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FIELD GUIDE

INPOST - 09

PALEO-EARTHQUAKE SIGNATURES – ACTIVE FAULT TOPOGRAPHY FROM NW HIMALAYA: A FIELD EXCURSION IN THE MESOSEISMAL ZONE OF 1905 KANGRA EARTHQUAKE – MW7.8, NW HIMALAYA

Javed N. Malik and Mahendrasinh S. Gadhavi







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Field Guide Book

INPOST-09

Paleo-earthquake Signatures – Active Fault Topography from NW Himalaya: A Field Excursion in the Mesoseismal Zone of 1905 Kangra earthquake – Mw7.8, NW Himalaya

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Table of Contents

1.	Team Leaders	1
2.	Abstract	2
3.	Preamble	3-6
4.	Research Problem	7
5.	Regional Geology	8-10
6.	Flora, Fauna, Climate and Weather Conditions	10
7.	Kangra Earthquake (Mw 7.8)	11-14
8.	Field Transect	15-16
9.	Field Map showing road and excursion stops	16
10.	Location(s) Description	17-32
11.	Geoheritage, UNESCO Heritage, Archaeological sites in the vicinity	33-63
12.	Local Conveniences	63-64
13.	Conclusion	64-65
14.	References	66
15.	Annexure	67-68

Team Leaders



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Prof. Javed H N Malik, at the Department of Earth Sciences, IIT Kanpur, is the foremost researcher in the fields of Active Fault Mapping, Paleoseismology, Paleo-tsunami and Archaeological studies in India. His work has led to identification of several new faults namely the Kangra Valley Fault; Taksal Fault, Pinjore Garden Fault, and Hajipur Fault in the Himalayan region. He was first to report active faults along the Kachchh Mainland and South Wagad from Gujarat. Also, identified evidence of several large-magnitude paleo-earthquakes that occurred in Himalaya during the historic period, and signatures of several mega-thrust earthquakes and associated seven transoceanic tsunamis from coastal stratigraphic records in Andaman. He is a recipient of National Geoscience Award in Disaster Management; S. S. Merh Award in Quaternary Geology; Young Muslim Scientist Award; B. B. Lal, Endowment Chair Professor for Archaeology (twice); Excellence in Teaching Award and is Fellow of Indian National Science Academy.



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Dr. Mahendrasinh Gadhavi is a geologist and academic specializing in structural geology, active tectonics, active fault mapping, and paleoseismology, with over two decades of field and research experience. His work has focused extensively on the Kachchh region and the Himalayan tectonic belt, contributing to several nationally funded active fault and seismic hazard investigations. He has substantial expertise in identifying and characterizing active faults through integrated geomorphic, structural, remote sensing, GIS, and field-based investigations. A key strength of his work is paleoseismic trench investigation and interpretation, including recognition of fault-related deformation, stratigraphic relationships, and earthquake-induced sedimentary and structural features preserved in trench exposures. His research contributes directly to understanding past earthquake chronology, fault segmentation, surface rupture, and seismic hazard assessment in India.

Abstract

The mighty Himalaya, marked in Zone-V of Indian Seismic Zonation Map is the best example of a continent-continent collision between the Indian and Eurasian plates. Moderate-to-large-magnitude earthquakes along the Himalayan arc is testimony to this ongoing deformation. The most notable large magnitude earthquakes those shock the Himalaya and its neighborhood during historic and recent past are namely the 1555 Kashmir (Mw7.6-8.0), 1505 Kumaon-Nepal (Mw8.7), 1803 Kumaon (Mw7.5), 1883 Nepal (Mw7.7), 1905 Kangra (Mw 7.8), 1934 Bihar-Nepal (Mw 8.4), and 1950 Assam (Mw8.7).

The excursion is aimed to showcase the exceptionally beautiful landscape and hazard potential of the mighty Himalaya. The journey begins from the Indian Plate (Indo-Gangetic Plain) climbing up to the Eurasian Plate – after seeing the present plate boundary of one of the most seismically active zones of the world – The Himalaya. We propose to show you the active fault topography along the frontal as well as hinterland active faults – the Himalayan Frontal Thrust (HFT), Pinjore Garden Fault (PGF), the Khetpurali-Taksal Fault (KTF), and the Kangra Valley Fault (KVF). Paleoseismic trench would be one of the attractions to see the signature of paleo-earthquake, along with a visit to look the seismic imprints preserved in historical architecture of the Baijnath Temple and the Kangra Fort.

Preamble

The mighty Himalaya, stretching east to west over a length of 2500 km in an arc-shaped landscape, is the best example of a continent–continent collision between the Indian and Eurasian plates. Underthrusting of the Indian plate resulted in development of several roughly east–west and northwest–southeast-trending fault zones (Fig. 1a, 2). Ongoing convergence between the Indian and Eurasian plates makes the Himalayan arc one of the most seismically active regions in the world. Occurrence of moderate-to-large-magnitude earthquakes along the arc is testimony to this ongoing deformation (Fig. 1a–b, 2). In the last 500 years the Himalayan region was shaken by several moderate to large magnitude earthquakes ranging from 6.5 ≥Mw ≤8.7, namely the 1555 Kashmir (Mw7.6–8.0), 1505 Kumaon-Nepal (Mw8.7), 1803 Kumaon (Mw7.5), 1883 Nepal (Mw7.7), 1905 Kangra (Mw 7.8), 1934 Bihar-Nepal (Mw 8.4), 1950 Assam (Mw8.7), 1991 Uttarkashi (Mw6.8); 1999 Chamoli earthquake (Mw 6.7), along with recent 2005 Muzaffarabad (Mw 7.6), 2015 Gorkha (Mw 7.8) and Kodari (Mw 7.3) in Nepal and 2015 Afghanistan (Mw7.5)(Malik et al., 2015; Bilham, 2020; Wesnousky, 2020) (Fig. 1a). According to Indian Seismic Zone Map, the Himalayan region falls under seismic zone V, which is the most vulnerable to large magnitude earthquakes with strong ground shaking. Being such a vulnerable region in Indian subcontinent the earthquake catalogue is rather incomplete. Therefore, due to non-availability of this information a proper appraisal of seismic risk and hazard for Himalaya is extremely difficult.

