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Active faults and related Late Quaternary deformation along the Northwestern Himalayan Frontal Zone, India

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Abstract
Numerous newly-identified traces of active faults in the Himalayan foothill zone along the HFF around Chandigarh, in Pinjore Dun, along the piedmont zone of the Lower Siwalik hill front and within the Lower Tertiary hill range reveal the pattern of thrust and strike-slip faulting, striking parallel to the principal structural trend (NNW-SSE) of the orogenic belt. The active Chandigarh Fault, Pinjore Garden Fault and Barsar thrust have vertically dislocated, warped and back-tilted fluvial and alluvial-fan surfaces made up of Late Pleistocene-Holocene sediments. West- and southwest-facing fault scarplets with heights ranging from 12 to 50 m along these faults suggest continued tectonic movement through Late Pleistocene to recent times. Gentle warping and backtilting of the terraces on the hanging wall sides of the faults indicate fault-bend folding. These active faults are the manifestation of north-dipping imbricated thrust faults branching out from the major fault systems like the Main Boundary Fault (MBF) and Himalayan Frontal Fault (HFF), probably merging down northward into a décollement. The Taksal Fault, striking NNW-SSE, shows prominent right-lateral movement marked by lateral offset of streams and younger Quaternary terraces and occupies a narrow deep linear valley along the fault trace. Right stepping along this fault has resulted in formation of a small pull-apart basin. Fault scarplets facing ENE and WSW are the manifestation of dip-slip movement. This fault is an example of slip-partitioning between the strike-slip and thrust faults, suggesting ongoing oblique convergence of the Indian plate and northward migration of a tectonic sliver. Slip rate along the Taksal Fault has been calculated as 2.8 mm/yr. Preliminary trench investigation at the base of the Chandigarh Fault Scarp has revealed total displacement of 3.5 m along a low angle thrust fault with variable dip of 20° to 46° due northeast, possibly the result of one large magnitude (M_w 7) prehistoric earthquake. Taking into consideration the height of the Pinjore surface (20 to 25 m), tentative age (8.9 ± 1.9 ka), displacement during one event and average angle of fault dip (25°) gives slip rate of about 6.3 ± 2 mm/yr, a rate of horizontal shortening of 5.8 ± 1.8 mm/yr and recurrence of faulting of 555 ± 118 years along the Himalayan Frontal Fault.

Key words *active faults – Northwestern Himalayan Front – paleoearthquake – thrust and right lateral strike-slip faults – slip-partitioning*

1. Introduction

Active faults are considered to be the source for earthquakes in the seismically-active zones of the world. Their identification bears significant importance towards recognizing the seismic hazard of these zones. Identification of active faults is of prime importance in the Himalayan region, one of the most seismically active intercontinental regions of the world. Ongoing crustal deformation is well reflected by the occurrence of small-, medium- and large-magnitude earthquakes along the Himalayan arc. The most prominent large-magnitude events that struck the foothill zone of Himalaya in the span of the last 100-120 years are the 1897 Shillong (*M* 8.7), 1905 Kangra (*M* 8.6), 1934 Bihar (*M* 8.4) and 1950 Upper Assam (*M* 8.5) earthquakes (Seeber and Armbruster, 1981; Yeats *et al.,* 1997) (fig. 1a). Along with these

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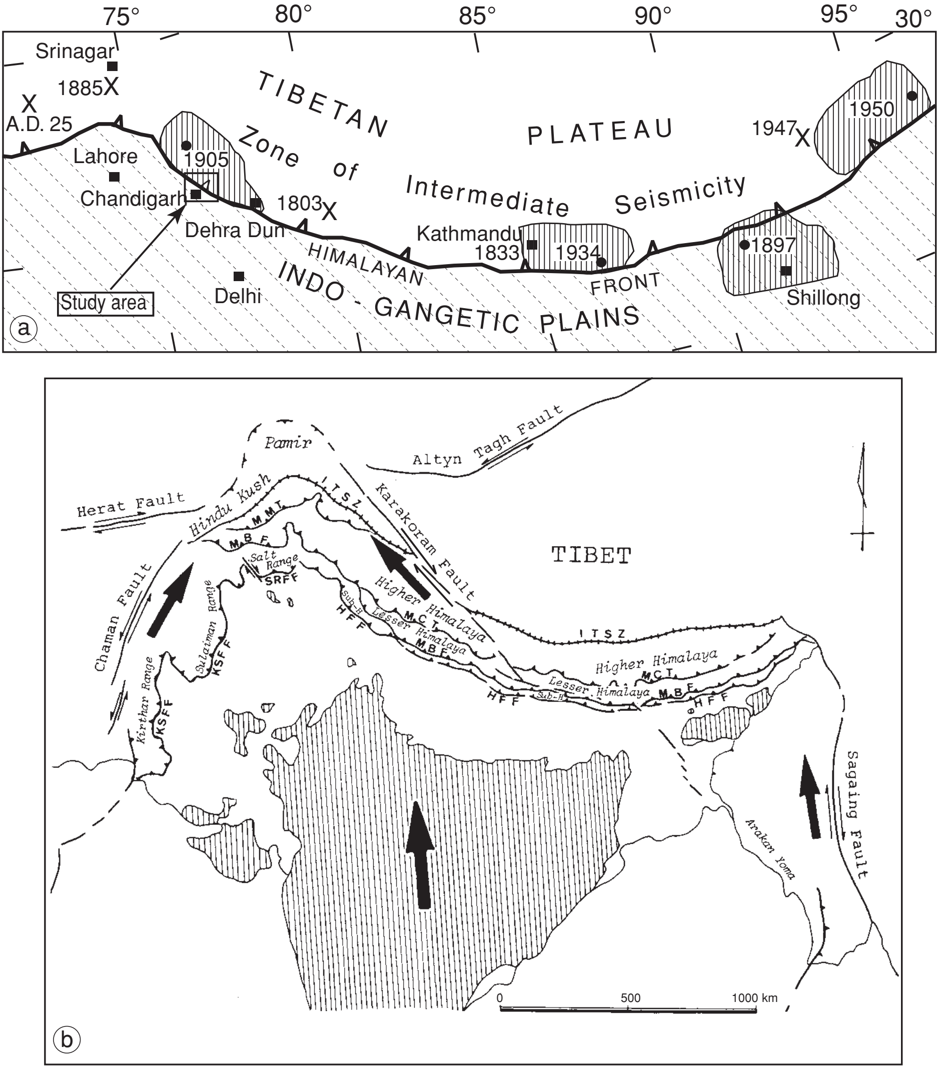

Fig. 1a,b. a) Map showing meizoseismal zones of four great earthquakes along Himalayan Front and other large magnitude events (after Yeats and Thakur, 1998). Box marks the study area around Chandigarh. b) Generalized tectonic framework of Himalaya and its surrounding area. ITSZ - Indus Tsangpo Suture Zone; MCT - Main Central Thrust; MBF - Main Boundary Fault; HFF - Himalayan Frontal Fault; SRFF - Salt Range Front Fault; KSFF - Kirthar Sulaiman Front Fault; Sub-H - Sub Himalaya.

events, few moderate earthquakes with $M > 6 < 7$ have also been recorded in recent years, *viz*., 1988 Bihar-Nepal (*M* 6.6); 1991 Uttarkashi (*M* 6.6) and 1999 Chamoli (*M* 6.5) events. It is believed that although there are few large and moderate quakes along the arc, energy is accumulating in the areas confined between large magnitude events, designated as seismic gaps. The area between the 1905

Kangra and 1934 Bihar-Nepal earthquakes (fig. 1a) has been categorized as the *Central Seismic Gap* by Khattri and Tayagi (1983) and has a high probability for one or more $M > 8$ Himalayan earthquakes in this century (Bilham *et al.,* 1998).

Investigations carried out on active tectonism for the past several decades have provided vital information on the ongoing crustal deformation and on recurrence of earthquakes in the Himalayas (Gansser, 1964; Nakata, 1972, 1975, 1989; Valdiya, 1984, 1989, 1992; Valdiya *et al.,* 1984, 1992; Nakata *et al.,* 1990; Yeats and Lillie, 1991; Yeats *et al.,* 1992; Powers *et al.,* 1998; Yeats and Thakur, 1998; Sukhija *et al.,* 1999a,b; Wesnousky *et al.,* 1999; Lave and Avouac, 2000; Kumar *et al.,* 2001; Oatney *et al.,* 2001). The ideal place to investigate active tectonics is along the front of the Himalaya, demarcating the present active tectonic boundary between the Indian and Eurasian plates (Nakata, 1972).

