A seismogenic active fault in the western Himalaya

On 24 March 1995, an earthquake of $M = 4.9$ and epicentral intensity of VII (on MSK-64 scale) had rocked Chamba area, Himachal Pradesh causing damage to a large number of buildings in the Chamba township. A detailed study indicates that earthquake activity was related to a neotectonic fault along the Ravi river. The active fault, initially recognized on morphotectonic criteria, attains significance as a seismogenic structure following the 1995 earthquake. The present study attempts to unravel the seismogenic nature of this active fault.

The area lies in the western Himalaya on the dorsal side of the Lesser Himalayan thrust sheets. The major regional tectonic elements are shown in Figure 1 *a*. One of the important tectonic features of the Himalaya is the Main Boundary Thrust (MBT). It is a set of north-dipping faults that separate foredeep from older rocks of the Lesser Himalayan Province and is active even today[1,2]. The southernmost fault, which delimits the sub-Himalayan zone, is termed as Himalayan Frontal Fault[3], which displaces the Siwalik strata at some of the locations, but for most of its length, is a blind thrust. The geological set up of the area based on the published maps of the Geological Survey of India (GSI) is shown in Figure 1 *b*. The rock formations range in age from Lower Proterozoic to Triassic. The sedimentary sequence of the Chamba basin is intruded by the Dhauladhar granite of Palaeozoic age, which occupies the southwestern part of the area. The Chamba Formation is the oldest (Lower Proterozoic) and Kalhel Formation is the youngest (Triassic) lithounit present in the area (Figure1 *b*).

The area is seismically active and lies in Zone IV of the Seismic Zoning Map of India (IS 1893 : 2002). Among the major seismic events of the region are the Kangra earthquake of 1905 ($M = 8$), Chamba earthquake of 1945 ($M = 6.5$), Dharamshala earthquake of 1986 ($M = 5.5$) and Himachal earthquake of 1968 ($M = 4.9$; Figure 1 *a*). From the seismotectonic point of view, the area falls in the western extremity of the Kangra reentrant, which is a major structural feature in the western Himalaya. In the Kangra reentrant a minimum of 23 km of shortening has occurred since 1.9–1.5 Ma, giving a shortening rate of 14 ± 2 mm/yr and due to continued convergence the region is likely to experience moderate to great earthquakes in future[4].

The focus of the present study is on a 20 km long N35°W–S35°E trending segment of a neotectonically active fault stretching along the course of Ravi river around Chamba town. In this reach the river occupies an anomalously wide valley, which has acted as a depocentre where about 250 m thick, predominantly coarse clastic Quaternary sediments have accumulated[5] (Figure 1 *b*). This valley is flanked by two regional mountain ranges, viz. Pir Panjal Range in the northeast and Dhauladhar Range in the southwest (Figure 1 *b*). It appears from the higher ele-