In Himalayan region most of the studies carried out were focused on identification of neotectonic and active tectonic signatures and in understanding the ongoing crustal deformation (Nakata, 1989; Valdiya, 1992; Wesnousky et al., 1999; Malik and Nakata, 2003, Singh and Tandon, 2010). No appropriate map showing precise locations of active faults and details of paleoseismic events were available. Our research team under a research project supported by the Ministry of Earth Sciences (MoES), New Delhi – has prepared a detailed Atlas of Active Fault Map for Central and Northwest Himalaya.

In the last two decades, several paleoseismic studies along the frontal zone of the Himalayas from India, Pakistan, Nepal, and Bhutan have provided significant information on the occurrence of earthquakes in the Himalayan region. Barring a few from Northwest (Kashmir-Punjab-Himachal) Himalayas, most of these paleoseismic studies are confined to Central (Kumaon-Nepal) and Northeast (Assam) Himalayas. Based on the available earthquake data (limited historical and recent), it is rather clear that Central and NE Himalayas have hosted more earthquakes compare to the NW Himalaya. Further, apart from variation in earthquake occurrence, the disparity in tectonic deformation is well reflected by the westward reduction in GPS convergence rates from 21± 2 mm/year in Central to 13.3 ± 1.7 mm/year in NW Himalaya (Banerjee and Bürgmann, 2002; Banerjee et al., 2008; Stevens and Avouac, 2015).

With the exponential increase in population and infrastructure development along the Himalayan front and around the Indo-Gangetic Plain, several concerns are raised about estimating seismic hazard (Malik et al., 2015; Dal Zilio et al., 2021). The current population scenario suggests that the death toll estimates may exceed 100,000 from a large-magnitude earthquake in Himalaya (Wyss, 2005; Bilham, 2020).

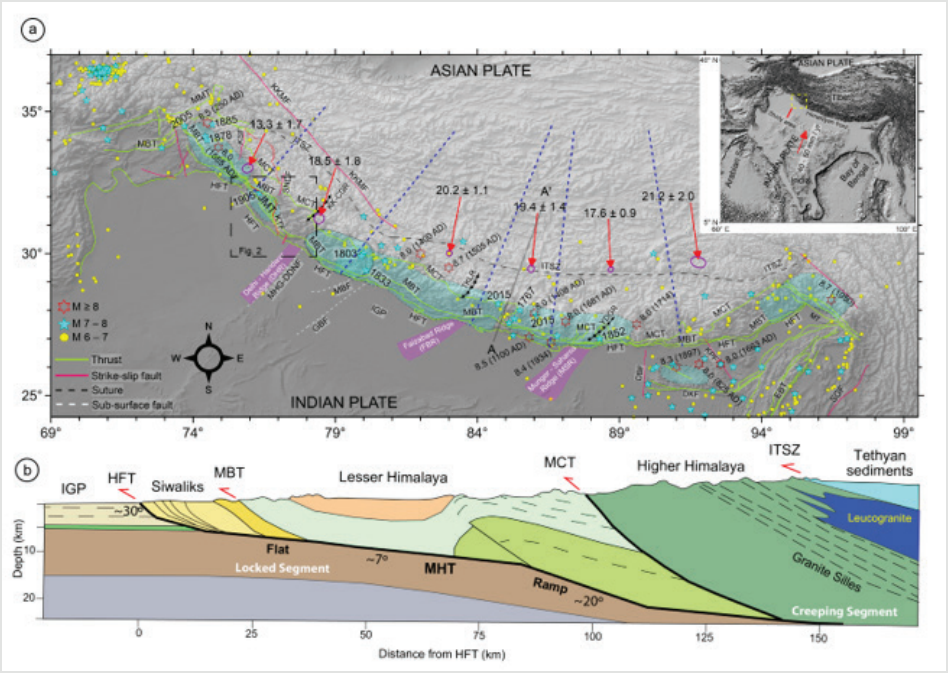


Fig. 1: (a) Locations of significant historical and recent large-magnitude earthquakes in the Himalaya and its neighborhood with major fault systems. The inferred extent of fault ruptures during 1505 (Mw 8.7), 1555 (Mw 7.6), 1905 (Mw 7.8), 1934 (Mw 8.4) are shown by light blue colour shaded portion with a dashed line (after Ambraseys and Bilham, 2000; Ambraseys and Douglas, 2004; Bilham and Ambraseys, 2005; Hetényi et al., 2016a; Bilham 2020; Coudurier-Curveur et al., 2020). Red stars - the location of great earthquakes Mw ≥ 8 with the magnitude and year of occurrence. Cyan stars - location of major earthquakes with Mw 7-8. Yellow dots - earthquakes since 844 CE with Mw 6-7 [Data source: IMD, IRIS, ISC, NGDC, and USGS]. Red arrows indicate GPS velocities in different regions along the Himalayan arc. Dashed black lines mark the separation from other areas with the variation of velocities (after Stevens and Avouac, 2015). Purple polygons show the subducting/under-thrusting basement ridges. Abbreviations – ITSZ: Indus-Tsangpo-Suture Zone; MCT: Main Central Thrust; MBT: Main Boundary Thrust; HFT: Himalayan Frontal Thrust (also referred as MFT: Main Frontal Thrust); MMT: Mishmi Thrust; MMT: Main Mantle Thrust; JMT: Jawalamukhi Thrust; SNDF: Sundarnagar Fault; KTF: Khetpurali Taksal Fault; KSF: Kishtwar Fault; EBT: Eastern Boundary Thrust; KPF: Kopilli Fault; DBF: Dhubri Fault; DKF: Dauki Fault; SGF: Sagaing Fault; KKMF: Karakorum Fault; IGP: Indo-Gangetic Plain; GBF: Great Boundary Fault; MBF: Moradabad Fault; MHG-DDNF: Mahendragarh-Dehradun Fault; MSR: Munger-Saharsa Ridge; KK-CGR – Kaurik-Chango Rift; TKLR - Thakola Rift and YDGR - Yadong Rift [basement ridges after Rao Ramachandra, 1973; Sastri et al., 1971; and faults after Dasgupta et al., 2000], (b) North-South geologic section across the Central Himalaya, (adopted from Elliott et al., 2016). Section location marks A–A' line in Fig. 1a.