Bearing this in mind, emphasis was given toward identification of active faults in the area around Chandigarh and Pinjore Dun (*Dun = valley*) located southeast of Kangra, which falls within the meisoseismal area of the 1905 earthquake (fig. 1a). Numerous new traces of active faults were identified for the first time using CORONA declassified satellite photos in the Himalayan foothill zone along the HFF around Chandigarh, in Pinjore Dun, along the piedmont zone of the Lower Siwalik hill front and within the Lower Tertiary hill range. The geometric pattern and distribution of the faults in this area reveal the pattern of thrust and strike-slip faulting, striking parallel to the principal structural orientation (NNW-SSE) of the orogenic belt.

For detailed paleoseismic studies, a preliminary trench investigation was carried out near Chandigarh along a branching fault of the HFF system. Here we summarize our preliminary findings from the trench study.

2. General tectonic outline

The mighty Himalaya stretching east to west over a length of 2500 km is a result of continental convergence and collision between India and Eurasia. Ongoing convergence is estimated as about 2000-3000 km since Late Cretaceous-Early Tertiary (Molnar and Tapponnier, 1977), at rates ranging between 44 mm and 60 mm/year (Minster and Jordan, 1978; Armijo *et al.,* 1989). Recent studies based on GPS measurements show that India and Southern Tibet converge at 20 ± 3 mm/year (Bilham *et al.,* 2001). This can be compared with the rates of 21 ± 3 mm/yr based on geological findings of deformed terraces in Southern Nepal (Lave and Avouac, 2000), 14 ± 4 mm/yr in Western Himalaya near Dehra Dun (Wesnousky *et al.,* 1999); 11 ± 5 mm/yr and 14 ± 2 mm/yr across the Himalayan Front in Dehra Dun and northwest of Dehra Dun (Powers *et al.,* 1998), and 15 mm/yr in Central Himalaya (Yeats and Thakur, 1998). It is believed that a convergence of about 300-400 km has been accounted for along the Himalayan mountain belt (Gansser, 1977), which involves the imbricate stacking of the frontal portion of the underthrusting Indian plate (LeFort, 1975). This is one fourth of the total (*i.e.* 44 to 60 mm/yr) convergence between the Indian and Eurasian plates (Minster and Jordan, 1978), with the rest of the convergence accommodated along the major strike-slip faults of Central Asia in Tibet and Nepal (Molnar, 1990; Avouac and Tapponnier, 1993).

Geological investigations suggest that the Himalaya was built-up by the sliver of the Indian continent that was overthrust to the south (Gansser, 1964; LeFort, 1975). From the beginning of convergence in Late Cretaceous time, followed by the collision in the Middle Eocene (50 Ma) along the Indus-Tsangpo suture zone, the successive zones of deformation have progressively advanced or jumped southward, resulting in faulting and folding along the prominent structural features of the Himalayan orogenic belt (Gansser, 1964; Seeber and Armbruster, 1981; Lyon-Caen and Molnar, 1983). These major tectonic features (Indus-Tsangpo Suture Zone - ITSZ; Main Central Thrust - MCT; Main Boundary Fault - MBF; and Himalayan Frontal Fault - HFF) have played a pivotal role in the structural and topographic architecture of the Himalaya (fig. 1b). The MCT and MBT are considered to be the sites of Cenozoic shortening along the entire length of the Himalaya (Gansser, 1964;

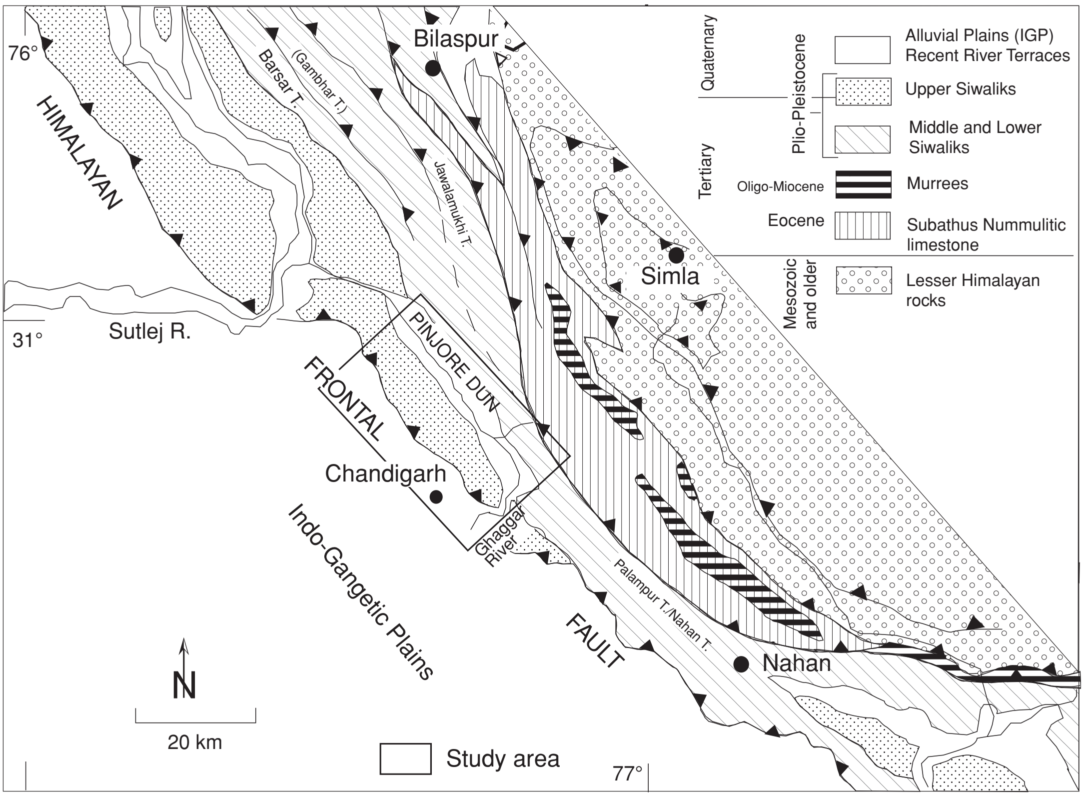

Fig. 2. Generalized geological map of Northwestern Himalayan Front around Chandigarh and Pinjore (after Gansser, 1964 and Valdiya, 1984).

Valdiya, 1984), however, the present tectonically active boundary between the Indian and Eurasian plates is marked by the HFF (Nakata, 1972, 1975, 1989), where active anticlines and synclines are the surface manifestations of displacement on a buried décollement fault (Yeats *et al.,* 1992, 1997)

The present study area is characterized by numerous NNW-SSE trending faults, part of the MBF and HFF systems (fig. 2). In the northeastern part, subsidiary thrusts of the MBF system, namely the Palampur/Nahan thrust, Barsar/Gambhar thrust and Jawalamukhi thrust, cut through the Tertiary succession (Valdiya, 1980). The Barsar thrust marks the boundary between the Lower Siwalik hill range and the Pinjore Dun, whereas the Jawalamukhi thrust cuts the Middle and Lower Siwalik succession. The southernmost edge of the study area is marked by the HFF that delineates the boundary between the detached complex folded-faulted Upper Siwalik hills comprising molassic sediments of Early Pliocene-Early Pleistocene age and the undeformed succession of the Indo-Gangetic plains.

3. Geomorphology

The terrain around the study area can be divided into four major geomorphic zones, from north to south: 1) the uplands comprising

Lower Siwalik/Lower Tertiary rocks of the Dagshai, Kasauli and Subathu Formations; 2) a longitudinal alluvial fill-depression, Pinjore Dun; 3) the isolated Upper Siwalik frontal range, and 4) Indo-Gangetic plains (figs. 3 and 4).

Pinjore Dun is a typical «piggyback» basin. It has been postulated that such basins or depressions were formed as thrust fronts propagated southward into the foreland, causing numerous structural and depositional changes and leading to subsequent development of new «piggyback» basins behind the thrusts (Ori and Friend, 1984; Burbank and Raynolds, 1988). The Duns are the most common and conspicuous feature of the foothill zone and are well documented from the Kumaun, Panjab and Nepal Himalaya. The sinuous nature of the MBF has controlled the development and distribution of these intermontane-basins (Powers *et al.*, 1998).

