

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

Vimal Singh^{1,4,*}, S. K. Tandon¹, Vaibhava Singh^{1,5}, Malay Mukul² and Edit Thamó-Bozsó³

¹Department of Geology, University of Delhi, Delhi 110 007, India

²Centre for Mathematical Modelling and Computer Simulation, Bangalore 560 037, India

³Geological Institute of Hungary, H-1143 Budapest, Stefánia út 14.1443, Pf.106, Hungary

⁴Present address: Centre for Earth Sciences, Indian Institute of Science, Bangalore 560 012, India

⁵Present address: Shell Technology India Pvt Ltd, Bangalore 560 048, India

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 $\sim 55.7 \pm 6$ ka BP.

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

THE Himalayan orogenic belt (Figure 1a) 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 1b). 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 1c) 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 1b 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)², (2) Sirsa Fault (V. Singh, unpublished thesis; Singh and Tandon³), (3) Pinjaur Garden Fault^{2,4}, (4) Pinjaur Thrust^{5,6}, and (5) Barsar and Nalagarh thrusts^{5,7} (Figure 1c). 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 HFT^{8,9} 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 fault⁵ (Figure 1b 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 2a). 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 2a). Relict bedding planes preserved in brecciated rocks of the hanging wall dip moder-

*For correspondence. (e-mail: vimalgeo@gmail.com)

