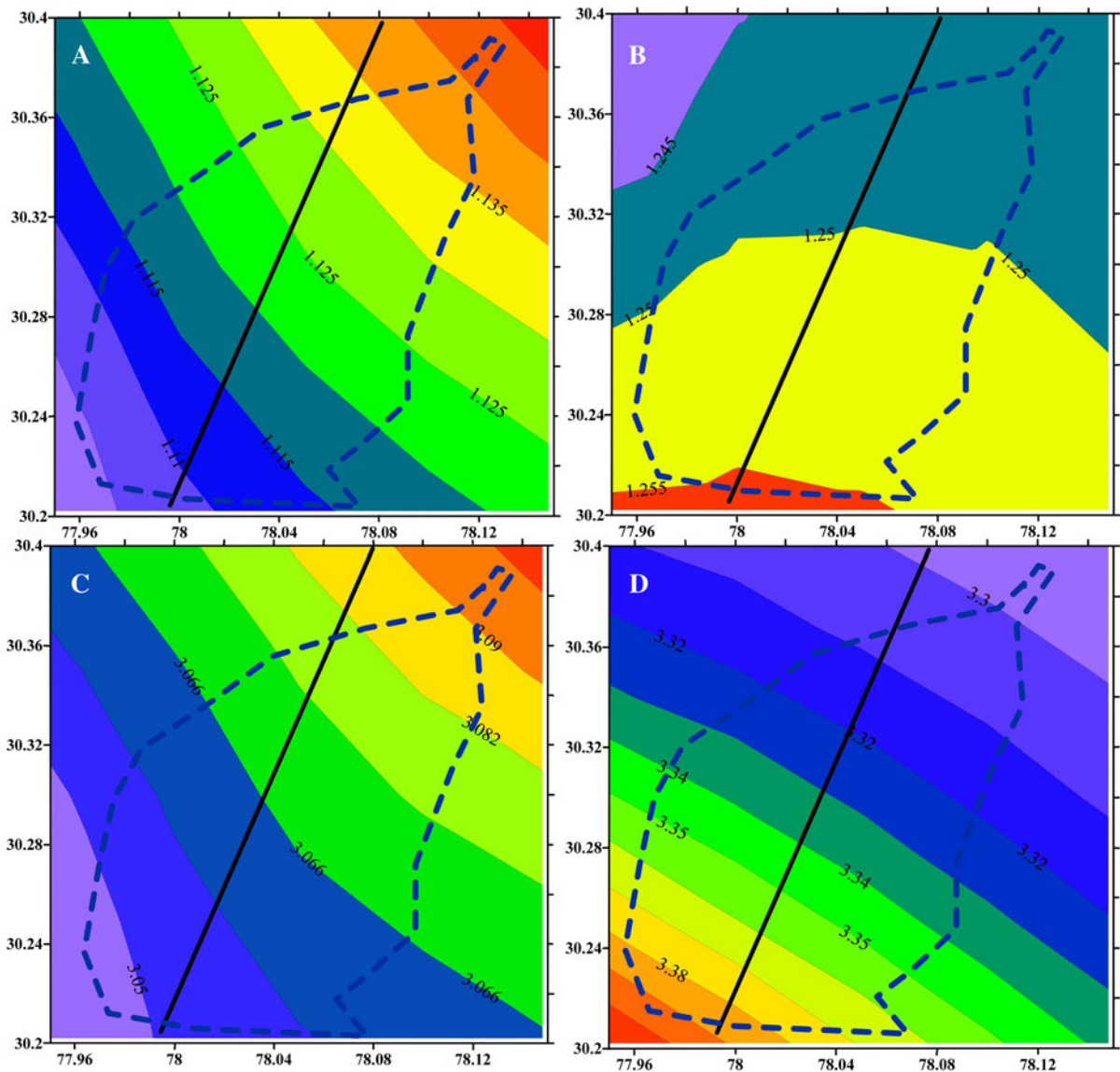
Figure 10
Spectral acceleration at 1 s for Dehradun (boundaries of the city shown as *dashed lines*) for **a** 225 years return period without HFF **b** 225 years return period with HFF, **c** 2,500 years return period without HFF and **d** 2,500 years return period with HFF

