are used for food, medicine, fertilizer, etc.[13]. Therefore, it is a cause of concern that coral reefs and associated organisms are threatened by the El Niño Southern Oscillation which affects the global climate[15,16]. This in turn, causes fluctuations in rainfall, resulting in drought in some areas and heavy rainfall in others[17]. Guerrero[17] had discussed the impacts of El Niño on Philippine fisheries. He had reported that for marine fisheries, the fishermen operating in near-shore shallow coastal waters had lower catch per unit effort (CPUE), while commercial fishermen operating in deep waters had relatively high CPUE during El Niño. Kumaraguru[8] had also reported a reduction in distribution of coral-associated fishes due to bleaching in the reefs of Palk Bay and Gulf of Mannar regions. This could be also due to an apparent movement of small pelagic fishes from the shallow to the deeper waters[18].

Although the corals have got bleached, they need to be protected because these bleached reefs will slowly recover in time by way of new growth of coral colonies over the old ones. The optimistic point to note here is that if we look at the scientific records, this phenomenon of coral bleaching has been taking place periodically all over the world. The process of natural selection is in operation, with the growth of new coral colonies and any disturbance in the system is only temporary. Therefore, in spite of the odds, the corals will resurge under the sea, which we need to protect and conserve for our benefit.

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Preliminary observations from a trench near Chandigarh, NW Himalaya and their bearing on active faulting

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Evidence of two parallel to sub-parallel active-fault traces along the Himalayan Front around Chandigarh has provided additional information on the imbricated faulting pattern that branches out from the Himalayan Frontal Thrust system, which probably merges down northward with décollement. Displacement in terraces along these branching faults and the maximum height of the scarp (38 m) suggest continued tectonic movement since late Pleistocene and cumulative slip along the faults. The preliminary trench

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investigation across the young fault reveals a total displacement of 3.5 m along a thrust fault, indicating remnant of one large-magnitude prehistoric earthquake.

IN the Himalaya, instrumental records suggest that the major seismic activity with moderate-magnitude earthquakes (> 6 or < 7) is concentrated to an approximately 50 km-wide belt located in the Lesser Himalaya, south of the Main Central Thrust (MCT)[1]. In a span of the last 100–120 years, four large-magnitude events have occurred along the Himalayan foothill zone: the 1897 Shillong (*M* 8.7), 1905 Kangra (*Ms* 7.8)[2], 1934 Bihar (*M* 8.4), and the 1950 Upper Assam (*M* 8.5) earthquakes (Figure 1 *a*). None of these produced any surfaces rupture. The area between 1905 Kangra and 1934 Bihar–Nepal earthquakes is categorized as the Central Seismic Gap[3], which bears high probability for one or more $M > 8$ Himalayan earthquakes during this century[4]. Studies carried out during the past several decades have provided important data on the ongoing crustal deformation in the Himalaya[1,5–7]. However, not much effort is spent in site-specific studies. Here we present some preliminary paleoseismic observations from trench excavated near Chandigarh (Figure 1 *b*).

The study area around Chandigarh marks the southernmost fringe of the Himalaya, where the undeformed succession of the Indo-Gangetic Plains is separated from the detached, complex folded-faulted Upper Siwalik Hills comprising molassic sediments of lower Pliocene–early Pleistocene age. The boundary is well-defined by the Himalayan Frontal Thrust (HFT) system (Figure 1 *b*).

The Ghaggar river, which is the major drainage in this area flows SSW, cuts transversely the NNW trending Upper Siwalik Hills before debouching into the plains. Five terrace levels were observed along the right bank