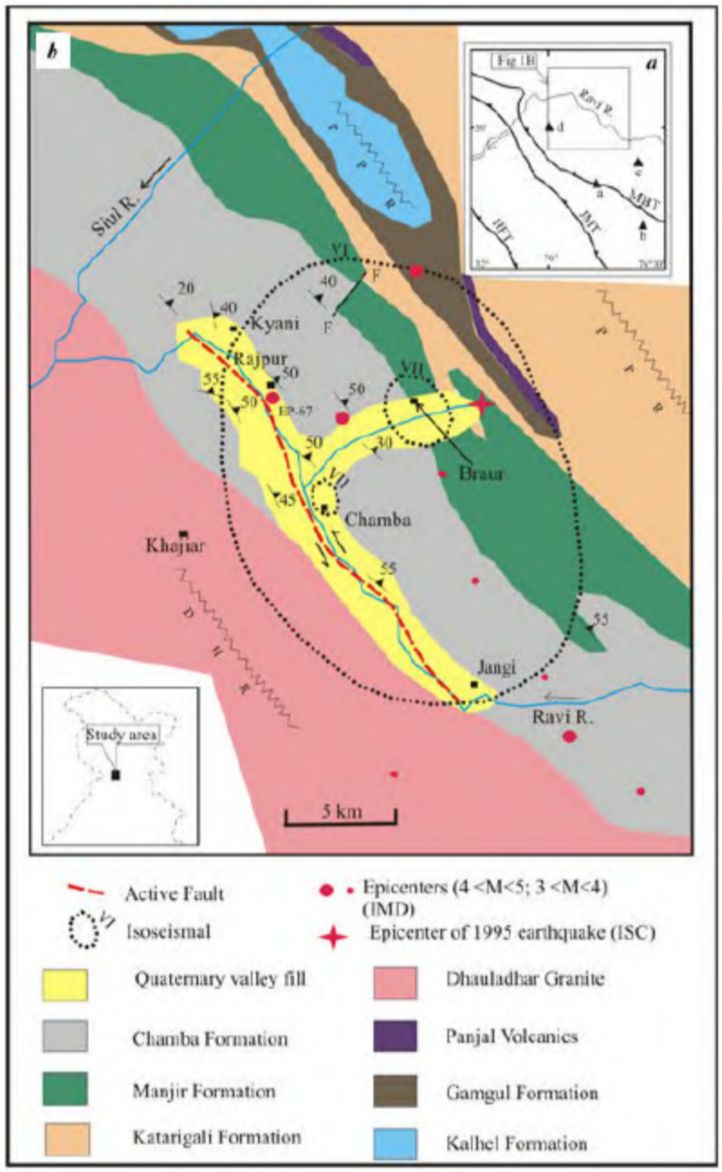

Figure 1. ***a***, Map showing regional tectonic features around the area of study. MBT, Main Boundary Thrust; JMT, Jwalamukhi Thrust; HFT, Himalayan Frontal Thrust. Triangles a, b, c and d represent epicentral locations of the earthquakes Kangra 1905; Dharamshala 1986; Himachal 1968 and Chamba 1945 respectively. ***b***, Map showing lithological units (modified from published maps of GSI). EP-67, Epicentre of 1967 Rajpur earthquake; DDR, Dhauladhar Range; PPR, Pir Panjal Range. Isoseismals of the 1995 earthquake are after Pande and Sharda[10]. The active fault is after Tandon and Joshi[6].

vation of older terraces on the Dhauladhar slopes that there has been renewed differential uplift of the Dhauladhar Range with respect to the Pir Panjal Range[6]. The tributary streams joining Ravi river from the Dhauladhar side have higher gradients compared to those from the Pir Panjal range[7]. This further substantiates the differential uplift of the Dhauladhar range.

The open and wide stretch of the valley around Chamba is described as a releasing bend formed due to sinistral strike slip movement along a strike fault, associated with neotectonic stress field[6]. The conventional mapping could not pick up this fault, as it is a strike fault without any offset in lithocontacts. However, a lineament has been identified along this stretch of the river[8]. It is only after the detailed study of landform evolution, alluviation history of the valley and Quaternary stress field that this active fault paralleling the Himalayan grain was established[6]. Previously, the fault was not considered important with a seismotectonic point of view. However, the detailed analysis of the effects of the 1995 earthquake is suggestive of its being the causative fault. This seismogenic nature is also corroborated by many of the earthquake events, recorded along this fault (Figure 1 *b*). The 1967 earthquake near Rajpur had occurred just on the surface trace of this fault (EP-67, Figure 1 *b*). Although there are no sufficient data to constrain the subsurface geometry of this fault, the distribution of epicentres adjacent to this fault is indicative of its having a dip towards northeast, i.e. along the dip direction of the rock formations. Interestingly, the recorded earthquake events, includeing micro-earthquakes (IMD data) have their epicentres on the northeastern side and there is hardly any epicentre lying on the southwestern side of the fault (Figure 1 *b*). This indicates that the ruptures have taken place on the northeastern part of the surface trace of this fault, endorsing the northeasterly dip of the fault plane. The relative vertical displacement of terrace surface near Chamba suggests that the southwestern side of this fault is upthrown in the Quaternary period compared to the northeastern side[9]. The Quaternary landform evolution and alluviation history of this intermontane valley has indicated both strike slip as well as dip slip components along this fault.

It is interesting to note that the epicentral location of the 1995 earthquake, as indicated by macroseismic investigations[10] (Pande and Sharda, GSI unpublished report, 1995), lies about 6 km northeast of the surface trace of the active fault with a hypocentral depth of about 10 km. The longer axis of the isoseismals trends in N25°W–S25°E direction, which closely matches with the trend of the active fault (N35°W–S35°E; Figure 1 *b*). Chamba town and all the villages located along this stretch of the Ravi river between Jangi and Kyani (Figure 1 *b*) show a consistently higher intensity compared to those located away from this stretch of the valley. The extent of isoseismal VI exactly encloses this part of the river. This is for the obvious reasons that vigorous shaking has occurred along the causative fault plane, which coincides with this segment of the valley. In most of these localities people heard a loud sound preceding the tremor, which is a common phenomenon in the epicentral tract. An isolated intensity high (VII on MSK-64 scale) was observed at Chamba (Figure 1 *b*), where more than 70% buildings developed cracks. A N35°W–S35°E trending (parallel to the fault) ground fissure showing maximum opening of 5 cm and extending for about 30 m length developed on the terrace surface in Chamba town (Pande and Sharda, GSI, unpublished report, 1995). This fissure pierced through the masonry walls of a house, producing gaping cracks. All the observations pertaining to the effect of this earthquake at Chamba town indicate that a secondary rupture took place at this segment of the active fault at a shallow depth, which was responsible for local accentuation of ground motions.

The above discussion and the evaluation of source mechanism[10] on the basis of isoseist characteristics indicate that the 1995 earthquake was associated with the active fault identified near Chamba and the main rupture had taken place at a depth of about 10 km where the fault may possibly be joining the Himalayan detachment surface. Thus the fault is seismogenic in nature, having been a source for a number of small earthquakes in the past. Such active faults need to be taken care of, before they give rise to large devastating earthquakes in future. The Chelungpu fault in the western flank of Taiwan fold belt, which gave rise to the devastating Chichi earthquake of 1999 ($Mw = 7.6$), has earlier been categorized as a less important active fault due to the lack of geochronological evidence and failure to recognize fault-related geomorphic features[11]. The identification of such active faults with the help of morphotectonic analysis and their further detailed study by way of palaeoseismic investigations, microseismic monitoring and geodetic surveys may become significant in hazard assessment. Besides, the location of the surface trace of the fault is also important due to its high vulnerability during an earthquake.

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