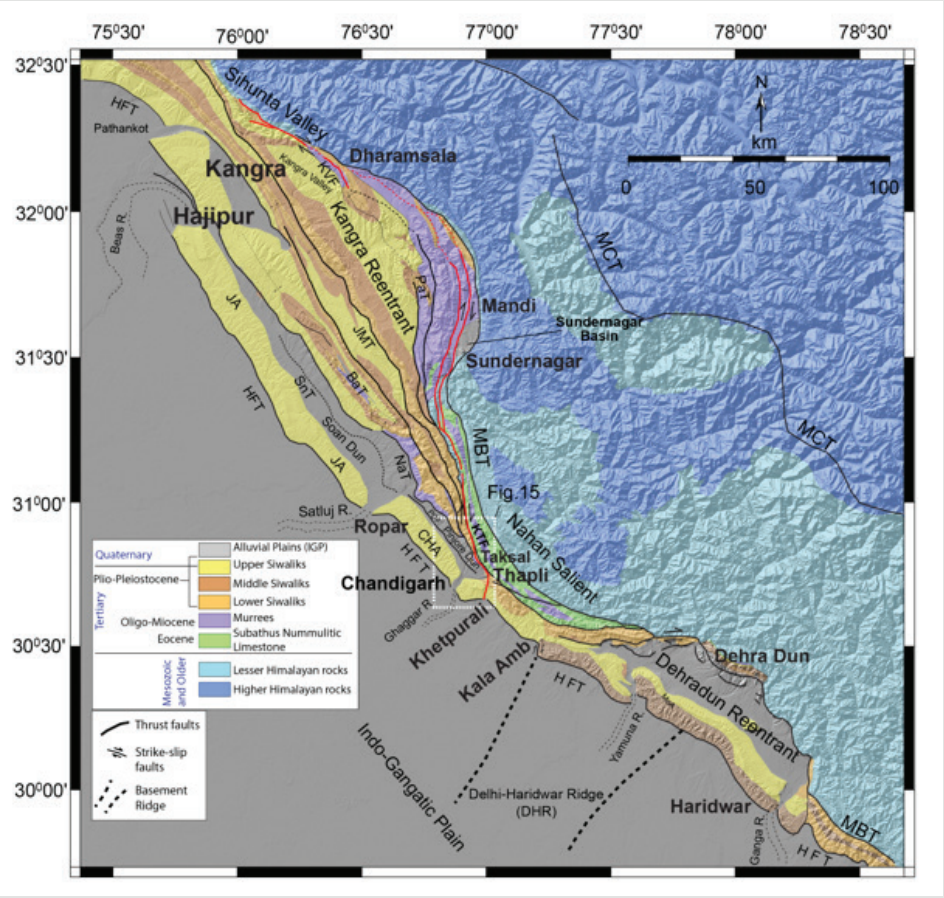


Fig. 2: Generalized geology of the area overlayed on the shaded-relief map. The map shows fault distribution around Nahan Salient, Dehra Dun, and Kangra re-entrants. Bold dashed lines mark the probable location of Delhi-Haridwar Ridge (DHR). This basement ridge striking NNE-SSW with respect to the under-thrusting Indian Plate beneath Tibetan Plate and Himalayan arc is responsible for changing the structural pattern in the Central and NW Himalaya. The Khetpurali-Taksal Fault (KTF - marked by bold red lines) system running for ~250 km south of Main Boundary Thrust demarcate the segment boundary between NW and Central Himalaya. The surface trace (active fault) of KTF with prominent right-lateral component strikes NNE-SSW near the frontal portion displacing Sub-Himalaya (Upper Siwaliks), takes a turn to NNW-SSE near Thapli village, and merge with Taksal Fault. Further, it passes through Sundernagar Basin near Sundernagar and Mandi and joins Kangra Valley Fault (KVF) in Kangra re-entrant. HFT - Himalayan Frontal Thrust; KTF - Khetpurali Taksal Fault; PGF - Pinjore Garden Fault; NaT - Nahan Thrust; SnT - Soan Thrust; JMT - Jawalamukhi Thrust; BaT - Barsar Thrust; KVF - Kangra Valley Fault; MBT - Main Boundary Thrust; MCT - Main Central Thrust. JA - Janauri Anticline; CHA - Chandigarh Anticline; MoA - Mohand Anticline. A white box with a broken line marks the location of Fig. 15.

The reason/s for the non-uniform distribution of convergence rates and occurrence of earthquakes along the Himalayan arc are not well understood, also the extent of possible surface ruptures of major paleo-earthquakes from paleoseismic trenches are debatable. An average repeat interval of 500–1000 years for major earthquakes has been inferred in Himalaya (Wesnousky, 2020). Moreover, a few paleoseismic studies from NW Himalaya have revealed that the recurrence is not systematic, and earthquakes have occurred with shorter intervals of 100–300 years (Malik et al., 2010a, 2015, 2017). Moreover, larger coseismic slips (≥ 9.3 m < 13 m) from the Central and NW Himalaya have been inferred for a single event (Wesnousky, 2020), where the slip exceeding 10 m imply earthquakes with moment magnitudes of Mw ≥ 8.5 (Bilham, 2020). Further the recent earthquakes, i.e., the 2005 Muzaffarabad earthquake (Mw 7.6), which occurred along an identified Balakot–Bagh active fault in Pakistan (Nakata et al., 1991), and 2015 Gorkha earthquake in Nepal have raised several questions towards the Seismic Hazard Assessment (SHA) in and along Himalayan region.

In last two decades ~42 paleoseismic studies have been conducted, but most of these are confined to the frontal part Himalaya only. No efforts were made to study the hinterland side to identify active faults and to know the paleoseismic history. Also, no attempt was made to identify or locate the 1905 Kangra (Mw7.8) earthquake; however, it has been suggested that the probable rupture could be along Jawalamukhi Thrust (JMT) located about 22 km from the Kangra Valley the epicentral zone of 1905 event.

