Geometry and development of the Jhajara thrust: An example of neotectonic activity in the Pinjaur Dun, NW Himalaya

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Mountain fronts of orogenic belts are marked by dynamic landscape changes under the influence of contemporary tectonic activity. Longitudinal valleys (locally called as Duns) constitute important landforms associated with some segments of the Himalayan mountain front. A neotectonic feature – the Jhajara thrust, has been identified in the Pinjaur Dun of NW Himalaya on the basis of structural mapping and tectonic geomorphological analysis. Optically stimulated luminescence dating on quartz sand samples from the geomorphic surface constrains the last displacement associated with the Jhajara thrust to before ~55.7 ± 6 ka BP.

Keywords: Dun, Jhajara thrust, mountain fronts, neotectonic activity.

The Himalayan orogenic belt (Figure 1 a) is marked by elevation increase from the Sub-Himalaya to the Lesser Himalaya and to the Central Himalaya1. Also, within the Sub-Himalaya, from its northern margin with the Lesser Himalaya (~ 1500 m) to the outermost Siwalik Hills bordering the Indo-Gangetic Plains (~ 600 m), elevation changes significantly (~900 m in the study area). Morphologic variability is quite marked in the Sub-Himalayan segments that include major NW–SE-oriented intermontane valleys, commonly referred to as Duns (Figure 1 b). Such Sub-Himalayan segments are associated with multiple mountain fronts whose structural and tectonic evolution significantly influences landform development. The morpho-tectonic evolution of the Sub-Himalaya can be derived from an integrated analysis of structural and landform development. In this context, a well-exposed structure – the Jhajara thrust is recognized and described, and its influence on landform development in a part of the Pinjaur Dun (Figures 1 c) has been investigated.

The Pinjaur Dun is located in the foothills of NW Himalaya. It is bordered by the Sub-Himalayan mountain and the outermost Siwalik Hills to its northeast and southwest respectively. On the basis of its width, the Pinjaur Dun can be divided into two parts – (a) the wider northwestern part, and (b) the narrower southeastern part (Figure 1 b and c). The present study is confined to the narrower southeastern part of the dun.

Several faults are recognized within the Pinjaur Dun and adjoining areas. From the southwest to the northeast the faults are: (1) Himalayan Frontal Thrust (HFT)3, (2) Sirsa Fault (V. Singh, unpublished thesis; Singh and Tandon4), (3) Pinjaur Garden Fault2,4, (4) Pinjaur Thrust5,6, and (5) Barsar and Nalagarh thrusts5,7 (Figure 1 c). The Sirsa fault marks the southwestern margin of the Pinjaur Dun, whereas the Barsar thrust and the Nalagarh thrust mark its northeastern boundary. The Barsar thrust (dipping 60° towards NE near the surface), the Nalagarh thrust, and the Pinjaur thrust (dipping 60° towards NE) traces are well exposed in the field, whereas the HFT (dipping NE), Sirsa fault (dipping towards SW) and the Pinjaur Garden Fault (dipping NE) are inferred by geomorphic expressions. Palaeoseismological studies carried out to recognize rupture and movement along the HFT8,9 and the Pinjaur Garden Fault10 show the most recent events associated with the faults to have deformed deposits near the surface. Two transverse structures have also been identified earlier, namely the Ghaggar tear fault6 and the Surajpur fault7 (Figure 1 b and c).

Geometry and geomorphic setting of the Jhajara thrust

A stream-cut exposure of a thrust between the Pinjaur thrust and the Pinjaur Garden Fault shows transport of the Lower Siwalik rocks towards the SW over the younger dun gravels (Figure 2 a). The ~520 m wide Jhajara related fault zone is defined in the hanging wall by highly fractured, brecciated rocks of the Lower Siwalik Subgroup and fault gouge (Figure 2 a). Relict bedding planes preserved in brecciated rocks of the hanging wall dip moder-
ately to the northeast. The dip direction of the bedrocks on the right bank varies from ENE to NE, whereas that on the left bank varies from NNE to NE (Figure 2b). Marked variation of the bedrock dip direction suggests a local warp within the study area.

**Geomorphic manifestation**

Four geomorphic surfaces – the Ghaggar, Kalka, Pinjaur and Jhajulla in descending order of their relative ages, have been recognized in this region by earlier workers. The Kalka, Pinjaur and Jhajulla surfaces are incised by the Jhajara stream (Figure 3a and e). The Kalka surface is present to the northwest of the Jhajara stream and is incised up to ~46 m; in some reaches the Jhajara stream flows along the Kalka surface (Figure 3a). The Pinjaur surface occurs on the left bank of the Jhajara stream, and is present on both banks towards the southwestern margin of the Dun (Figure 3a). The stream flows over the Jhajulla surface near the intermontane valley mountain front (Figure 3a).
The width of the Jhajara stream becomes narrow over 2.5 km stretch associated with the exposure of the Jhajara thrust. Stream channel widths are reduced to ~4–7 m in contrast to ~35–50 m upstream and downstream of the narrow stream reach (Figure 3b). There are some well-developed terraces (T1, T2) in this thrust-related reach (Figure 3b and c).