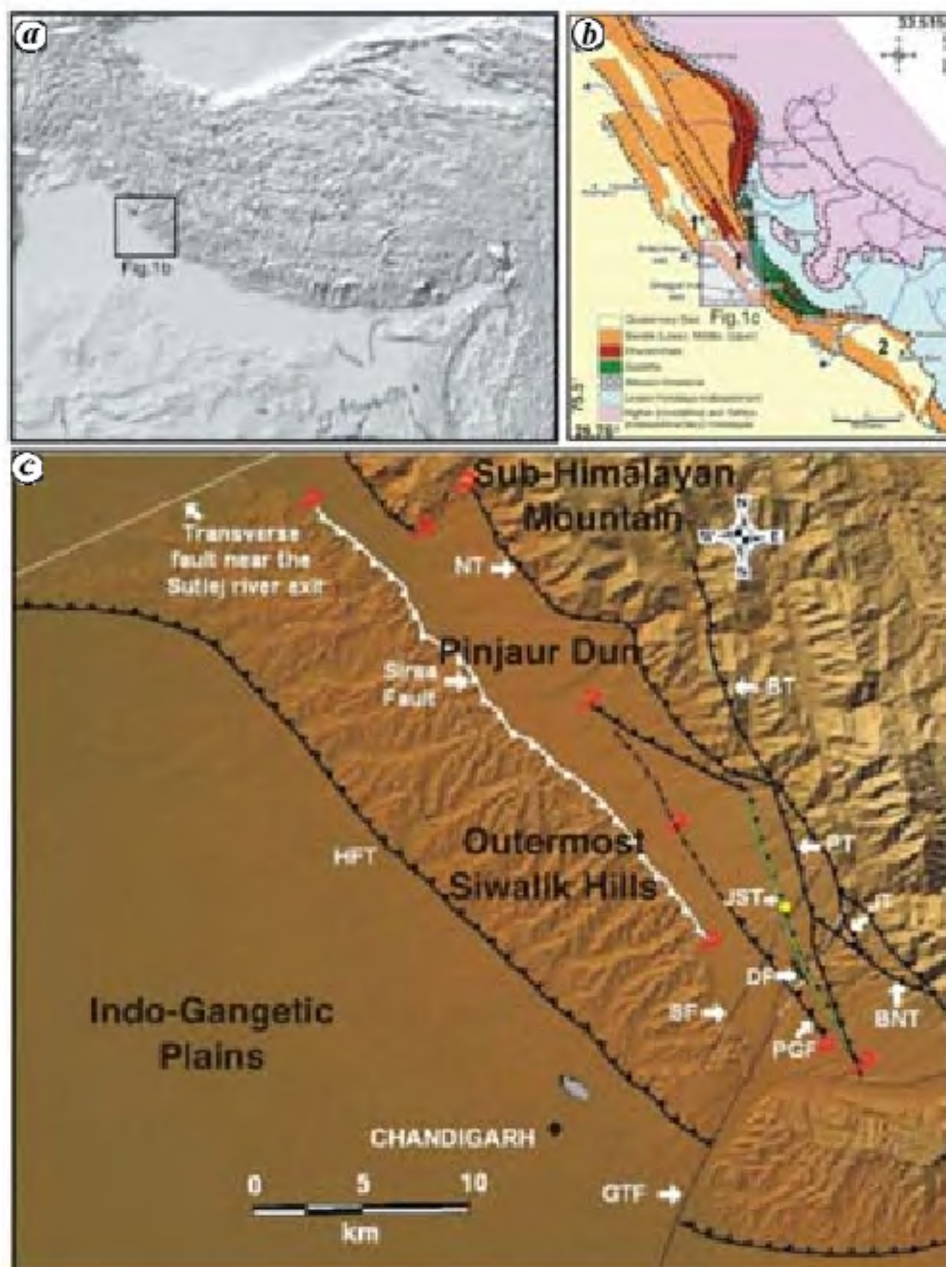


Figure 1. *a*, Synoptic view of the Himalayan arc (GTOPO-30). Box marks the relevant segment of the Himalayan front. *b*, Regional geological map of the area (after Raiverman *et al.*⁷). Box indicates area of study. 1, Pinjaur Dun (narrow part); 1', Pinjaur Dun (wide part) and 2, Dehra Dun. *c*, Structural map of the study area. Yellow dot shows the location of Basdevpura village. BT, Barsar Thrust; NT, Nalagarh Thrust; JT, Jaital Thrust; BNT, Batinan Thrust; PT, Pinjaur Thrust; JST, Jhajara Thrust; DF, Damdama Fault; PGF, Pinjaur Garden Fault; SF, Surajpur Fault; HFT, Himalayan Frontal Thrust; GTF, Ghaggar Tear Fault (V. Singh, unpublished).

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 2*b*). 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 workers². The Kalka, Pinjaur and Jhajulla surfaces are incised by the Jhajara stream (Figure 3*a* 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 3*a*). 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 3*a*). The stream flows over the Jhajulla surface near the intermontane valley mountain front (Figure 3*a*).