The proposed field excursion forms a part of NW Himalaya where thrust and fold-belts are distributed in a 100 km wide zone between Himalayan Frontal Thrust (HFT) and Main Central Thrust (MCT)(Fig. 2). The area comprises splays of imbricated north dipping thrust faults, viz. SnT (Soan Thrust), NaT (Nalagarh Thrust), BaT (Barsar Thrust) and the JMT (Jawalamukhi Thrust). It has been suggested that not only HFT is active, but also the hinterland faults have shown signatures of recent tectonic movements (Malik and Mohanty, 2007). Based on recent paleoseismic investigation along HFT it is suggested that out of the 14±1 mm/yr of convergence (GPS measurement, Banerjee and Burgmann, 2002) across 100 km wide zone in NW Himalaya almost half i.e., 7.6±1.7 mm/yr is consumed by HFT, and rest is consumed by the faults in the hinterland side (Malik et al., 2010a).

The field excursion would cover seeing active fault scarps along HFT, Pinjore Garden Fault (PGF), Khetpurali Taksal Fault (KTF), and Kangra Valley Fault (KVF) (Fig. 2). We propose undertake a detailed field visit looking at active fault scarps, offset of streams and terrace risers, and active fault topography along the KVF. We also plan to open-up a paleoseismic trench to showcase the deformation in young Quaternary stratigraphy revealing the past seismic events.

Research Problem

Understanding how large continental faults accumulate and release strain remains one of the foremost challenges in earthquake science. Although significant advances have been made through geodesy, seismology, remote sensing, and numerical modeling, major uncertainties persist regarding the spatial distribution of crustal deformation, earthquake recurrence, fault segmentation, rupture propagation, and strain partitioning within active mountain belts. The Himalayan arc exemplifies these challenges, where several great historical earthquakes have occurred, yet the geometry of active faults, the role of hinterland structures, and the interaction between frontal and out-of-sequence faults remain poorly constrained. These knowledge gaps hinder robust seismic hazard assessment, particularly in densely populated regions where future large earthquakes pose substantial societal risks.

The Northwest Himalaya represents one of the least understood regions of the Himalayan collision zone. While numerous paleoseismic investigations have focused on the HFT, comparatively little attention has been given to active hinterland structures such as the PGF, KTF, JMT, and KVF. Consequently, fundamental questions remain unresolved regarding how deformation is partitioned between these fault systems, how ruptures propagate across structural segments, and whether historical events such as the 1905 Kangra earthquake involved blind, frontal, or hinterland faulting.

The proposed field transect is unique because it provides a continuous geological cross-section across one of the world's most active continental collision zones, extending from the Indo-Gangetic Plain to the Higher Himalaya. Unlike conventional field excursions that focus on isolated localities, this transect integrates observations across multiple active tectonic domains, allowing participants to examine the complete tectonic architecture from the Himalayan Frontal Thrust through major hinterland fault systems to the Kangra Valley. The excursion combines active fault scarps, displaced river terraces, offset stream channels, fault-controlled geomorphology, paleoseismic trench exposures, and historically damaged monuments affected by the 1905 Kangra earthquake within a single, coherent framework. This rare combination enables direct linkage between long-term landscape evolution, Quaternary deformation, paleoseismic records, and documented historical earthquakes.

Equally important, the transect demonstrates how multidisciplinary approaches—including tectonic geomorphology, high-resolution topographic mapping, paleoseismology, Quaternary stratigraphy, geochronology, and historical earthquake archaeology—can be integrated to reconstruct earthquake histories and fault evolution. The opportunity to observe active fault topography together with paleoseismic trench exposures and earthquake-induced damage preserved in heritage structures provides an exceptional natural laboratory for understanding the complete earthquake cycle. As such, this field transect offers insights that extend well beyond the Himalaya and are directly applicable to active continental collision zones worldwide, including the Alps, Zagros, Andes, Taiwan, and New Zealand, where similar questions concerning fault interaction, strain partitioning, and seismic hazard remain active areas of research.

Regional Geology

The pioneer work by Gansser, (1964); Ranga Rao, (1972); Valdiya, et al. (1984); Valdiya, (1980, 1992, 1999); Thakur, (1993); Powers et al. (1998), have added considerable knowledge towards understanding the geology and tectonic setup of NW Himalaya. Powers et al. (1998) gave a detailed picture of NW Himalaya on the basis of surface and sub-surface geology, oil-well, seismic reflection survey and magneto-stratigraphic data. The stratigraphic succession of the region which depicts a better understanding of the different formations, and their characteristic lithologic composition is given in Table 1. The area comprises a complete sequence of Paleozoic, Mesozoic and Tertiary rocks (Fig. 3).