The Pinjore Dun is 8 to 10 km wide extending parallel to Lower Siwalik/Lower Tertiary hills with altitude ranging from 600 to 1600 m in the northeast and hogback ridges of Upper Siwalik hills with altitude of 400 to 600 m in the southwest (figs. 3 and 4). The Dun is about 45 km in length, merging farther north with the Soan Dun. It is made up of thick alluvial fill of Late Pleistocene to Holocene age overlying the Middle and Lower Siwalik succession. These sediments represent debris deposits of coalesced alluvial-fans that were brought down by the Himalayan rivers, along with finer-grained fluvial and lacustrine deposits. Due to recent crustal movements, these sediments have been dislocated along several tectonic lines parallel to the Nahan thrust resulting in development of different levels of surfaces (Nakata, 1972).

Major antecedent streams emerging from the Lower Siwalik/Lower Tertiary hills in the east flow perpendicular to the Pinjore Dun and join the longitudinally-flowing major tributaries of the Sutlej and the Ghaggar Rivers. Sirsa River, a major tributary of the Sutlej River, flowing northwest parallel to the Dun, is characterized by a larger area of drainage as compared to the southeast-flowing Jhajra River, a tributary of the Ghaggar River. The divide of the Sirsa and Ghaggar drainage systems is located near Basdevpura at the southeastern end of the Dun, an unusual geomorphic feature (figs. 3 and 4). It is difficult to understand the cause for the drainage diversion near village Basdevpura. However, we assume that differential crustal uplift, along with the minor climatic fluctuations in Pinjore Dun during the Late Quaternary, was one of the causes for the diversion.

The morphology of the various surfaces and the sediment succession comprising mainly alluvial-fan debris made of cobble-boulder size sandstone clasts ranging in size from 25 to 100 cm, along with fine-grained fluvial and lacustrine sediments, suggests that initially the Pinjore valley was aggraded under an alluvialfan environment, and continued until the stream flows were unconfined. Later, the channelized flows might have caused incision of the alluvial-fan surfaces and contemporaneous aggradation within the confined riverbanks, resulting in formation of different terrace levels all along their course. Distribution of terraces varies along the different river valleys. The terraces in the southeastern part of Pinjore Dun and along the Ghaggar gorge, where the Ghaggar River crosses the Upper Siwalik hills, have been classified and described in detail by Nakata (1972, 1989). Five terrace levels were observed in the Pinjore Dun and along the Ghaggar River. These are named the Ghaggar surface, Kalak surface, Pinjore surface, Koshallia surface and younger alluvial surface (Nakata, 1972, 1989) (fig. 3).

The degree of dissection and the distribution of these surfaces suggest that the Ghaggar surface is the oldest, followed by the Kalak, Pinjore and Koshallia surfaces. Along the Ghaggar gorge, on the right bank of the Ghaggar River, five terraces were recognized. Scattered occurrences of terraces were also observed along these streams in the upper reaches within the Lower Siwalik/Lower Tertiary hills, and are classified as lower and higher upland terraces. They are tentatively correlated with the Pinjore and Koshallia surfaces of the Dun. The Pinjore surface is one of the most widespread surfaces. According to Nakata (1989), this surface must have developed during the Last Glacial. However, a radiocarbon date of the oldest paleosol from the Middle Gangetic Plain along the

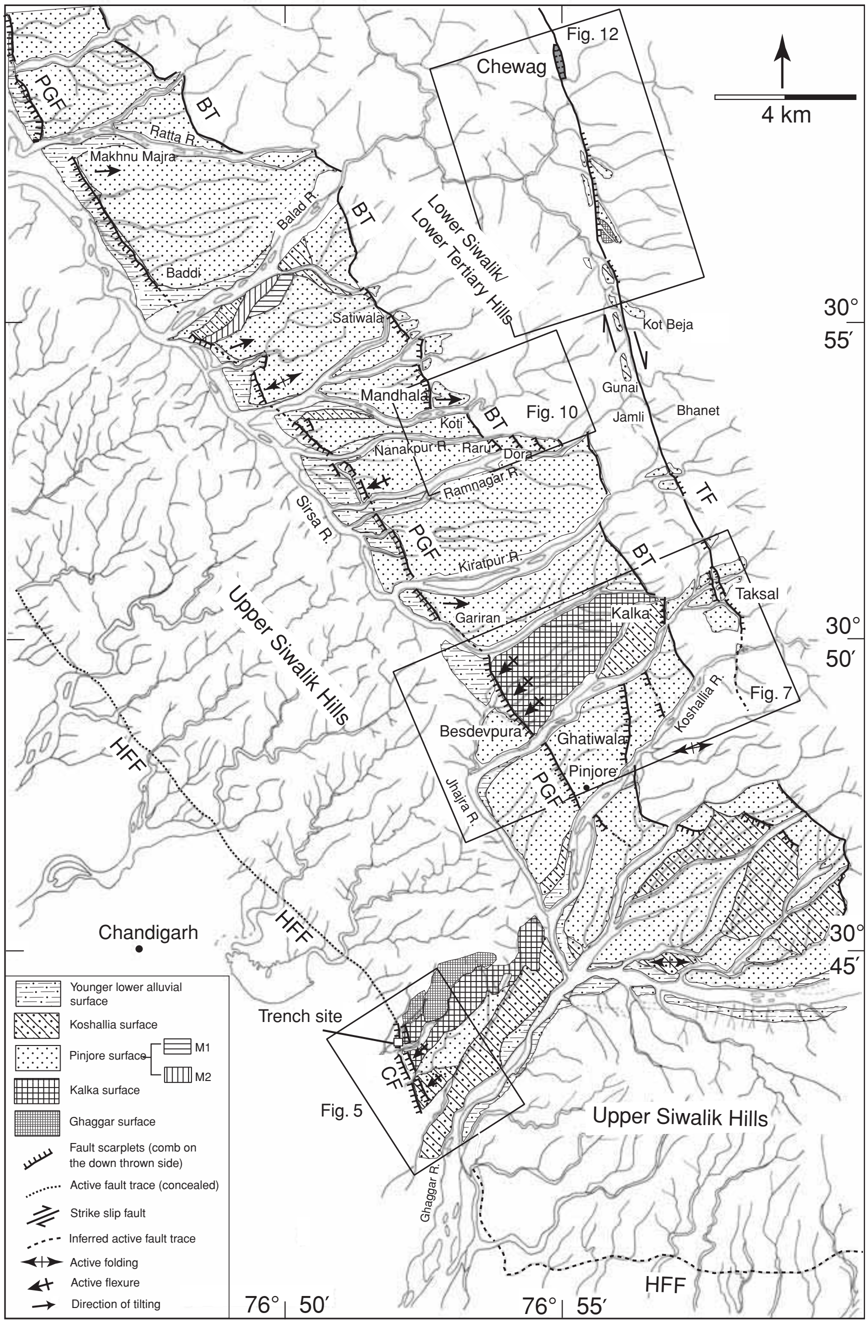

Fig. 3. Map showing distribution of terraces and active fault traces along Northwestern Himalayan Foot Hill Zone around Chandigarh and Pinjore Dun. CF - Chandigarh Fault; HFF - Himalayan Frontal Fault; PGF - Pinjore Garden Fault; BT - Barsar Thrust and TF - Taksal Fault. Combs on the active faults indicate down thrown side.