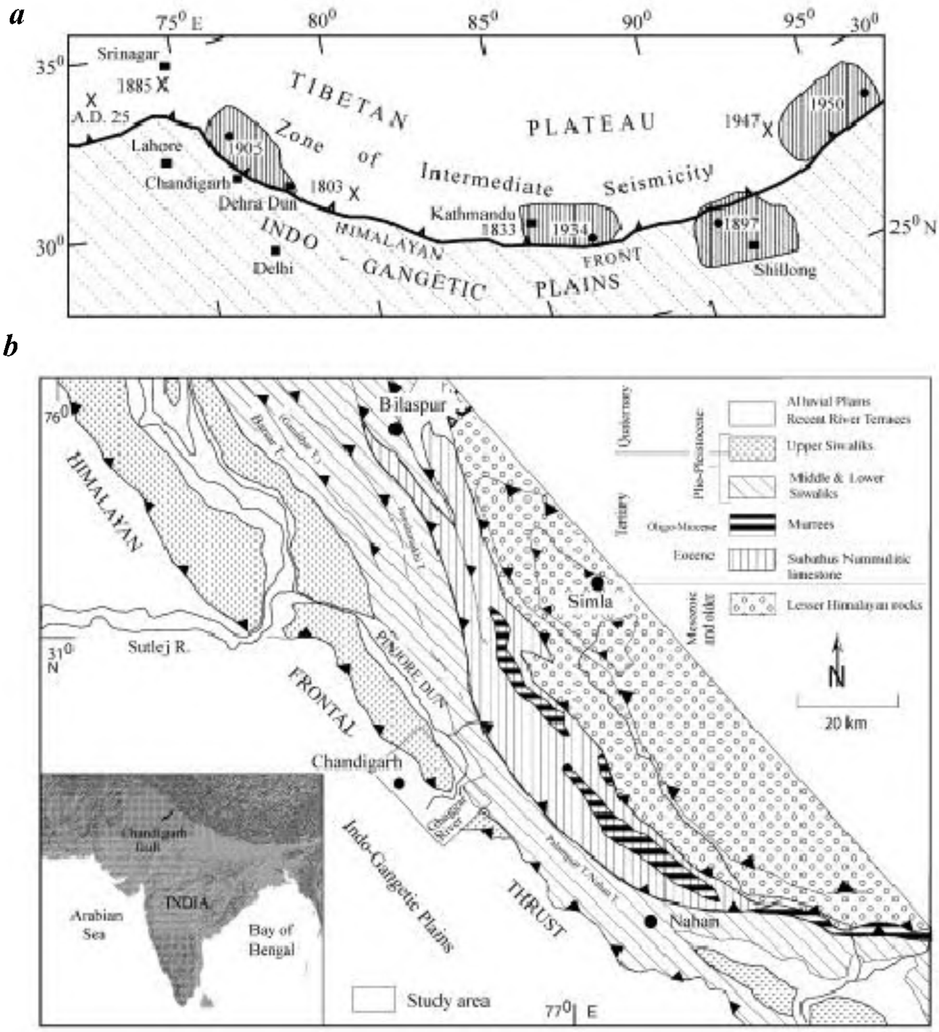

Figure 1. *a*, Map showing meizoseismal zones of four great earthquakes along the Himalayan Front and other large-magnitude events (after Yeats and Thakur[15]); *b*, Generalized geological map of northwestern Himalayan Front around Chandigarh (after Gansser[16] and Valdiya[17]). (Inset) DEM of India showing location of Chandigarh fault.

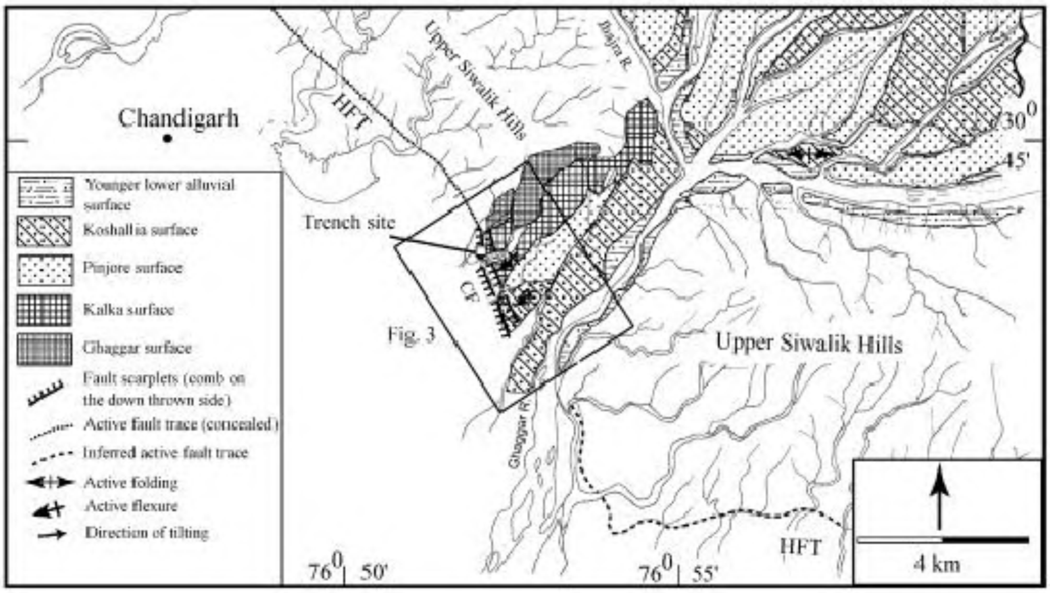

Figure 2. Distribution of terraces and active fault traces along northwestern Himalayan Foot Hill Zone around Chandigarh along the right bank of Ghaggar river. Box highlights the area of satellite photograph and location of trench site. CF, Chandigarh Fault; HFT, Himalayan Frontal Fault (modified after Nakata[8]).