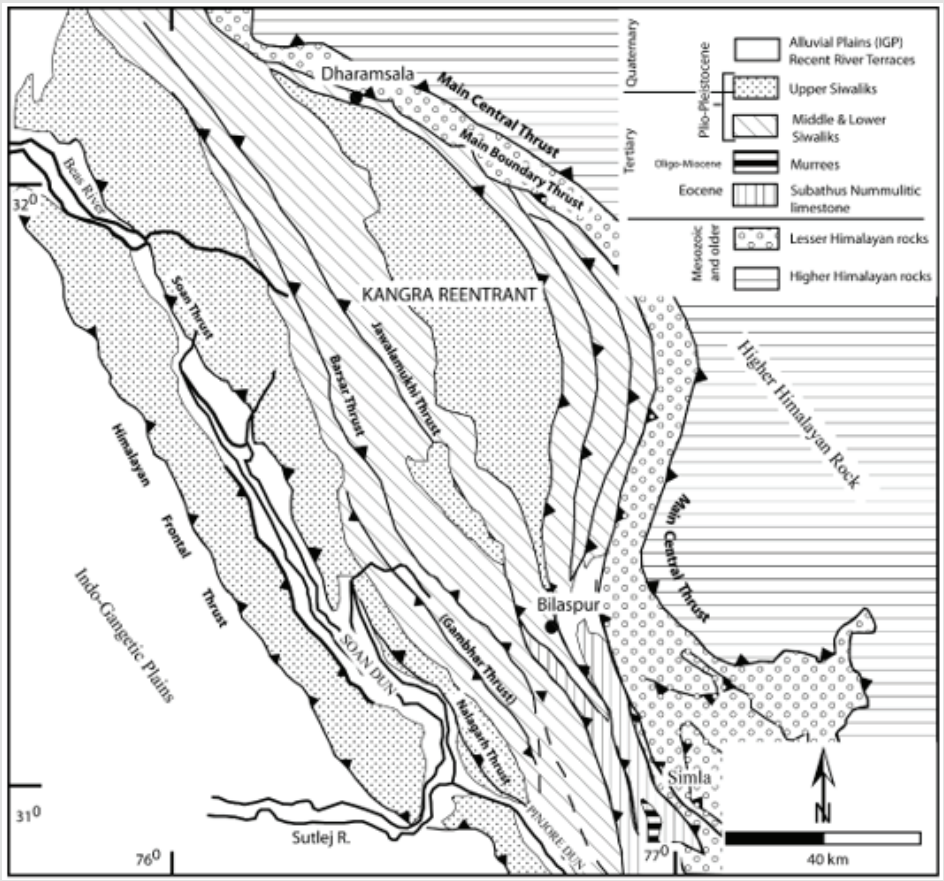


Fig.3: Generalized geological map of northwestern Himalayan Front around the Kangra Re-entrant [adopted from Malik and Mohanty, 2007] (structural and geological details after Gansser, 1964; Valdiya et al., 1984; Powers et al., 1998).

The field transects form the part of Kangra Re-entrant where the thrust faults and associated folded ranges are distributed in a 100 km wide zone between the HFT and the MCT, comprising several splays of imbricated faults (Fig. 2). The region can be divided into two main tectonic belts: the Main Himalayan Belt and the Frontal Folded belt, separated by MBT (Kumar et al., 1989). In this area the MBT shows a prominent change in strike, marked by sinuous pattern with variable strike of Reentrant known as Kangra recess. Along the NW part, the width of the Sub-Himalaya varies with formation of wide synclinal valleys (Duns) at different locations. Dubey et al., (2004) have proposed a model for the structural evolution of the Kangra Reentrant based on the structural style complemented by magnetic and petro-fabric strain studies. The stages are (1) Initiation of fractures, (2) Extension phase, (3) Compression phase, and (4) Superposed deformation. They have concluded that the Kangra Reentrant is a combination of frontal and oblique ramp structure. The Kangra Reentrant displays fault-propagation folds and fault-bend folds (Powers et al., 1998). From the stratigraphic and structural evidence, it has been suggested that The Main Boundary Thrust (MBT) was formed as normal fault during extensional phase before the Himalayan orogeny and it got reactivated as a thrust fault during the Tertiary Himalayan orogeny.

Table 1: Different Stratigraphic formations in the NW Himalaya (after Powers et al., 1998)

Age	Formation	Description
Pleistocene	Neogal	Conglomerates of plains and duns; river terraces and glacio-fluvial deposits of foothills
Pliocene-Pleistocene	Upper Siwalik	Conglomerate with increasing sandstone away from MBT; some calcite cementation; clay and silt stones
Miocene-Pliocene	Middle Siwalik	Sandstone with minor claystone; conglomerate prominent close to MBT; appearance of Kyanite as marker
Miocene	Lower Siwalik	Alternations of sandstone and claystone with minor silt stone and pebble horizons
Miocene	Upper Dharamsala	Greenish gray sandstone with minor claystone
Oligocene	Lower Dharamsala	Purple clay and siltstone with minor sandstone
Paleocene-Eocene	Subathu Group	Red and green nummulitic shale, minor limestone and sandstone
Cretaceous-Paleocene	Singtali Formation	Limestone
Cambrian	Vindhyan Group	Sandstone, siltstone and limestone, some weekly metamorphosed
Pre-Cambrian	Delhi-Aravali Groups	Calc and garnet schist, arkosic sandstone,and marble

The faults like SnT (Soan Thrust), NaT (Nalagarh Thrust), BaT (Barsar Thrust), PaT (Palampur Thrust) and the JMT (Jawalamukhi Thrust) show great significance in the evolution of the area (Kumar and Mahajan, 2001) and have played an important role in shaping the present complex landscape of the NW Himalaya (Malik and Mohanty, 2007). It has been suggested that the 1905 earthquake rupture corresponds to the Jawalamukhi Thrust (JMT, Fig. 2) and that the slip was never transferred to the HFT (Wallace et al., 2005). In this region, the MCT, MBT and PaT follow the shape of the re-entrant whereas other prominent faults like HFT and the secondary faults: SnT, NaT, BaT, and JMT show NNW-SSE trend, parallel to the Himalayan arc. Based on the morphometric analysis, it has been suggested that not only the HFT, but all these hinterland faults are also active (Malik and Mohanty, 2007).

Flora, Fauna and Climate, weather conditions

The state is home to dense forests of Deodar, Oak, and Pink Rhododendron, as well as alpine meadows adorned with exquisite flora like the Brahma Kamal, a rare and sacred flower. Its fauna is equally captivating, featuring the elusive Snow Leopard, the vibrant Himalayan Monal, and the critically endangered Western Tragopan, which holds the honor of being the state bird. With its vast altitudinal range—from verdant valleys to towering snow-capped peaks—Himachal Pradesh stands as a sanctuary for ecological diversity, blending natural beauty with environmental significance.

The field visit area forms a part of Kangra Re-entrant, NW Himalaya. It covers the survey of India toposheets no. 52 D/3, 52 D/4, 52 D/8 and 52 D/12, encompassing the areas around Sihunta (Chamba), Dharamsala, Kangra and Palampur (Kangra) of Himachal Pradesh, India. The area is thickly populated with a population of ⊠1,500,000. Beas River forms the major drainage system in the valley. The present study area is drained by a numerous major and minor streams, locally known as “Khads”, which are sourced from Higher Himalayas in north - the Dhauladhar range. The climate of the valley is sub-tropical. The Dhauladhar range which marks the northern boundary of the valley is an important agent affecting the climate of the region. The valley receives an average annual rainfall of about 1800-3000 mm. Most of the rainfall, about 80%, is received during June to September months. During winters the temperature drops down to freezing point resulting in snowfall in northern parts around Dharamsala, Palampur and Baijnath areas. The mean annual temperature of the valley ranges from 13° to 20° C. Tectonically the study area is very active as it falls under Zone V and has experienced a large magnitude earthquake 1905 Kangra (Mw 7.8). Besides 1905 Kangra earthquake, several small to moderate magnitude earthquakes with magnitude $4.5 \geq M \leq 5.5$ have been recorded during 1968, 1978 and 1986 from this region (Kumar and Mahajan, 2001). This indicates that the Kangra-Dharamsala area has high level of seismic activity due to ongoing deformation.