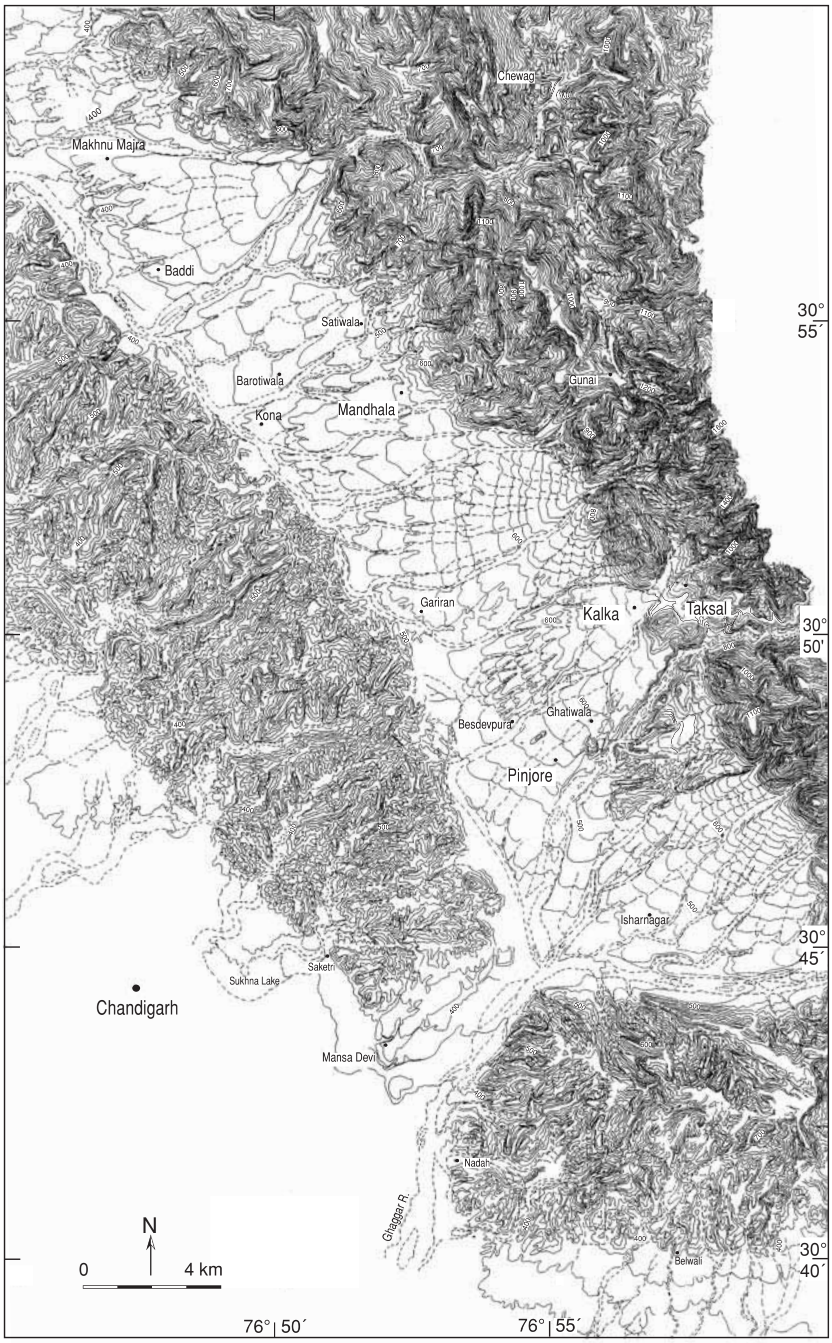

Fig. 4. Detailed contour map of the area of fig. 3. Contour interval is 20 m, dashed lines show outline of major as well as minor streams.

Ghaghra and the Gandak rivers (tributaries of the Ganga River) gives an age of 10 ka, which developed during a dry period (Mohindra, 1995), and a terrace near Mohand town along the NW Himalayan Front gives an age of ≤ 3663 ± 215 BP (Wesnousky *et al.,* 1998). Also the OSL dates of the alluvial-fan sediments from Dehra Dun valley located ~ 150 km southeast of the study area suggests that the fan sedimentation in Dehra Dun valley started at around 50 ka and lasted up to 10 ka. After 10 ka, a thin prograding sequence was deposited due to uplift of the fans (Singh *et al.,* 2001). It is also suggested that a major change in climate from a cold, dry climate with strong seasonal variations prevailing since 50 ka to warm and humid climate at about 10 ka resulted in a change in depositional processes from sediment gravity-flows to braided streams (Singh *et al.,* 2001). Singh *et al.* (2001) have dated 4 levels of terraces exposed along the left bank of the Yamuna River: terraces YT4, 10.7 ± 2.2; YT3, 9.5 ± 2.3; YT2, 8.9 ± 1.9 and YT1, 6.1 ± 1.2 ka. The geology, geomorphology and tectonic setting of Dehra Dun and Pinjore Dun are fairly similar. Hence with the presumptions: 1) that the climatic conditions might have remained the same during Upper Pleistocene and Holocene in both the areas; 2) alluvial fan sedimentation took place in similar fashion in both the Duns by the rivers flowing down the thrust front with a similar provenance of Lower Siwalik hills, and 3) also the tectonic scenario along the Himalayan Front was similar, it can be envisaged that the fan aggradation in the Pinjore Dun might have initiated at around 50 ka and lasted up to 10 ka. We have correlated the 4 levels of the Yamuna River terraces with the 4-level of terraces exposed along the Ghaggar River-Ghaggar, Kalka, Pinjore and Koshallia terraces. This gives a tentative age of 8.9 ± 1.9 ka for the Pinjore surface. However, dating of the individual surface material will help to confirm this chronology.

4. Geometry and pattern of active faulting

Many prominent geomorphic features such as warping and backtilting of fluvial and alluvialfan surfaces and southwest-facing fault scarplets in the Quaternary succession were observed along the active fault traces showing thrust movement. Along the faults showing strike-slip movement, lateral offsets of streams, offset of Quaternary terraces, linear valleys running along the fault and narrow deep gorges were the common features observed (figs. 3 and 4).

4.1. *Active faulting along the Himalayan Frontal Zone*

The surface expression of the active fault traces along the HFF is discontinuous (fig. 3). However, it is presumed that the fault connects in the subsurface but has not ruptured up to the surface at all places along its length. The length of individual active faults ranges between 2 and 10 km, with fault strikes between N25°W and N-S.

Active faulting at places has vertically displaced and warped the Late Pleistocene to Holocene alluvial-fan succession, developing sharp vertical scarplets facing southwest towards the Gangetic plains (figs. 3 and 5). The most prominent deformation along the HFF was observed on the right bank of the Ghaggar River, about 5 km southeast of Chandigarh (Nakata, 1989), named the *Chandigarh Fault*. Two parallel fault traces were identified between Panchkula and Mansadevi by satellite photo interpretation as well as in the field (figs. 5 and 6). These faults striking N25°W to N-S have uplifted the Ghaggar, Kalka, Pinjore and Koshallia terraces, resulting in fault scarps 15 to 38 m high transverse to the Ghaggar River channel. The distance between the faults varies from 0.25 to 0.3 km. The faults are downthrown to the southwest, superficially resembling a pattern of normal faulting. However, the topographic expression observed in the field and on satellite photos shows gentle warping of the surfaces near the fault traces (fig. 6). To the north, these faults follow the range front around Saketri village. Here the Upper Siwalik hill range is marked by a straight dissected front with well-developed triangular facets.

These active fault traces represent the younger branching faults of the HFF system. These probably merge downward and northward into the

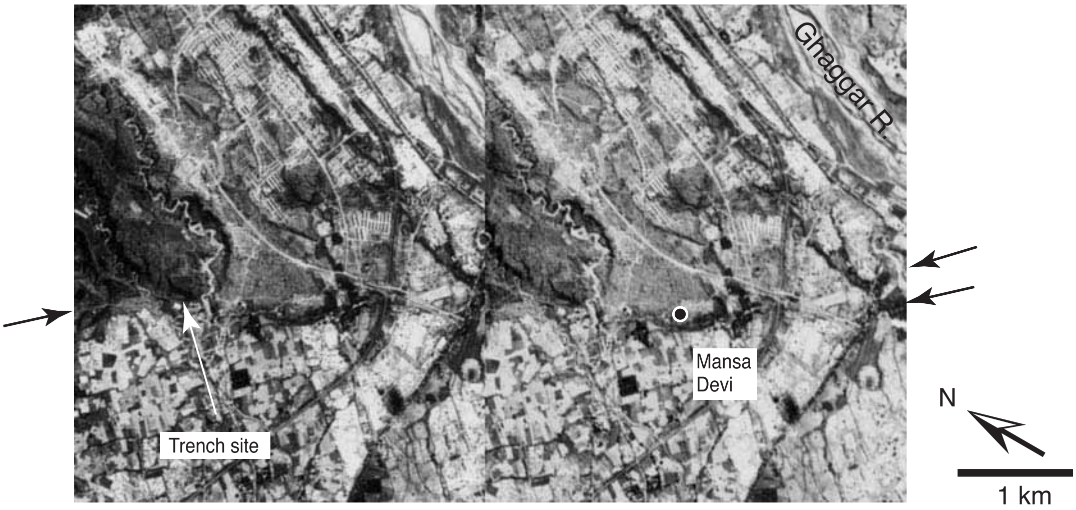

Fig. 5. Stereo-pair of satellite photos showing active fault traces (marked by arrows) along the Himalayan Front southeast of Chandigarh on the right bank of Ghaggar River (refer fig. 3 for location of active fault traces). Two active fault traces (Chandigarh Fault) running parallel to one another between Panchkula and Mansadevi with strikes N25°W to N15°E have vertically displaced and warped the Ghaggar, Kalka, Pinjore and Koshallia terraces comprising an alluvial-fan sediment succession of Late Pleistocene to Holocene age. Warping is clearly seen near the fault line. Vertical uplift along the faults has resulted in 15 m to 38 m high southwest facing fault scarplets. These scarps are transverse to the course of the Ghaggar River channel, representing the younger branching out faults of the HFF system.