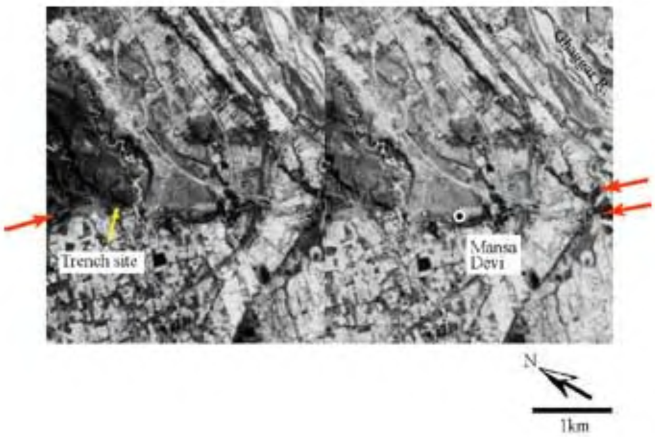

Figure 3. Stereo-pair of satellite photographs showing active fault traces (marked by red arrows) along the Himalayan Front, southeast of Chandigarh on the right bank of Ghaggar river (refer Figure 2 for location). Location of trench is shown by yellow arrow.

where it crosses the Upper Siwalik Hills (Figures 1 *b* and 2). From the amount of dissection and level of stratigraphic position, these terraces/surfaces are categorized as the Ghaggar, Kalka, Pinjore, Koshallia and younger alluvial terraces[5]. It is presumed that these terraces might have developed due to incision caused by periodic uplift along the Himalayan Front. The surface morphology and sediment content are dominated by matrix-supported gravelly clasts (pebble–boulder) of sandstones derived from Lower Siwalik Hills in the upper reaches; these terraces are co-relatable with the terraces occurring in the Pinjore Dun valley[5].

The most prominent deformation along the HFT was observed on the right bank of the Ghaggar river, northeast of Chandigarh[8]. The remote-sensing data and field studies have shown existence of active fault traces in the foothill zone, with the average length varying from 2 to 10 km and strike from N335° to N15°E (Figures 2 and 3). The digression in the strike is due to the sinuous nature of the mountain-front. The surface expressions of the faults are marked by discontinuous pattern. It is assumed that the fault connects subsurface, but has not ruptured up to the surface at all places. Besides, there occur straight, linear mountain-fronts marked by well-developed triangular facets indicating the ongoing tectonic activity in this region, because tectonically-active fronts usually display prominent, large facets that are generated along the base of the escarpments[9,10].

Two traces of active faults running parallel to one another between Panchkula and Mansadevi with strikes N335° to N15°E have vertically displaced and warped the Ghaggar, Kalka, Pinjore and Koshallia terraces comprising late Pleistocene to Holocene alluvial-fan sediment succession (Figures 2 and 3). Vertical uplift along these faults has resulted into 15 to 38 m high fault scarplets facing the Gangetic Plains. These scarps are transverse to the course of the Ghaggar river channel. The distance between the faults varies from 0.25 to 0.3 km. The first fault trace exhibits a 20 m high fault scarp along its northwest fringe, which was responsible for uplifting the Kalka and Pinjore terraces near Mansadevi, and the scarp height reduces up to 6 m towards southeast where it has displaced the Koshallia terrace (Figures 2 and 3). This fault is named as the 'Chandigarh fault' (CF). We carried out trenching to confirm the amount of displacement and the pattern of faulting of the Chandigarh fault system (Figures 2 and 3).

Figure 4. Northwall view of E–W trending trench at the base of Chandigarh fault scarp near Mansadevi (refer to Figures 2 and 3 for location). Fault strands are marked by red arrows. Thread on the wall shows grid of 1 m × 1 m. Cd, Channel deposit; S1 and S2, Massive sand deposits; Cb, Channel bar; Ocd, Older channel deposit.