Kangra Earthquake (Mw 7.8)

The April 4, 1905, Kangra earthquake (Mw 7.8) was the most devastating Himalayan earthquakes in the recent geologic past. This earthquake in Himachal Pradesh killed 20,000 lives and destroyed 100,000 buildings (Ambraseys and Bilham, 2000, Figs. 4-6). This event was felt over a wide area extending about 300 km from Kangra to Dehradun. Two distinct areas: one extending eastward from Kangra to Mandi and Kulu, and the Dehradun area were affected by the 1905 earthquake (Thakur et al., 2000). The area surrounding Kangra felt a maximum intensity of X (Middlemiss, 1910, Quittmeyer and Jacob, 1979).

Recent study by Malik et. al., 2015 reveals that the surface rupture associated with 1905 Kangra earthquake was not along JMT, however, it ruptured through the meizoseismal zone of Kangra Valley.

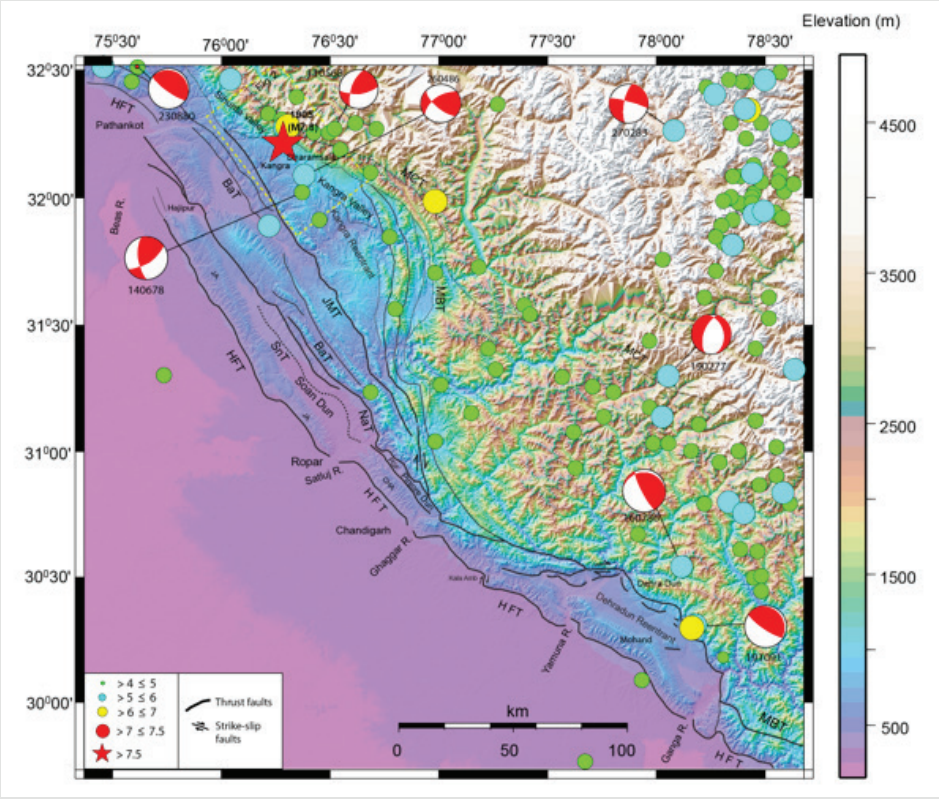


Fig. 4: Distribution of earthquakes around Dehra Dun and the Kangra region. Focal plane mechanisms around Kangra are of the Dharamsala earthquakes that occurred in 1968, 1970, and 1986. The earthquakes of 1968 and 1978 are marked by prominent left-lateral strike slip with oblique component, whereas the 1986 event shows right-lateral strike-slip motion (Kumar and Mahajan, 2001). Other focal mechanisms are from the Global Centroid Moment Tensor catalog.



Fig. 5 (a-f): Photographs showing the damage after the 4th of April 1905 earthquake. a) McLeodganj, Dharamsala. b) Barjeswari temple, Kangra c) Area below Kangra Bhawan after earthquake d) Bazar Dharamsala e) Palampur market after earthquake f) Chari village near Dharamsala after earthquake. (Image by Middlemiss, C.S. Courtesy Collection "Earthquake Engineering Research Center and Memoirs of the GSI, Volume XXXVIII, 1910).