décollement; their geometry typically resembles the imbricate faulting pattern seen in fold and thrust belts (Burbank *et al.,* 1992). Evidence of the displacement of different terrace levels along the branching faults, as well as the maximum height of the scarp (38 m), suggests continued tectonic movement through Late Pleistocene to Holocene times. Due to lack of age constraints on the respective surfaces, it is difficult to estimate the timing of events. However, if we consider that the Pinjore surface was formed at around 8.9 ± 1.9 ka, then the Koshallia and other younger surfaces might have developed during the Late Holocene. Later, these surfaces were subjected to periodic uplift and deformation. The gentle warping of the terraces near the fault line on the hanging wall side suggests that the sediment succession has been warped or folded in response to riding over a bend in a fault with a steeper fault plane near the surface. This type of geometry of deformation is commonly associated with the thrusts that normally step up in the direction of slip to a higher décollement or a ramp in a décollement resulting in fault-bend folding as defined by Suppe (1983). The straight faceted range front is suggestive of ongoing tectonic activity.

4.2. *Active faulting in Pinjore Dun*

The active fault traces extending across the Pinjore Dun have vertically displaced and back-tilted various surfaces along them (figs. 3, 4 and 7). The fault traces marked by the discontinuous pattern belong to one single fault system that extends laterally for more than 45 km NNW-SSE, named here the *Pinjore Garden Fault*. It is well exposed between the Pinjore and Baddi town, along the Pinjore-Nalagarh state highway.

The Pinjore Garden Fault has displaced the older Kalka surface and Pinjore surface along

Fig. 6. View of Chandigarh Fault scarp near Mansadevi. Two southwest-facing fault scarps, marked by arrows show vertically displaced flat alluvial-fan surfaces (Ghaggar and Kalka surface). The height of the lower scarp is about 15-16 m, and the higher one is about 38 m from the foreground in the Indo-Gangetic plains. The alluvial-fan surface extends northeast for about 2-3 km. Trench site is marked on the left side of the photo. (Photo looking towards northeast).

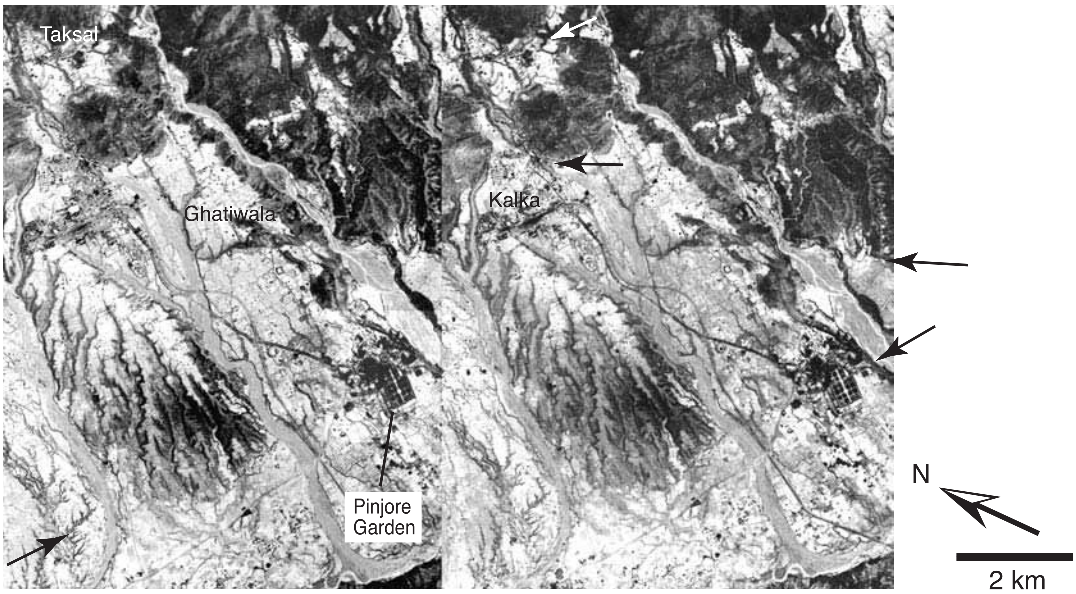

Fig. 7. Stereo-pair of satellite photos showing active fault traces cutting across the Pinjore Dun and along the Lower Siwalik range front (refer to fig. 3 for location). The active faults are marked by arrows. The lower portion of the photo shows vertically dislocated Pinjore and Kalka surfaces along Pinjore Garden Fault trending N25°W-N35°W. This fault passes through the Mughal Garden. The Kalka surface near the fault line is warped and highly dissected compare to the Pinjore surface. In the central portion of the photo, an active fault near Ghatiwala village has vertically displaced and back-tilted the Pinjore surface. Prominent west- and southwest-facing scarp seen in the upper left of the photo represents the southeastern extension of Barsar thrust and Taksal Fault, respectively.

with the younger surfaces giving rise to WSW- and SW-facing fault escarpments. Average height of the fault scarps ranges from 2 to 12 m, although at some localities, the scarps are as high as 15 to 16 m. Investigation around Pinjore reveals that an active fault striking N35°W passes through the Mughal Garden located between the Koshallia and Jhajra rivers, where the 12 m high «Big Step» marks the fault scarp (fig. 8). This garden was constructed around 1600 A.D., using the fault scarp as the «main step». The height of the scarp in the south is about 8 to 10 m and extends further south up to Isharnagar village on the left bank of Koshallia River. Towards the north, the height of the scarp is only 1.5 m to 2 m, and still farther north, the scarp has a height of about 8 to 12 m near village Ratpur. Here, along with the alluvial fan deposits, the older Siwalik bouldery deposits (Upper Siwaliks?) are also displaced. Farther north, the fault passes through the village Basdevpura uplifting and warping the sediments of Kalka surface located between the Jhajra and Sirsa rivers, which is presently marked by intensive gully erosion (Nakata, 1972, 1989). Prominent backtilting of the Pinjore surface was noticed near Gariran village on the left bank of the Kiratpur River, at Kona village between the Surajpur and the Nanakpur rivers and at Makhu-Majra village on the left bank of Ratta River. The general tilt ranges from 6° to 8° NE. Local warping or folding was recognized on the satellite photos near Marhanwala, where the Pinjore surface is tilted SW and NE. Long-term displacement along this fault is well documented on the left bank of the Balad River, where three levels of terraces are displaced.

Two active faults were identified east of Pinjore town, striking N-S and NNW-SSE near Ghatiwala and Ramsar villages. These faults, between the Koshallia and Jhajra rivers (figs. 3 and 7), have displaced the Pinjore surface, resulting in a west-facing tectonic escarpment. The active fault near Ghatiwala extends laterally for about 2 km. Maximum uplift of about 31 m along this fault can be seen in the central portion (Nakata, 1989), uplifting the older Tertiary succession along with the overlying 3 to 5 m thick Quaternary deposits and backtilting the surface 8° to 10° east (fig. 9). This fault dies out

Fig. 8. Active fault scarp used as main step (Big Step) at Mughal Garden in Pinjore town. The height of the scarp is about 12 m and reduces to about 8-10 m in the south and 1.5-2 m in the north. This garden was constructed across this scarp around 400 years ago in 17th century. Arrow shows trace of active fault scarp.

Fig. 9. Back-tilting of Pinjore surface along with the underlying older Tertiary succession along active fault (marked by arrow) near Ghatiwala village. Tilt is about 8°-10° east (view looking southwest).

northward into the floodplain of Jhajra River, whereas to the south, it follows the range front.

The pattern of displacement along the Pinjore Garden Fault System revealed by the active fault scarps, developed on older as well as younger surfaces, suggests that this fault system has remained active. Backtilting and warping of the surfaces near the fault line are suggestive of movement along a low-angle thrust fault dipping northeast, similar to the pattern of deformation observed in the Himalayan Frontal portion along the Chandigarh Fault. Looking to the intact structure of the Mughal Garden at Pinjore, it is noteworthy that since the construction of this garden, no major earthquake has struck this region, *i.e.* no movement has been recorded along the Pinjore Garden Fault in the last 400 years. Thus, it is presumed that strain is accumulating along this fault, indicating high seismic risk and potential for a large magnitude earthquake in the future. The dislocation of the Pinjore surface by two locally-developed parallel faults east of Pinjore town according to Nakata (1989) is the geomorphic expression of imbricated thrusts branching from the Nahan thrust. However, the present study reveals that these faults are the manifestation of a branching fault of the boundary fault or Barsar thrust.