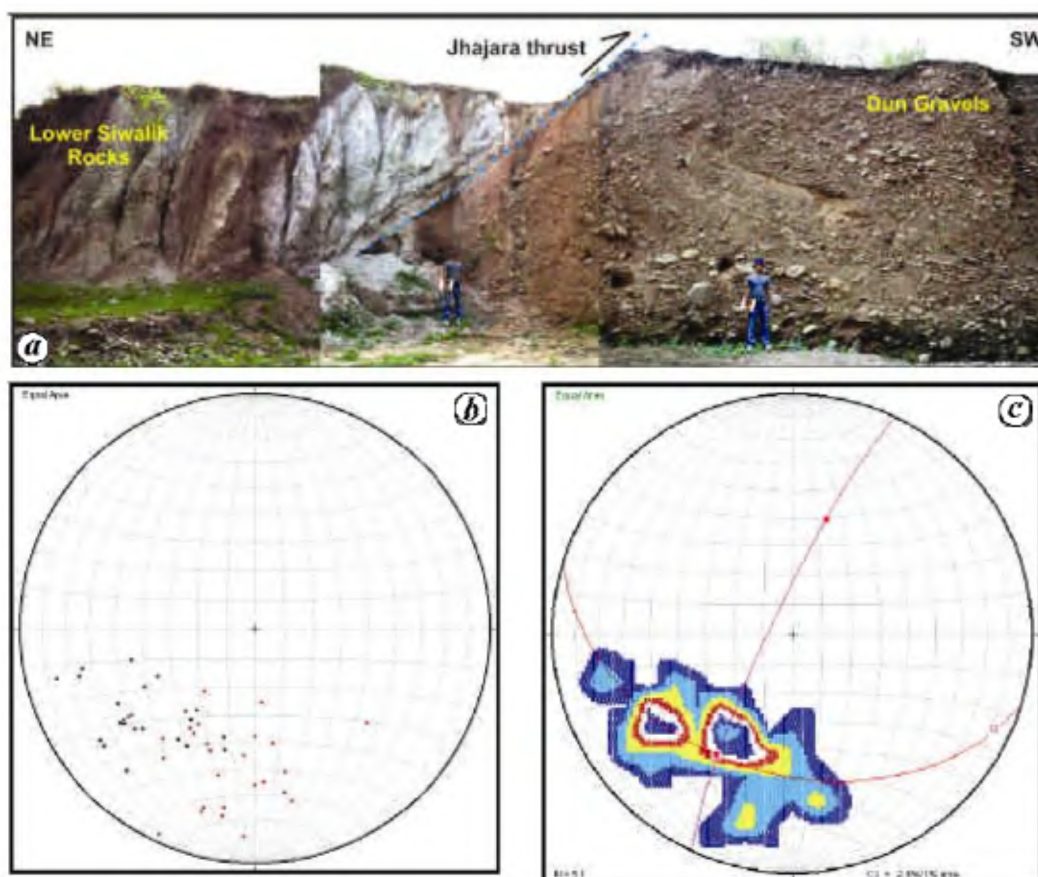


Figure 2. *a*, Photomosaic of the Jhajara Thrust; arrow shows direction of hanging wall movement. *b*, Equal area stereoplot of poles to bedding for bedrocks exposed in the Jhajara stream; black coloured dots represent right bank bedrocks and red ones represent left bank bedrocks in the Jhajara stream. and *c*, Equal area plot showing density of the poles to bedding. Red contours show high density, whereas blue ones show low density.

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 3 *b*). There are some well-developed terraces (T1, T2) in this thrust-related reach (Figure 3 *b* and *c*).

A semi-logarithmic plot of longitudinal stream profile (stream bed elevation vs length of the stream) developed by Hack¹¹ is called as Hack profile. Hack¹¹ 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 value¹². The Hack profile¹¹ 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 3 *d*). 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 3 *d*). 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 3 *e*). 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 1 *c*).