deterministic modeling of the HFF fault that super-poses the traditional PSHA the results indicate a lower PGA value than the earlier studies. To accommodate the epistemic uncertainties in using different source types, models for earthquake occurrences and atten-uation models a logic tree approach has been finally used to recommend the strong ground motion in De-hradun for earthquake engineering purpose.

Finally the above results are compared with the values used in the national building code. Dehradun is located in Zone IV in the Indian Standard Code (IS-1893, 2002), which is assigned there with an acceleration of 0.24 g in the case of the maximum considered earthquake (MCE), and the results repor-ted above are on the higher side with the PGA ground motion of the Indian Code.
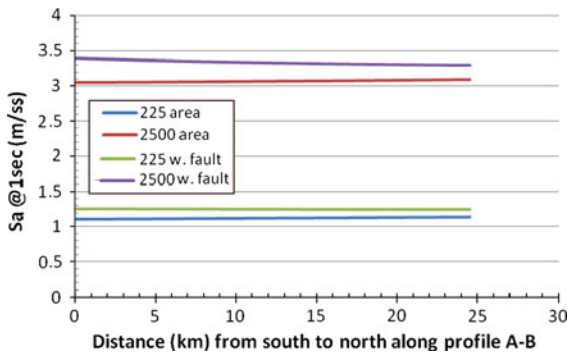
Figure 11
Spectral Accelerations at 1 s period across Dehradun city showing the change in the trend for 225 and 2,500 years return period considering two cases namely with and without the effect of HFF
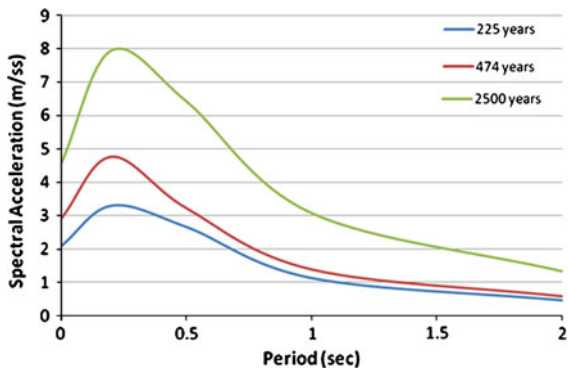

Figure 12
Spectral acceleration for Dehradun city

9. Conclusions

The seismic hazard for the province capital of Uttarakhand, Dehradun, has been modelled using

both a classical PSHA and a hybrid probabilistic approach. The classical area source model was used in conjunction with a line fault model where the activity rate of the area source model was quantified with Poissonian recurrence models whereas the fault line activity was modelled by using characteristic recurrence relationships. The basis for this model was the substantiated findings of an active but partly blind HFF that is traced southeast of Dehradun, and that may be a source for future strong earthquakes. The modelling approach has been that of a characteristic earthquake with a 200 year recurrence.

The results indicate that Dehradun, on a 0.0044 annual probability, is exposed to PGA shaking around 2.2 m/s^2 (with slightly increasing hazard to the north). The spatial pattern within the city is reversed when the HFF model is included, but at reasonable values. The disaggregation results demonstrate that in terms of PGA (high frequency shaking) the main influence is within distances of 40 km from the city. For lower frequencies (around 1 Hz) Dehradun will be affected by the earthquakes occurring at distances even exceeding 100 km.

In terms of PGA the results seem to be lower than other recent regional studies. We attribute the difference with the more recent studies to the attenuation relations used, and justified, in this study.