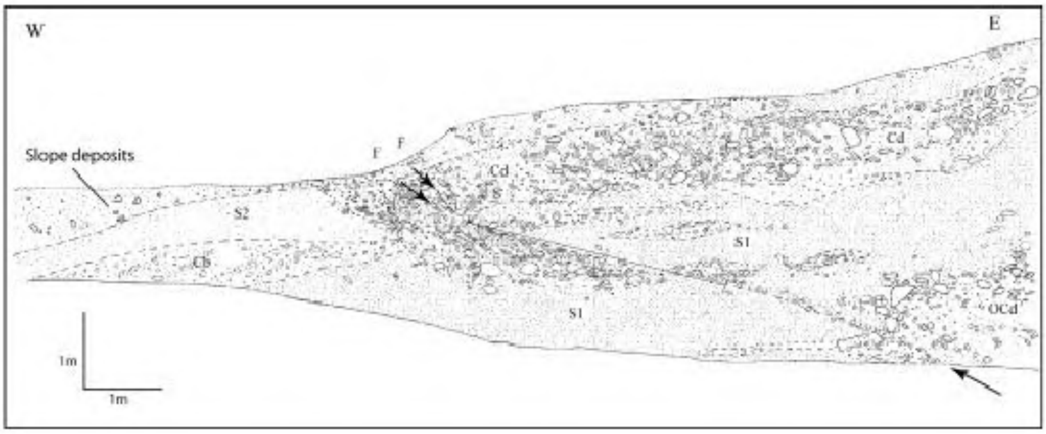

Figure 5. Detail trench log of northwall. Line along the fault trace shows the amount of displacement measured between the displaced Cd and S1 units taking into consideration the lower bounding surface between them.

At the base of a N15°E striking 20 m high fault scarp along CF, a 14 m long, 2 to 4 m deep and 4.5 m wide E–W trending trench was excavated (Figures 2 and 3). The trench was subsequently logged and documented (Figures 4 and 5). Exposed succession in the trench was categorized into unit Ocd–older channel fill deposits composed of loose matrix (very fine gravel + medium–coarse sand + silt)-supported pebble–cobble–boulder of sandstone of Dagshai, Kasauli and Subathu Formation, units S1 and S2 – massive medium-to-coarse sand facies, unit Cd – channel-fill deposit consisting pebble–cobble and unit Cb – channel bar made of comparatively finer gravel clasts seen in Ocd and Cd facies.

A fault strand (F) has displaced Ocd, S1 and Cd lithounits in the eastern and central portion of the trench (Figures 4 and 5). The external geometry of unit Cd shows slightly erosive contact with respect to the underlying S1 unit and concave-up lower-bounding surface representing shallow channel-fill deposits. Overall succession is capped by slope deposit, which was deposited after the event. This phase of deposition was responsible for the degradation of the scarp and erosion of the channel-fill deposit. The fault plane was traced for about 6.5 m from the base in the east up to near-surface in the west. The fault shows variable dip ranging from 20 to 46° due east. The fault is marked by a steeper dip of about 46° near the surface in the western portion of the trench, and reduces to about 20° towards the east. In the central segment the dip of the fault is as low as 4 to 8°, and again becomes steeper in the lower part. The fault plane is distinctly marked by 10 to 12 cm thick crushed zone or brecciated zone comprising angular gravel, where it passes through the S1 unit (Figures 4 and 5). The brecciated zone suggests that the gravel clasts were crushed and dragged along the fault during the movement from the underlying lithounit. Further west, the fault contact between the S1 and Cd units shows typical shear-fabric marked by aligned discoidal pebbles along their long axes orientated parallel to the fault-plane contact (Figures 4 and 5). Total displacement of about 3.5 m was measured taking into account the lower bounding surface between Cd and S1 units. The movement from east to west has resulted into slight deformation within unit Cd, which resembles folding near the tip of the fault. Since we did not find any distinct signatures of pedogenic features in the sandy lithounit (S1), we presume that unit S1 is quite young, probably representing late Holocene surface, which was subsequently overlain by unit Cd and finally displaced along the thrust fault.