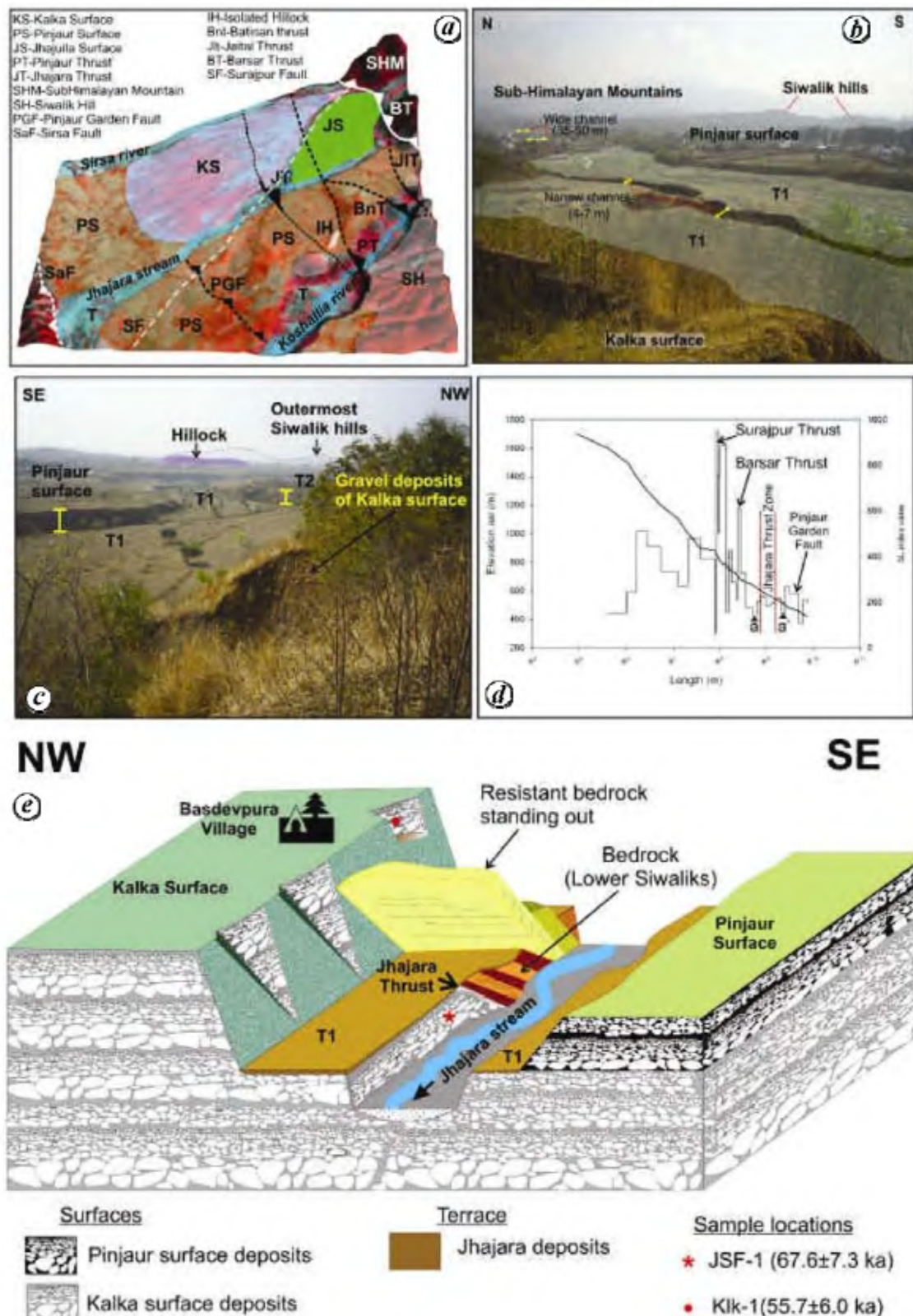


Figure 3. *a*, Digital Terrain Model of study area showing various geomorphic elements and structures present. *b*, Photograph showing geomorphic elements in the field. Note the width of the stream (Jhajara stream) becomes narrow downstream. *c*, Photograph showing geomorphic elements further downstream 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 2 a); 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 3 e).

OSL dating

For OSL dating quartz was extracted from within the 100–160 μm grain size fraction using H_2O_2 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 sediments^{13,14}. 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 $^{90}\text{Sr}/^{90}\text{Y}$ 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) protocol^{15–17} was used to estimate equivalent doses. Dose recovery tests, dose response growth curve and thermal transfer tests were measured for the samples. Equivalent doses (D_e) 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 3 e). Results of OSL dates are given in Table 1. OSL dating of fluvial sediments is sometimes problematic^{20–24}. 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 $\sim 55.7 \pm 6.0$ 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 $\sim 67.6 \pm 7.3$ 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 2 a). Activity along the Jhajara thrust stopped before $\sim 55.7 \pm 6.9$ 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 3 d) 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 $\sim 30^\circ$, 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 $\sim 55.7 \pm 6.0$ 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 1. Results of quartz OSL dating

Sample	Number of aliquots	Equivalent dose (Gy)	Dose rate (Gy/ka)	Water content (dry wt%)	OSL age (ka)
KLK-1	28	123.1 ± 9.8	2.2 ± 0.2	13.6	55.7 ± 6.0
JSF-1	25	208.2 ± 15.9	3.1 ± 0.2	10.1	67.6 ± 7.3

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 study⁵ 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 that has ruptured the Pinjaur surface (which is younger than 55.7 ± 6.0 ka).