There are many uncertainties related to the quantification of the seismic activity in this part of the Himalayas. One main deficiency for a more precise quantification of the seismic potentials is the short earthquake catalog: even with the high seismicity and long cultural population catalogs reliable for
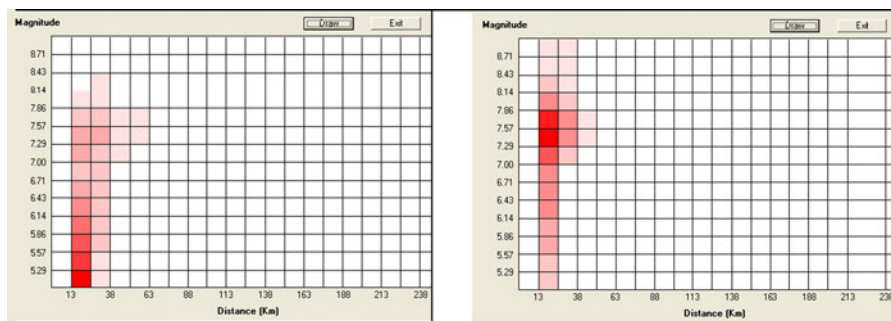

Figure 13
Deaggregation for the site 77.95 and 30.2 for PGA at 1.46 m/ss (left) and at 3.5 m/ss (right) using AMBRASEYS et al. (2005). Software: ORDAZ et al., (2003)
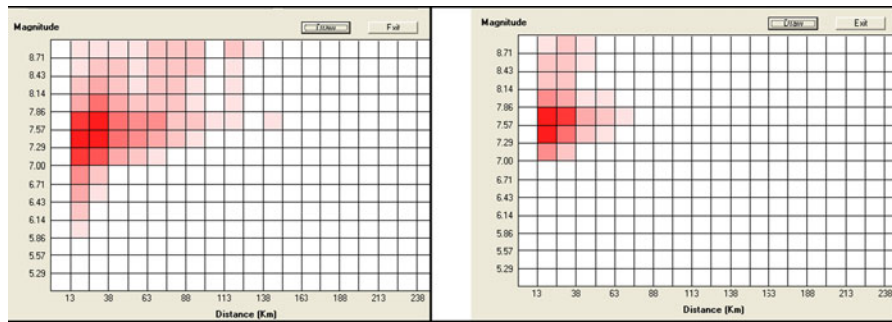
Figure 14

Deaggregation for the site 77.95 and 30.2 for spectral acceleration of 1 s at 0.612 m/ss (*left*) and at 1.46 m/ss (*right*) using Ambraseys *et al.* (2005). Software: Ordaz *et al.,* (2003)

quantification are very short. Only three reasonably quantitatively consistent catalogs exist, the USGS PDE catalog which is only since 1973, the ISC catalog which is consistent over some 100 years and the Harvard CMT catalog. While this hazard study may not be the final word on seismic hazard in Dehradun it has demonstrated the importance of hazard contribution form a hidden fault, of which there are many in Himalaya.

For the further improvement of seismic hazard evaluations in the Himalaya two factors are of importance:

- The development of an attenuation relation specifically derived from sufficient local strong motion data. The attenuation relation and its scatter is decisive for any hazard results, and in the present study we were using the combination of Ambraseys *et al.* (2005), Sharma *et al.* (2009) and Sadigh *et al.* (1997). With the new strong motion network that is now running in the Himalaya region (PESMOS; http://pesmos.in/2011/index.php) it is realistic to hope for significantly improved attenuation relations in the future, however, data from strong earthquakes are needed for proper calibrations and regressions.
- The catalog of historical earthquakes cannot compensate for the presently uncertain evaluation of recurrence times and recurrence places for the larger (6.5+) earthquakes in the Himalayas. An alternative to waiting for the large earthquakes to occur is an improved geodetic monitoring of the main mapped faults around the foothills and the main population centres. When the strain rates on

main faults near the urban centres are mapped it will bring significant value to the future seismic hazard evaluations.

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