4.3. *Active faulting along the Lower Siwalik range front*

The Lower Siwalik hill range trending NNW-SSE marks the northeastern boundary of the Pinjore Dun (figs. 3 and 4). To the south, this range is flanked by the boundary fault, probably the Barsar thrust of Valdiya (1980), a branching fault of the MBF system. At some localities along this thrust, there is little evidence for active faults displacing the proximal portion of the Late Pleistocene-Holocene alluvial fan sediment succession. The rest of the portion along the hill range is marked by a sharp contact with the plain showing a faceted range front.

Discontinuous geomorphic expression of the active fault traces with strike N-S and NNW-SSE suggests dislocation of the alluvial-fan surface around villages like Kalka, Raru, Dhora, and between Mandhala and Satiwala (figs. 3 and 10). At Kalka the active fault trace striking N-S has displaced the fan surface (Pinjore surface), giving rise to a 50 m high scarp. The scarp is located on the right bank of the Jhajra River and extends laterally for about 0.5 km. Three sub-parallel active fault traces showing *en échelon* pattern were identified around Raru and Dhora villages, on the right bank of Ramnagar River (figs. 3 and 10). These faults striking NNW-SSE are characterized by a SW-facing tectonic escarpments developed by displacement of the fan surface. The average length of these faults ranges between 0.25 and 0.6 km; the faults are about 0.3 km apart. The height of the first scarp (on the way to Dhora from Raru) is about 18 to 20 m; the second scarp is 9 to 12 m high and the third more than 25 m high. Farther north, the tectonic activity follows the boundary of the range front marked by well-developed triangular facets around Koti village.

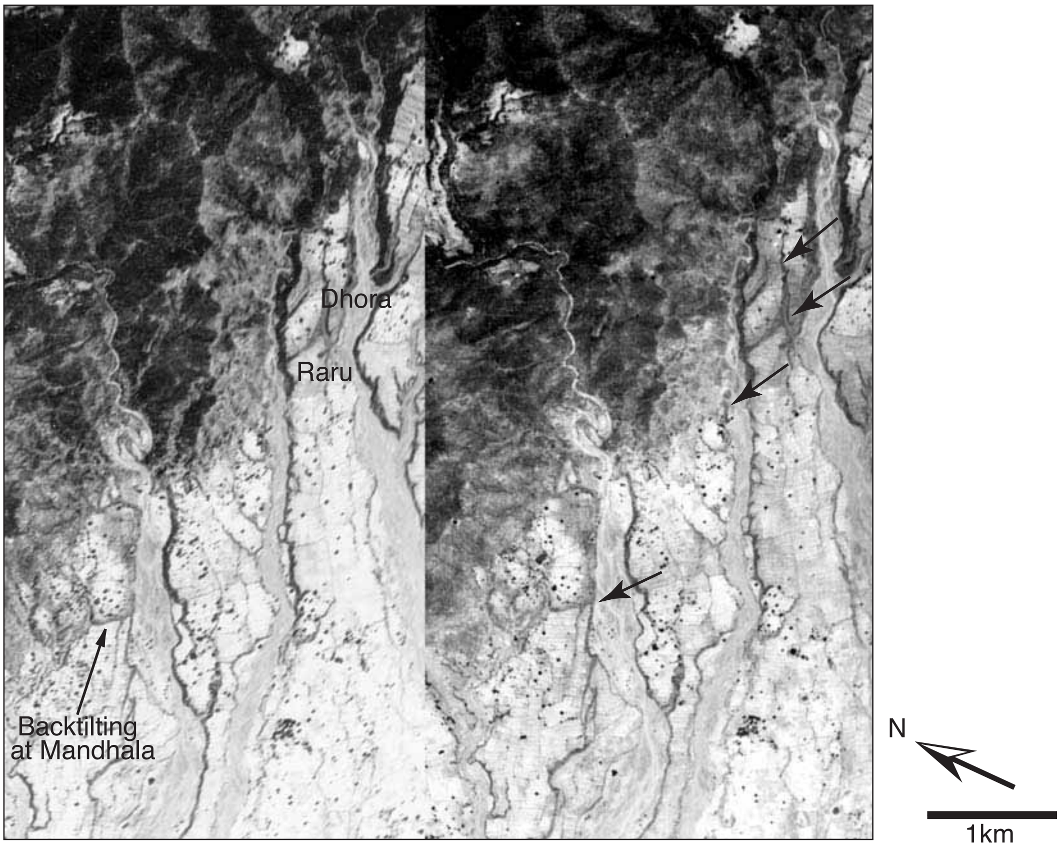

Fig. 10. Stereo-pair of satellite photos showing three sub-parallel active fault traces marked by typically *en échelon* pattern around Raru and Dhora villages and prominent backtilting of alluvial fan surface near Mandhala village (refer to fig. 3 for location). The height of the active fault scarp at Mandhala is about 20 m. These active faults represent the Barsar thrust following the range front. Between Raru and Mandhala, the range front is marked by straight dissected front with well-developed triangular facets.

Fig. 11. Faulted and back-tilted surface representing proximal part of alluvial fan (Pinjore surface) along the range front fault (Barsar thrust) at Mandhala. Height of the fault scarp is about 20 m. Arrow indicating fault scarp. (View looking north).

The active faults exhibit a consistent left-stepping pattern. However, no distinct lateral offset was observed on the ground as well as on satellite photos. At Mandhala village, the active fault extending N-S for about 1.5 km has vertically uplifted the fan surface, giving rise to a west-facing fault scarp 20 m high and backtilting the surface towards the east (figs. 3 and 11). The slope of the surface is about 10° E. North of Mandhala, the discontinuous traces of active faults displacing fan sediments with west-facing fault scarplets are seen as far as Satiwala village; no prominent backtilting was noticed.

The above-mentioned evidence suggests that the active fault traces along the Barsar thrust are the manifestation of reactivated tectonic activity along the MBF that propagated southward along these imbricated thrust faults. The vertical uplift and associated backtilting suggest a similar pattern of deformation observed along the Chandigarh Fault and Pinjore Garden Fault. The prominent left-stepping pattern of the active faults probably suggests some component of strike-slip movement associated with the thrust faulting, but due to lack of evidence, it is difficult to pinpoint the lateral offset on the surface.

4.4. *Active faulting within the Lower Tertiary hills*

In addition to the fault traces showing thrust movement in the southwest portion of Pinjore Dun, an active fault trace showing right-lateral displacement of the Koshallia River channel by 250 m along the Nahan thrust near Taksal town was observed by Nakata (1989). In the present study, we were able to identify the extension of this fault on satellite photographs as well as in the field. The right-lateral strike-slip fault striking NNW-SSE (N15°W) and extending for a distance of about 20 km between Taksal and Chewag, is here named the *Taksal Fault* (figs. 3, 4 and 7).

This fault has right laterally displaced the Lower Tertiary succession as well as younger Quaternary fluvial terrace sediments. Lateral offset of streams as well as fluvial terraces and occurrence of narrow deep straight valleys are common tectonic features observed along the entire fault trace. Fault scarplets of 12 to 30 m height facing ENE and WSW are the manifestation of the dip-slip movement. A maximum vertical displacement of about 50 to 56 m was observed near Taksal on the left bank of Koshallia River. The offsets of the streams are not consistent all along the length of the fault trace. Right-lateral offset of the minor as well as the major streams varies from 250 m to 1350 m. Minimum displacement of 250 m and maximum of 1350 m has been observed around Taksal town and around Kot Beja village, respectively (figs. 3 and 12). No distinct branching pattern was observed along the fault, except at Chewag village (figs. 3 and 12). The right-stepping pattern near Chewag has resulted in the formation of a small, elongated lenticular-shaped pull-apart basin due to normal faulting along the releasing bend of the faults. This