A semi-logarithmic plot of longitudinal stream profile (stream bed elevation vs length of the stream) developed by Hack is called as Hack profile. Hack also defined stream length gradient index (SL index) as the product of slope of a reach and distance from the headwater divide. This method is useful in identifying active fault zones present in the course of a river where the profile shows increase in slope and high SL index value. The Hack profile of the Jhajara stream shows two prominent, steep segments with high SL index values where it crosses the Surajpur and Barsar thrusts (intermontane valley mountain front; Figure 3d). The segment of the stream where it has relatively incised the valley and crosses the Jhajara thrust, does not show prominent break in slope; but this zone is bounded by two segments that have low SL index values (Figure 3d). This observation suggests that the stream has attained equilibrium and graded across the Jhajara thrust. Comparatively higher SL index values obtained to the south of the Jhajara thrust zone are related to the undated recent activity along the Pinjaur Garden Fault.

**Age constraint on the Jhajara thrust**

*Approach*

To place age constraints on the timing of the last tectonic activity along the Jhajara thrust, we performed optically stimulated luminescence (OSL) dating on quartz extracted from samples obtained from two different elevations of the Kalka surface (Figure 3e). The sample at the lower elevation was collected from the footwall of the Jhajara thrust, whereas that collected from the higher elevation covered the Jhajara thrust. Therefore, the lower sample age indicated the time when the fault was active, whereas the age of the upper sample indicated the time when the thrust became inactive. For OSL, medium-grained sand samples were taken from outcrops near Basdevpura village (Figure 1c).
Figure 3. a, Digital Terrain Model of study area showing various geomorphic elements and structures present. b, Photograph showing geomorphic elements in the field. Note the width of the stream (Jhajara stream) becomes narrow downstream. c, Photograph showing geomorphic elements further downstream of (b) in the Jhajara stream; d, Hack profile and step SL index curve of the Jhajara stream showing prominent breaks where the Barsar and Surajpur thrusts are present, and noticeable high SL index value where the Pinjaur Garden Fault is present. a and a’ mark the two low SL index values bounding the Jhajara thrust zone; e, Sketch of the Jhajara thrust and associated geomorphic elements. Location of samples used for OSL dating is marked.
The boulder beds are dominant where the thrust trace is seen cutting through the Kalka surface deposits (Figure 2a); the bottom sample was collected from a lensoid sand body occurring in the boulder beds. Towards the top, the Kalka surface deposits cover the thrust and some include relatively thick beds (~1 m) of sand; the second sample was collected from these sand beds (Figure 3e).

### OSL dating

For OSL dating quartz was extracted from within the 100–160 μm grain size fraction using H2O2 to remove the organic material, and 10% HCl to dissolve carbonates. The quartz-rich fraction was separated by heavy liquid (aqueous solution of sodium polytungstate) and then it was etched with 40% HF for 60 min to remove any remaining feldspar and the outer ~10 μm layer from the quartz grains; this removes any quartz which has absorbed a dose from alpha radiation in the surrounding sediments13,14. The clean quartz grains were mounted on stainless-steel discs in an 8 mm diameter monolayer using silicone spray. OSL measurements were made using a Risø TL/OSL automatic reader with a calibrated 90Sr/90Y beta source, delivering about 0.12 Gy/s to the quartz. The luminescence purity of the quartz extracts was checked using infrared stimulation. Blue light-emitting diodes were used for the optical stimulation of quartz for 40 s, at 125°C, pre-heat temperature being 260°C. A Single-Aliquot Regenerative-dose (SAR) protocol15–17 was used to estimate equivalent doses. Dose recovery tests, dose response growth curve and thermal transfer tests were measured for the samples. Equivalent doses (Di) are based on 25–28 aliquots per sample. The dose rates were calculated based on laboratory high resolution gamma spectrometry analyses (Camberra GC3020) of the sediment surrounding the OSL sample, using the conversion factors of Adamiec and Aitken18.

The dose-response curves show that dose measurements up to the applied 320 Gy are possible. Recuperation (R4/N%) is <1% in the measured aliquots, and recycling ratios vary from 0.9 to 1.1 in 93% of the measured aliquots. Dose recovery ratios are between 1.07 and 1.25. These three internal tests show that the applied protocol can accurately measure a known laboratory dose administered to these samples19. The equivalent doses are about 123 and 208 Gy; the dose rates are 2.2 and 3.1 Gy/ka calculated using the recent water content (Table 1). The samples are above the groundwater level. Sample KLK-1 is about 45 m above the recent river bed, while JSF-1 is 1.6 m above it (Figure 3e). Results of OSL dates are given in Table 1. OSL dating of fluvial sediments is sometimes problematic20–24. The sampling location lies ~8 km from the river head, and we presume effective resetting of the luminescence signal during transport and sedimentation.