- Heim, A. and Gansser, A., Central Himalaya Geological Observations of Swiss, 1939 (reprinted 1975), Hindustan Publishing Corporation, Delhi, pp. 1–246.
- Nakata, T., Geomorphic history and crustal movement of the foothills of the Himalaya, Report of Tohoku University Japan, 1972, 7th series (Geography), vol. 2.
- Singh, V. and Tandon, S. K., Evidence and consequences of tilting of two alluvial fans in the Pinjaur dun, northwestern Himalayan foothills. *Quat. Int.*, 2007, **59**, 21–31.
- Malik, J. N. and Nakata, T., Active faults and related Late Quaternary deformation along the Northwestern Himalayan Frontal Zone, India. *Ann. Geophys.*, 2003, **46**, 917–936.
- Sahni, M. R. and Khan, E., Tectonic features of the area around Pinjaur. *Curr. Sci.*, 1963, **32**, 77–79.
- Sahni, M. R. and Khan, E., Stratigraphy, structure and correlation of the upper Shivaliks east of Chandigarh. *J. Paleontol. Soc. India*, 1964, **4**, 61–74.
- Raiverman, V., Ganju, J. L., Ram, J. and Misra, V., Geological map of Himalayan foothills between Ravi and Yamuna rivers. Report, Oil and Natural Gas Commission, Dehradun, 1990.
- Malik, J. N., Nakata, T., Philip, G. and Virdi, N. S., Preliminary observations from a trench near Chandigarh, NW Himalaya and their bearing on active faulting. *Curr. Sci.*, 2003, **85**, 1793–1798.
- Kumar, S., Wesnousky, S. G., Rockwell, T. K., Briggs, R. W., Thakur, V. C. and Jayangondaperumal, R., Paleoseismic evidence of great surface rupture earthquakes along the Indian Himalaya. *J. Geophys. Res.*, 2006, **111**, B03304.
- Malik, J. N. and Mathew, G., Evidence of paleoearthquakes from trench investigations across Pinjore Garden fault in Pinjore Dun, NW Himalaya. *J. Earth Syst. Sci.*, 2005, **114**, 387–400.
- Hack, J. T., Stream-profile analysis and stream-gradient indices. *USGS J. Res.*, 1973, **1**, 421–429.
- Keller, E. A. and Pinter, N., *Active Tectonics: Earthquakes, Uplift and Landscape*, Prentice Hall, New Jersey, 2002, 2nd edn, p. 362.
- Aitken, M. J., *Thermoluminescence Dating*, Academic Press, London, 1985.
- Aitken, M. J., *An Introduction to Optical Dating. The Dating of Quaternary Sediments by the Use of Photon-stimulated Luminescence*, Oxford University Press, Oxford, 1998.
- Murray, A. S. and Wintle, A. G., Luminescence dating of quartz using an improved single aliquot regenerative-dose protocol. *Radiat. Meas.*, 2000, **32**, 57–73.
- Murray, A. S. and Wintle, A. G., The single aliquot regenerative dose protocol: Potential for improvements in reliability. *Radiat. Meas.*, 2003, **37**, 377–381.
- Murray, A. S. and Olley, J. M., Precision and accuracy in the optically stimulated luminescence dating of sedimentary quartz. *Geochronology*, 2002, **21**, 1–16.
- Adamiec, G. and Aitken, M., Dose-rate conversion factors: Update. *Ancient TL*, 1998, **16**, 37–50.
- Wintle, A. and Murray, A. S., A review of quartz optically stimulated luminescence characteristics and their relevance in single-aliquot regeneration dating protocols. *Radiat. Meas.*, 2006, **41**, 369–391.
- Clarke, M. L., Rendell, H. M. and Wintle, A. G., Quality assurance in luminescence dating. *Geomorphology*, 1999, **29**, 173–185.
- Wallinga, J., Optically stimulated luminescence dating of fluvial deposits: a review. *Boreas*, 2002, **31**, 303–322.
- Stokes, S., Bray, H. E. and Blum, M. D., Optical resetting in large drainage basins; tests of zeroing assumptions using single-aliquot procedures. *Quat. Sci. Rev.*, 2001, **22**, 879–885.
- Murray, A. S., Olley, J. M. and Caitceon, G. G., Measurement of equivalent doses in quartz from contemporary water-lain sediments using optically stimulated luminescence. *Quat. Sci. Rev. (Quat. Geochronol.)*, 1995, **14**, 365–371.
- Jain, M., Murray, A. S. and Boetter-Jensen, L., Optically stimulated luminescence dating. How significant is incomplete light exposure in fluvial environments? *Quaternaire*, 2004, **15**, 143–157.

ACKNOWLEDGEMENTS. We thank Drs A. K. Dubey, Senthil Kumar and the anonymous reviewer for their useful comments. We also thank Prof. Rajiv Sinha, Drs Annamária Nádor, Orsolya Sztanó and Árpád Magyari, Ms Edit Babinszki and Mr Sumesh for help during the OSL sample collection. Gamma spectrometry measurements were taken at the Eötvös Loránd Geophysical Institute of Hungary. The OSL dating was supported by Indo-Hungarian Bilateral Programme. V.S. thanks the University Grants Commission, New Delhi for providing Senior Research Fellowship. We also acknowledge the Department of Geology, University of Delhi for providing facilities and help in carrying out this work.

Received 23 April 2007; revised accepted 23 January 2008