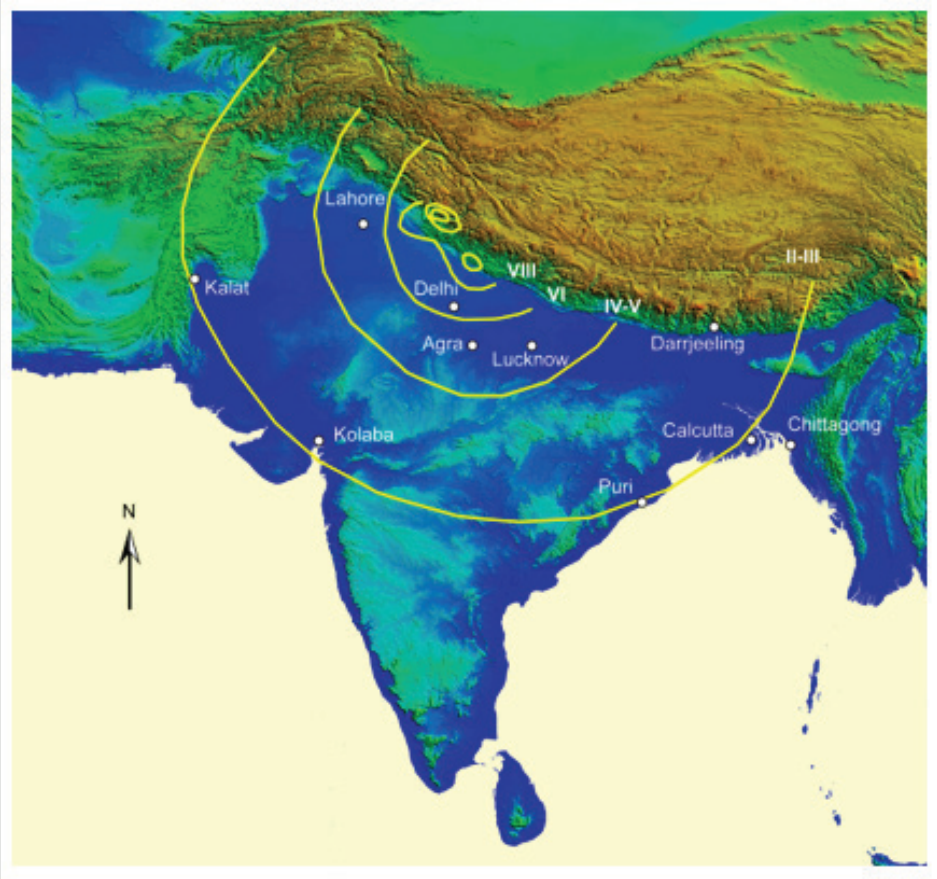


Fig. 6: Rossi–Forel isoseismal contours of 1905 Kangra earthquake (Redrawn from Ambraseys and Bilham, 2000).

The occurrence of the 1905 great Kangra earthquake and other moderate earthquakes in this region resulted in shortening structures and transverse strike slip faults due to convergence of Indian plate at the Indus-suture zone, in making the region highly seismic (Kumar and Mahajan, 2001).

However, since there was no surface rupture of the main frontal thrusts associated with 1905 Kangra earthquake, it is possible that a larger magnitude earthquake may be necessary to cause this slip (Wesnousky et al., 1999). It has also been suggested that the 1905 earthquake rupture corresponds to the Jawalamukhi Thrust (JMT) and that the slip was never transferred to the HFT (Wallace et al., 2005). Whereas Yeats and Lillie (1991) suggested that the 1905 Kangra earthquake occurred on a blind thrust. On the basis of repeat precision leveling Chander (1987) analyzed the elevation changes by the 1905 Kangra earthquake and it was suggested that the rupture causing the Kangra earthquake was concealed. Recent

micro-earthquake studies especially in the meizoseismal zone suggest that, although, the stress was released during 1905 event, high stress concentration still exists in this region (Kayal, 2001). Further built-up of inter-seismic strain may still trigger large magnitude earthquakes (Thakur et al., 2000). Indeed, the magnitude of the 1905 event has been reevaluated from Mw 8 to Mw 7.8 (Ambraseys and Bilham, 2000), suggesting that most of the portion of the western Himalayan arc has remained un-ruptured during the historic past (Ambraseys and Bilham, 2000). The location of the 1905 Kangra earthquake is in the domain of the MBT fault system, and probably did not result into surface ruptures along the HFT located 100 km to the southwest of the epicentral area. As in aforesaid text a probable location of the rupture of 1905 earthquake could be along JMT. If this is acceptable then, it can be suggested that the frontal fault/s still have potential to produce a large magnitude earthquake in near future.

The area is now thickly populated with a population of ≥1,500,000 (Fig. 7), so if similar magnitude earthquake occurs in future, it would be extremely devastating?



Fig. 7: View of thickly populated Kangra Valley, Himachal Pradesh, India.

Field Transect

Day-1 (4th February 2027; Thursday) Travel to Chandigarh

• Leaving Lucknow by evening flight (~7:00 PM) and reaching Chandigarh

– Night Stay @ Chandigarh

Day-2 (5th February 2027; Friday) Leaving for Dharamsala & field visit

• 07:30 AM - 08:30 AM Break Fast

• 09:30 AM onwards – Leave for Dharamsala. On the way we would see Active Fault Topography of Himalayan Frontal Thrust (HFT), Khetpurali Taksal Fault (KTF), and Pinjore Garden Fault (PGF). Visit around Chandigarh – field along Himalayan Frontal Thrust (HFT) - will see the active fault scarp near Mansadevi, Khetpurali Taksal Fault (KTF) - river section near Thapli – outcrop display vertically displaced bedrock + Quaternary (terrace) deposits, and Pinjore Garden Fault (PGF) – hinterland fault which cut across the intermountain valley.

• Night stay at Dharamsala

Day-3 (6th February 2027; Saturday) Field visit & Stay at Dharamsala

• 07:30 AM - 08:30 AM Break Fast

• 09:30 AM – Leave for fieldwork

• 10:00AM – 03:00 PM Visit to St. John Church, 1200 AD Baijnath Temple, and Kangra Fort

• Night stay at Dharamsala

Day-4 (7th February 2027; Sunday) Field visit & Stay at Dharamsala

• 07:30 AM - 08:30 AM Break Fast

• 09:30 AM –Leave for fieldwork

• 10:00 AM – 04:00 PM Fieldwork around Tangroti and Pathiyar. Visit around Tangroti: Tectonic Geomorphology showing evidence of right lateral movement along Kangra Valley Fault (KVF) and related signatures marked by offset of streams, displaced and uplifted terraces. Trench excavation across the KVF near Pathyar and Dadh. Detailed discussions on trench walls.

• Night stay at Dharamsala

Day-5 (8th February 2027; Monday) Field visit & Stay at Dharamsala

• 07:30 AM - 08:30 AM Break Fast

• 09:30 AM –Leave for fieldwork

• 10:30 AM – 4:30 PM – Fieldwork in and around Sihunta and Naddi. Visit to Sihunta valley: Distinct fault scarps, offset of streams with younger displacements and rotational movement along KVF. Visit to Dal Lake (Sag Pond), Naddi.