The occurrence of two parallel to sub-parallel active fault traces probably represents the branching-out faults of the HFT system that probably merge down northward with décollement; their geometry typically resembles the imbricated faulting pattern seen in the fold and thrust belt[11]. Displacement of the Ghaggar, Kalka, Pinjore and Koshallia terraces along CF and the maximum height of the scarp (38 m) suggest continued tectonic movement since late Pleistocene and cumulative slip along the fault. However, we did not observe any re-orientation of gravel clasts or evidence of repeated events; thus it is suggested that the faulting we observed in the trench represents the latest event. Owing to lack of age constraints of the respective terraces, it is difficult to estimate the timing of the

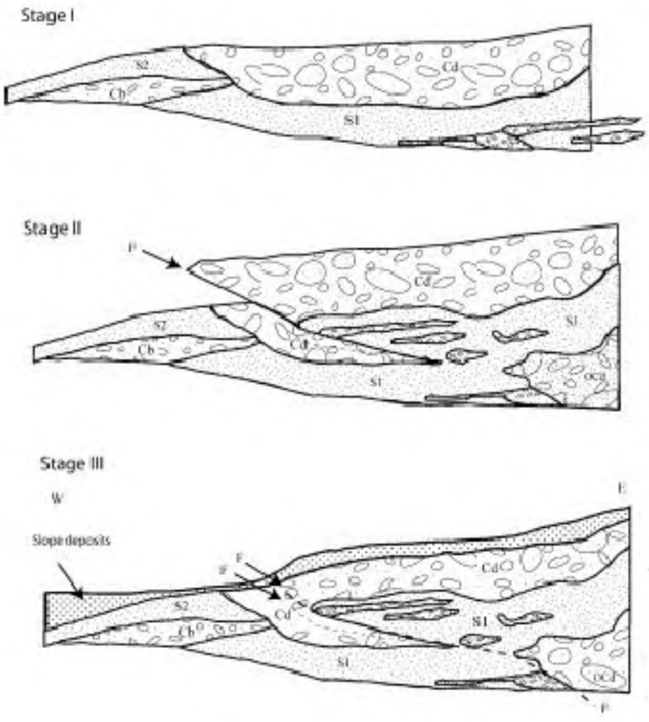

Figure 6. Stage I: Simplified version of trench log showing stratigraphic position of lithounits before faulting, after eliminating the displacement along the fault. Cd represents the channel trough and marks erosive contact with the underlying S1 (sandy) unit and other units like S2 and Cb on the left-hand-side of the succession. Stage II: Trench log showing stratigraphic relationship of the lithounits after faulting, where Cd and S1 have been faulted and moved up. OCd unit must have been upthrusted from below. Stage III: Final picture of the trench after the scarp was subjected to erosion, followed by phase of deposition of slope-derived material.

seismic event/s. However, the extensively-occurring Pinjore surface does not show well-developed reddish soil cover. On the basis of this, Nakata[8] suggested that the Pinjore surface probably formed during Last Glacial period. The OSL ages of the Quaternary deposits from the Pinjore Dun indicate that the sedimentation commenced in this valley well before 57 ka BP and continued up to around 20 ka BP[12]. If this is acceptable, then the Koshallia and other younger surfaces might have developed between upper Pleistocene to Holocene times, and since then these surfaces have been subsequently subjected to periodic/episodic uplift and deformation. The gentle warping of the terraces near the fault line on the hanging wall as well as warping in the sediment succession suggest that this deformation is due to the movement over the bend in the 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 ramp in décollement, as defined by Suppe[13].

The displacement of the youngest unit Cd in the trench, and insignificant cover of well-developed soil over it suggest that this is the latest event in this area. The net displacement along the fault (F) of about 3.5 m indicates a single large-magnitude paleoearthquake event (Figure 6). Taking average angle of the fault (25°) gives vertical displacement of about 1.5 m and horizontal crustal shortening of about 3.2 m for one large magnitude event. In addition to this recent paleoseismic investigation of Black Mango Tear Fault, a tear fault along the HFT in northwestern Himalaya has revealed evidence of two large surface-rupture earthquakes during the past 650 years, subsequent to AD 1294 and AD 1423 and another at about AD 260 (ref. 14). With the assumption that HFT dips $30 \pm 10°$, a fault slip and crustal shortening of $9.62^{+7.0}_{-3.5}$ mm/year and $8.42^{+7.0}_{-3.6}$ mm/year respectively was proposed. This suggests that the HFT system and its branching-out faults have been ruptured in the historic past, and are active faults which are capable of triggering large magnitude earthquakes in future.

The active faults identified, here in addition to that by Nakata[8] and the preliminary paleoseismic investigation have provided significant information towards the ongoing tectonic deformation along the Himalayan arc. Paleoseismic studies are essential to construct a long-term earthquake database of unknown large magnitude prehistoric events, which will help in evaluating the seismic hazard of these regions.

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