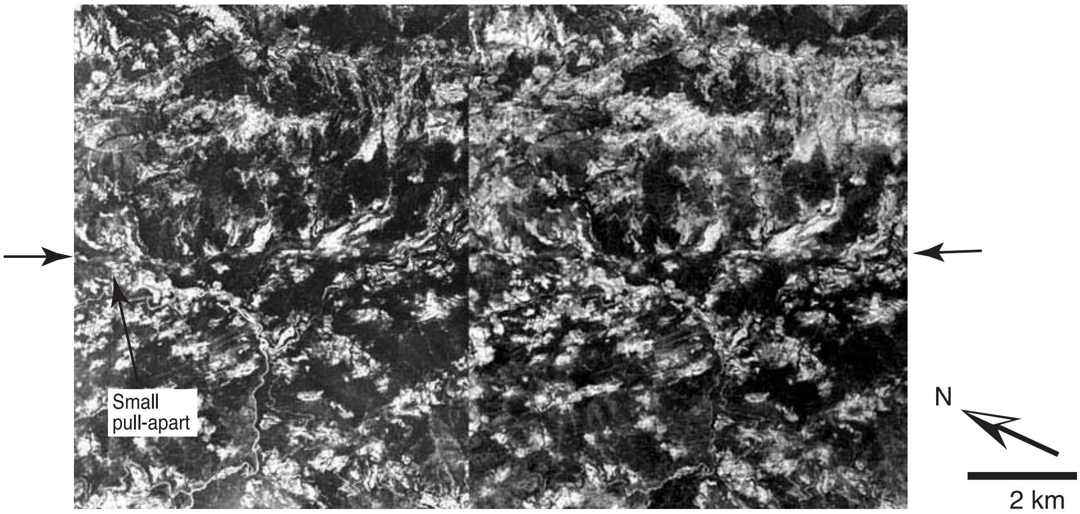

Fig. 12. Stereo-pair of satellite photos showing right-lateral stream offsets along NNW-SSE trending Taksal Fault between Banet and Chewag villages (refer to fig. 3 for location). The fault has displaced along it Tertiary strata as well as Quaternary sediments. Along with the streams, younger terraces are seen displaced right laterally along the fault. Right stepping along the fault has resulted in formation of small pull-apart near Chewag village.

small basin is about 230 m long in NNW-SSE direction along the strike of the fault, and 30 m wide in its center, narrowing to 11 m at the northern end and 10 m at the southern end. The sediment succession within the pull-apart basin shows a typically horizontally stratified succession marked by alternating layers of fine- and coarse-grained silty sand.

Displacement of the Lower Tertiary succession, Younger Quaternary fluvial terraces and variable stream offsets suggests continued tectonic movement from Late Tertiary to recent times. The small pull-apart at Chewag is indicative of a right stepover resulting in formation of a dilatational secondary structure. The occurrence of this right lateral strike-slip fault parallel to the principal structural trend (NNW-SSE) of the Himalaya as well as the thrust fault to the west (*i.e.* Barsar thrust, Pinjore Garden Fault and Chandigarh Fault) is a clear evidence of slip-partitioning taking place between the reverse faults and the strike-slip fault. This right-lateral strike-slip fault marks a part of the MBF system and has been due to the influence of ongoing oblique convergence between India and Eurasia. Our observations are consistent with the observations made by Mc Caffrey and Nabelek (1998) and Oatney *et al.,* (2001).

5. Paleoseismic investigation along Himalayan Front

At the base of a 16-20 m high fault scarp striking N-S along Chandigarh Fault, a 14 m long; 2 to 4 m deep and 4.5 m wide E-W trench was dug to confirm the amount of displacement and the pattern of faulting of the HFF system (figs. 3, 5 and 13). The exposed sediment succession in the trench predominantly shows two sedimentary units comprising poorly-sorted pebble-cobble clasts with occasional occurrence of boulders and a medium- to coarse-grained massive sandy unit.

Exposed sediments in the trench were subdivided into five facies (fig. 13). Unit OCd represents older channel fill deposits composed of loose matrix-supported pebble-cobble-boulders

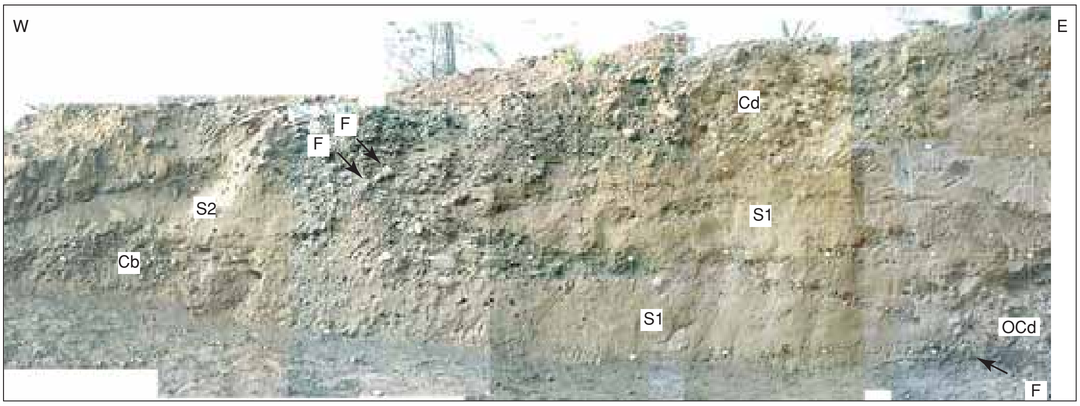

Fig. 13. North wall of E-W trending trench at the base of Chandigarh Fault scarp near Mansa Devi (refer to figs. 3 and 5 for location). Low-angle thrust fault with dip ranging from 20° to 46° east has displaced poorly-sorted gravelly unit representing old channel trough and massive sand units by 3.5 m. In the lower portion of the trench, the fault plane is distinctly marked by 10 to 12 cm thick crushed zone or brecciated zone comprising angular clasts that were crushed and dragged along the fault during the movement from the underlying unit. Aligned discoidal pebbles along their elongated axes mark the fault passing through the channel deposit, which are oriented parallel to the fault plane contact. String on the wall shows grid of 1 m. Cd - channel deposit; S1 and S2 massive sand deposit; Cb - channel bar; OCd - older channel deposit.

of sandstone of Dagshai, Kasauli and Subathu formations: the matrix is mainly fine gravel, coarse sand and silt. Units S1 and S2 are the massive medium to coarse sand facies, unit Cd is a channel fill deposit made of pebbles and cobbles with a sandy matrix, and unit Cb is a channel bar made of comparatively finer gravel clasts seen in OCd and Cd facies, with matrix of medium-fine sand, silt and clay.

Only one fault strand (F) was identified, which has displaced OCd, S1 and Cd exposed in the eastern portion of the trench. Total displacement of about 3.5 m was inferred along a low-angle thrust fault with dip ranging from 20° to 46° east at a depth of 4 m below the present surface. The fault is marked by an angle of dip of about 46° near the surface in the western portion of the trench and a lower angle of dip of 20° towards the east. The movement from east to west along this fault has resulted in slight deformation within the channel deposit, revealed by the pattern of clast fabric marked by reoriented gravels, resembling folding near the tip of the fault plane.

Due to lack of numerical age constraints, it is difficult to pinpoint the time of this event. However, looking to the displacement along fault (F) cutting the unit Cd, the youngest unit, and an insignificant cover of well developed soil, it is suggested that this event is the latest event in this area along the Chandigarh Fault. The net displacement along the fault (F) of about 3.5 m indicates one single large paleo-earthquake. If we consider that the 3.5 m is the maximum displacement during one event, then the empirical relationship of Wells and Coppersmith (1994), suggests M_w 7 for this event. Taking the average angle of the fault (25°) gives a vertical displacement of about 1.5 m and a horizontal shortening of about 3.2 m for one large magnitude event.

6. Discussion and conclusions

The present study along the Northwestern Himalayan Frontal Zone around Chandigarh and Pinjore Dun has helped in understanding the ongoing crustal deformation and its relationship with the plate motion along the Indo-Eurasian plate boundary. The sense of movement along these fault traces identified on the basis of geomorphic as well as field investigations indicates thrust and strike-slip faulting. Overall pattern and geometry of active fault traces identified along the Himalayan Front, within Pinjore Dun and along the Lower Siwalik range front suggest that the ongoing tectonic deformation within the Himalaya has propagated southward along the various branching faults that belong to the major fault systems like the MBF and HFF. These branching faults are the manifestation of imbricated thrust faults in this region. The displacement of various terraces along these branching faults marked by vertical scarplets with maximum height ranging between 12 and 56 m suggests continued tectonic movement through Late Pleistocene to Holocene times and cumulative slip along the Chandigarh Fault, Pinjore Garden Fault and Barsar thrust. Gentle warping of the terraces near the fault line on the hanging wall and backtilting suggests fault-bend folding.