### Results

The lower sample yielded an age of 67.6 ± 7.3 ka BP, whereas the upper sample yielded an age of 55.7 ± 6.0 ka BP. The younger age suggests that sedimentation over the Kalka surface possibly stopped at ~55.7 ± 6.0 ka BP, whereas the Jhajara thrust became inactive before this period (because topmost sediments of the Kalka surface covering the Jhajara thrust show no deformation).

### Development and significance of the Jhajara thrust

The Kalka surface was the first major geomorphic unit to be formed in the southeastern part of the Dun. The OSL dates suggest that the deposition of this surface started before ~67.6 ± 7.3 ka. The Jhajara thrust running parallel to the trend of the major faults broke through and brought the Lower Siwalik Subgroup rocks to the surface. These Lower Siwalik rocks are in contact with the Dun gravels, indicating that sedimentation in the Dun must have begun such that these Dun gravels show coeval deformation (Figure 2a). Activity along the Jhajara thrust stopped before ~55.7 ± 6.9 ka; the Pinjaur surface sediments and the Dun sediments overlying the Jhajara thrust in the SSE and NNW do not show any deformation, which supports the foregoing interpretations. Low SL index value and smooth Hack profile (Figure 3d) across the Jhajara thrust also suggests the absence of recent tectonic activity across this fault. But a relatively higher SL index value to the southwest of the Jhajara thrust zone related to the Pinjaur Garden Fault indicates tectonic activity. A trench study10 shows the Pinjaur Garden Fault to be dipping at ~30°, suggestive of a shallow dipping thrust. The Pinjaur Garden Fault has displaced both the Kalka surface and the Pinjaur surface, suggesting that the displacement before ~55.7 ± 6.0 ka was transferred on this imbricate in front of the Jhajara thrust, after which the Jhajara thrust became relatively inactive.

The geometry of the Jhajara channel shows a distinct change in behaviour between the Jhajara thrust and the

<table>
<thead>
<tr>
<th>Sample</th>
<th>Number of aliquots</th>
<th>Equivalent dose (Gy)</th>
<th>Dose rate (Gy/ka)</th>
<th>Water content (dry wt%)</th>
<th>OSL age (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KLK-1</td>
<td>28</td>
<td>123.1 ± 9.8</td>
<td>2.2 ± 0.2</td>
<td>13.6</td>
<td>55.7 ± 6.0</td>
</tr>
<tr>
<td>JSF-1</td>
<td>25</td>
<td>208.2 ± 15.9</td>
<td>3.1 ± 0.2</td>
<td>10.1</td>
<td>67.6 ± 7.3</td>
</tr>
</tbody>
</table>
Pinjaur Garden fault; the stream channel is narrow and incised. This change is necessitated in order to maintain its gradient across the irregularity caused due to uplift along the Jhajara thrust and the Pinjaur Garden Fault. This incision by the stream has caused the formation of terraces near the fault zone (here the term fault zone is used for the area between the Jhajara thrust zone and the Pinjaur Garden Fault; Figure 3 c and d).

On the other hand, another interesting observation made during this study was that the Surajpur fault trace when extended towards the NE, coincides with the trend of the Jhajara stream in the exposed fault zone (Figure 3 a). This gives rise to a possibility that a rupture along the Surajpur fault after the formation of the Jhajara thrust, could have uplifted the northwestern (or hanging wall) block of the Surajpur fault, that in turn affected the Jhajara thrust and its overlying topography; evidence of this is observed in the correspondence between the strike of the fault and the boundary of the Kalka surface (Figures 1 c and 3 a). A previous study that identified this fault in the outermost Siwalik hills has shown the older Tatrot Formation rocks on the northwestern (or hanging wall) block of the fault to be in contact with the younger Pinjaur Formation on the southeastern (or footwall) block. However, there are no field evidences to support this observation and more detailed analysis of the Surajpur fault will be required to establish this.

Conclusion

The Jhajara thrust is an important neotectonic feature occurring in the southeastern part of the Pinjaur Dun. Tectonic activity along this thrust occurred before 55.7 ± 6.0 ka and was later transferred on the Pinjaur Garden Fault; the stream channel is narrow and incised. This change is necessitated in order to maintain its gradient across the irregularity caused due to uplift along the Jhajara thrust and the Pinjaur Garden Fault. This incision by the stream has caused the formation of terraces near the fault zone (here the term fault zone is used for the area between the Jhajara thrust zone and the Pinjaur Garden Fault; Figure 3 c and d).

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