The «Big Step» of Pinjore Mughal Garden representing the active fault scarp suggests that no movement has been recorded along the Pinjore Garden Fault since the construction of this garden 400 years ago. Thus, this fault has a high seismic hazard for a large magnitude earthquake in the future. The occurrence of the right-lateral strike-slip Taksal Fault striking NNW-SSE in the northeastern side of the thrust faults is a clear evidence of slip-partitioning between reverse faults and a strike-slip fault. Seven streams showing prominent lateral offset along the fault were taken into account to calculate offset ratio ($a = D/L$), where D is the amount of stream offset along fault and L is upstream length of the displaced stream (Matsuda, 1966) (fig. 14). This gives an offset ratio of about 0.28. A relationship between long-term slip rate (S) along lateral slip of fault and offset ratio ($a = D/L$) has been rough-

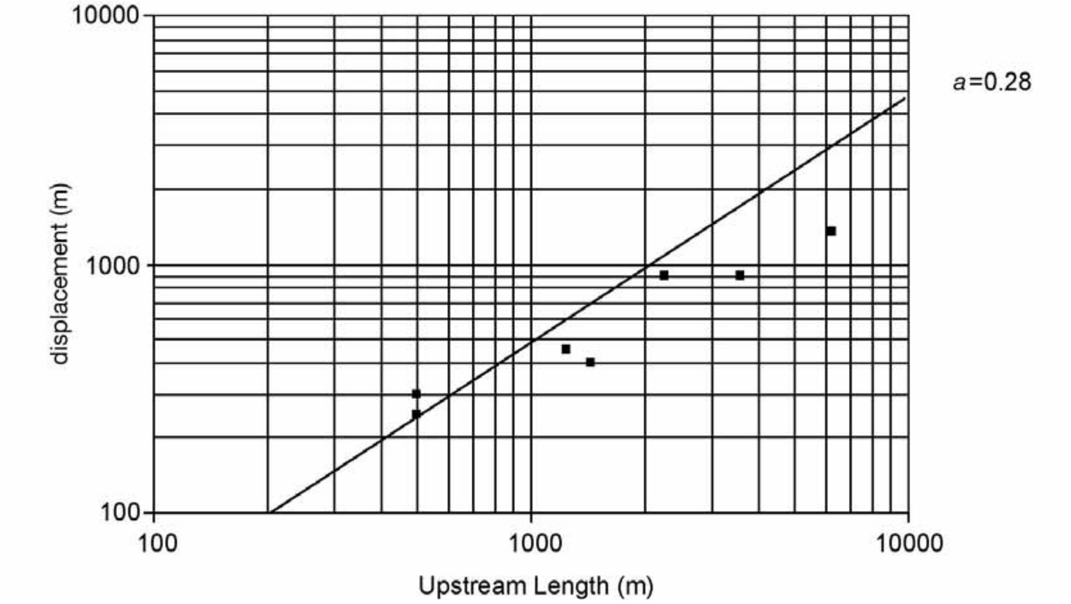

Fig. 14. Relationship between amounts of stream offset along the fault and upstream length from the fault trace of the Taksal Fault between Banet and Chewag.

ly calculated as S (m/1000 years), *i.e.* $10a$ (Matsuda, 1975). This relationship gives a slip rate along Taksal Fault of about 2.8 mm/yr. The strike of Taksal Fault almost parallel to the principal structural trend (NNW-SSE) of the arcuate Himalayan belt as well as the thrust faults is indicative of change in the direction of maximum principal compressive stress axis from N-S in the Eastern Himalaya to NE-SW in the Western Himalayan Frontal Zone (Nakata *et al.,* 1990). This also explains the phenomenon of ongoing oblique convergence of the Indian plate (Nakata *et al.,* 1990). However, the model on the basis of small-circle approximation with radius 1696 ± 55 km of Himalayan arc suggests that the regional convergence vector and stress fields are radial to the arc (Bilham *et al.,* 1998; Bendick and Bilham 2001). McCaffrey and Nabelek (1998) suggested that active tectonics of the Himalaya and the southern half of Tibet show a strong resemblance to the subduction style at the curved oceanic trenches such as Sumatra, with oblique convergence and occurrence of trench-parallel strike-slip and extension. They also suggested that radial vergence in earthquake slip vector along the front, east-west extension in Southern Tibet, and right-lateral slip on the Karakoram Fault are on account of the basal shear caused by the oblique sliding of Indian plate along the arcuate plate boundary. Also recent studies around Dehra Dun valley suggest that strike-slip movement on the Trans-Yamuna active fault system may be related to arc-parallel lateral translation of the Karakoram fault block and east-west extension of the Southern Tibet block, in response to the oblique convergence between the Indian and Eurasian plates (Oatney *et al.* 2001). Our observations are consistent with the model suggested by McCaffrey and Nabelek (1998) and the observation made by Oatney *et al.* (2001). This also explains the westward reduction of convergence rates from Nepal to India (Yeats and Thakur, 1998) and phenomenon of slip partitioning between thrust and strike-slip faults.

A preliminary trench investigation at the base of the Chandigarh Fault scarp revealed total displacement of 3.5 m along a low-angle thrust fault with variable dip of 20° to 46° northeast, suggesting a large magnitude (M_w 7) prehistoric earthquake. Presuming an average dip of the fault of 25°, the vertical component of displacement is about 1.5 m, and horizontal crustal shortening is about 3.2 m for one event. It is quite logical that the Chandigarh Fault has displaced various surfaces along it such as the Ghaggar, Kalka, Pinjore and Koshallia surfaces. It is envisaged that the fan aggradation within the Pinjore Dun initiated at around 50 ka and lasted up to 10 ka, and the Pinjore surface gives an age of 8.9 ± 1.9 ka. Taking into account the age and the height of the Pinjore surface along the Chandigarh Fault ranging between 20 and 25 m, the displacement of 3.5 m per event with dip of the fault 25° gives a slip rate of about 6.3 ± 2 mm/yr, a rate of horizontal shortening about 5.8 ± 1.8 mm/yr and recurrence of faulting 555 ± 118 years along the Himalayan Frontal Fault. A recent paleoseismic investigation along the Black Mango tear fault in the same region has also revealed evidence of two large surface rupture earthquakes during the past 650 years, subsequent to 1294 A.D. and 1423 A.D. and another at about 260 A.D. (Kumar *et al*., 2001) Also paleoseismic investigations along the Sirmurital Fault in Dehra Dun valley on the basis of two colluvial wedges suggest that two earthquakes have struck this region in the last 1000 years (Oatney *et al.,* 2001).

The direct estimates of the convergence rate along the HFF based on geological findings suggest shortening rate of 11 ± 5 mm/yr and 14 ± 2 mm/yr across Dehra Dun and northwest of Dehra Dun respectively (Powers *et al.,* 1998); horizontal shortening of ≥ 11.9 ± 3.1 mm/yr, and a slip rate along fault of ≥ 13.8 ± 3.16 mm/yr near Dehra Dun (Wesnousky *et al*., 1999). The offset of Late Pleistocene and Holocene terrace deposits indicates a convergence rate of about 21 ± 3 mm/yr in Nepal (Lave and Avouac, 2000), and the investigation along the Black Mango tear fault suggests fault slip and crustal shortening of $9.62^{+7}_{-3.5}$ mm/yr and $8.42^{+7}_{-3.6}$ mm/yr (Kumar *et al*., 2001). These rates are consistent with GPS measurements that give a convergence rate of 20 ± 3 mm/yr. This suggests that our results are consistence with the results of the above mentioned workers, because the slip rate of about 6.3 ± 2 mm/yr which we got along the Chandigarh Fault shows the minimum slip rate. Trench investigations along the other active faults, *viz*., the Pinjore Garden Fault, Barsar thrust and Taksal Fault will be able to give a complete summary of the slip along these faults in this region.

Our investigation has thrown considerable light on the occurrence of active faults and evidence of large magnitude pre-historic earthquake in this area. The concentration of active faults and their geographic location clearly show that these faults pass through or are near populated areas such as Chandigarh, through Pinjore Dun where lie many small towns and villages. Similar is the case along the piedmont zone and in the hill range where traces of active faults pass through small villages. It is envisaged that these areas fall under a high seismic hazard zone and the active faults are the biggest threat if large magnitude earthquake struck this region in future. Detail paleoseismic studies are very much important to build up a long-term earthquake database of large magnitude prehistoric events. Our finding will play a key role and path for future detailed studies and towards evaluating seismic hazard of this region.

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