Day-6 (9th February 2027; Tuesday) Travel to Chandigarh – take flight for New Delhi

• Leaving for New Delhi

Field Map showing road and excursion stops

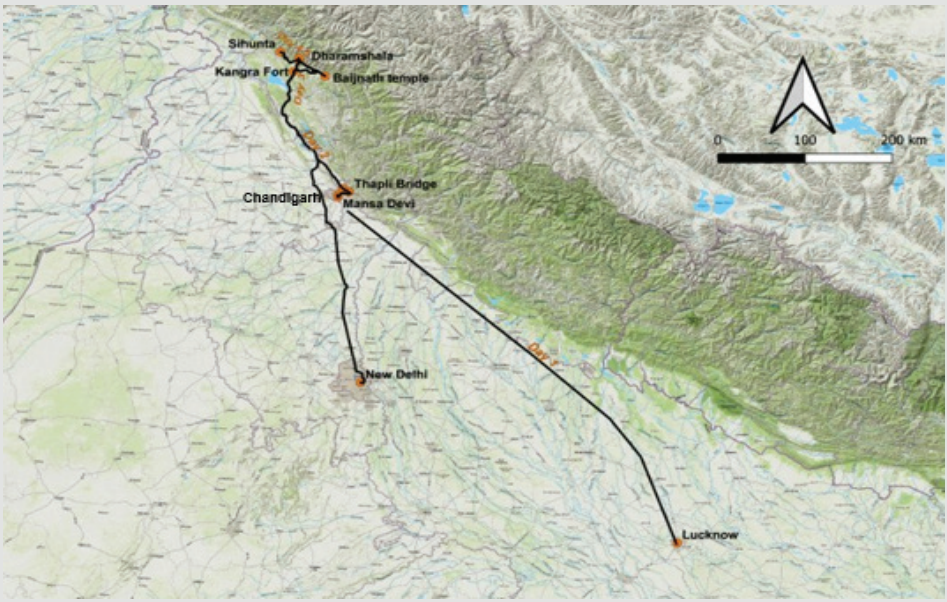


Fig. 8: Route map of field excursion during post-INQUA 2027. Day 1: The trip starts from Lucknow on 4th February 2027 and travel to Chandigarh (night stay). Day 2: On 5th February we would leave for Dharamsala and on the way visit a few locations to see the active fault topography along Himalayan Frontal Thrust (HFT), Pinjore Garden Fault (PGF) and Khetpurali Taksal Fault. Day 3: We visit the Kangra Fort, St. John's Church and Baijnath Temple – these structures experienced damage during 1905 Kangra earthquake. Day 4-5: Visit a few more location showing active fault topography along the Kangra Valley Fault (KVF) and a paleoseismic trench provided we get permission to open it.

Location(s) Description

Day-1, STOP 1: Chandigarh Fault [Himalayan Frontal Thrust], Mansadevi

The study area around Chandigarh city marks the southernmost fringe of the Himalaya, located southeast of Kangra, which falls within the meizoseismal area of 1905 Kangra earthquake (Figs. A, 8, 9). This city is a Union Territory considered to one of the most planned cities in India. The plan was prepared by Swiss French architect Le Corbusier, following the earlier plans by the Polish architect Maciej Nowicki and the American planner Albert Mayer (https://en.wikipedia.org/wiki/Chandigarh).



Fig. A: Locations to be visited during the Day-2.

Here the HFT system defines the boundary between the undeformed alluvial successions of the Indo-Gangetic Plain and the detached and strongly folded-faulted Siwalik Hills comprising Siwalik molasse of Mid Miocene to late Pleistocene age (Fig. 10a-b; 11).

Most prominent deformation in the frontal portion along the HFT was observed on the right bank of the Ghaggar River, northeast of Chandigarh (Nakata 1989). In addition, the deformation identified by Nakata (1989), we reported the preliminary observations about the existence of two active fault traces striking N25°W in the foothill zone with the average length varying from 2 to 10 km (Figs. 10a-b and 11). The surface expressions of the faults are not well marked and masked due to rapid deposition and poor preservation of coarse-grained alluvial deposits along the dynamic range front.

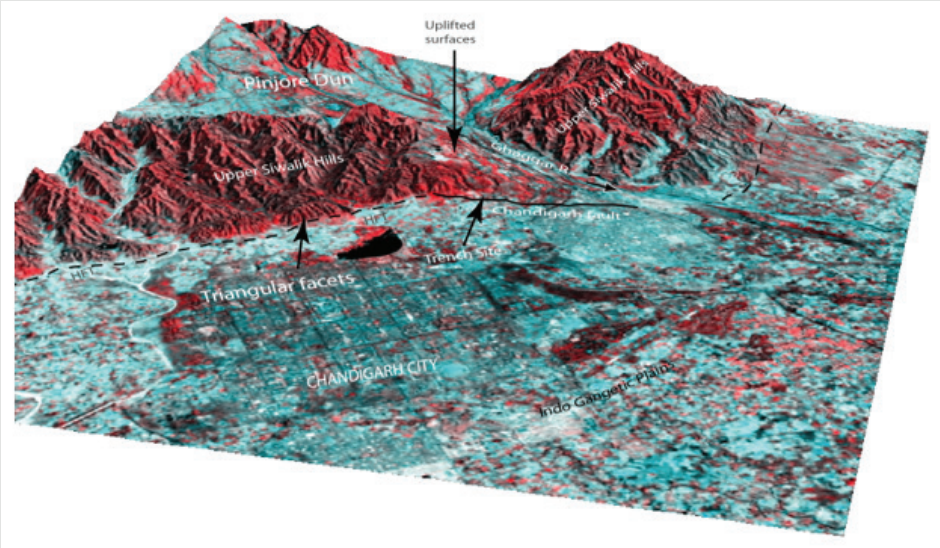


Fig. 9: 3-D perspective view of the terrain of the study area around Chandigarh, NW Himalaya (LANDSAT TM data overlain on DEM prepared from USGS SRTM 3 arc seconds data). Continuous black line shows the trace of "Chandigarh Fault". Uplifted alluvial surface are seen to east of the Chandigarh Fault (CF). Further to the northwest CF along HFT the front is marked by well-developed triangular facets. The HFT marks the boundary between the Sub-Himalaya (Upper Siwalik Hills) and the Indo-Gangetic Plain. Note the location of Chandigarh City, which is one of the major cities in Gangetic Plain.

Besides these, straight linear mountain-fronts marked by well-developed triangular facets also indicate the ongoing tectonic activity in this region (Figs. 9, 11). These two traces of active faults running parallel to each other between Panchkula and Mansadevi have vertically displaced and warped the Ghaggar, Kalka, Pinjore and Koshallia terraces (Nakata 1972, 1989) comprising late Pleistocene to Holocene alluvial-fan sediments (Figs. 12a). The occurrence of fault scarps with height varying from 15 to 38 m is indicative of long-term uplift/deformation along these faults through late Pleistocene to Recent times. These scarps are transverse to the course of the Ghaggar River channel. 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 (Figs. 11, 12a).

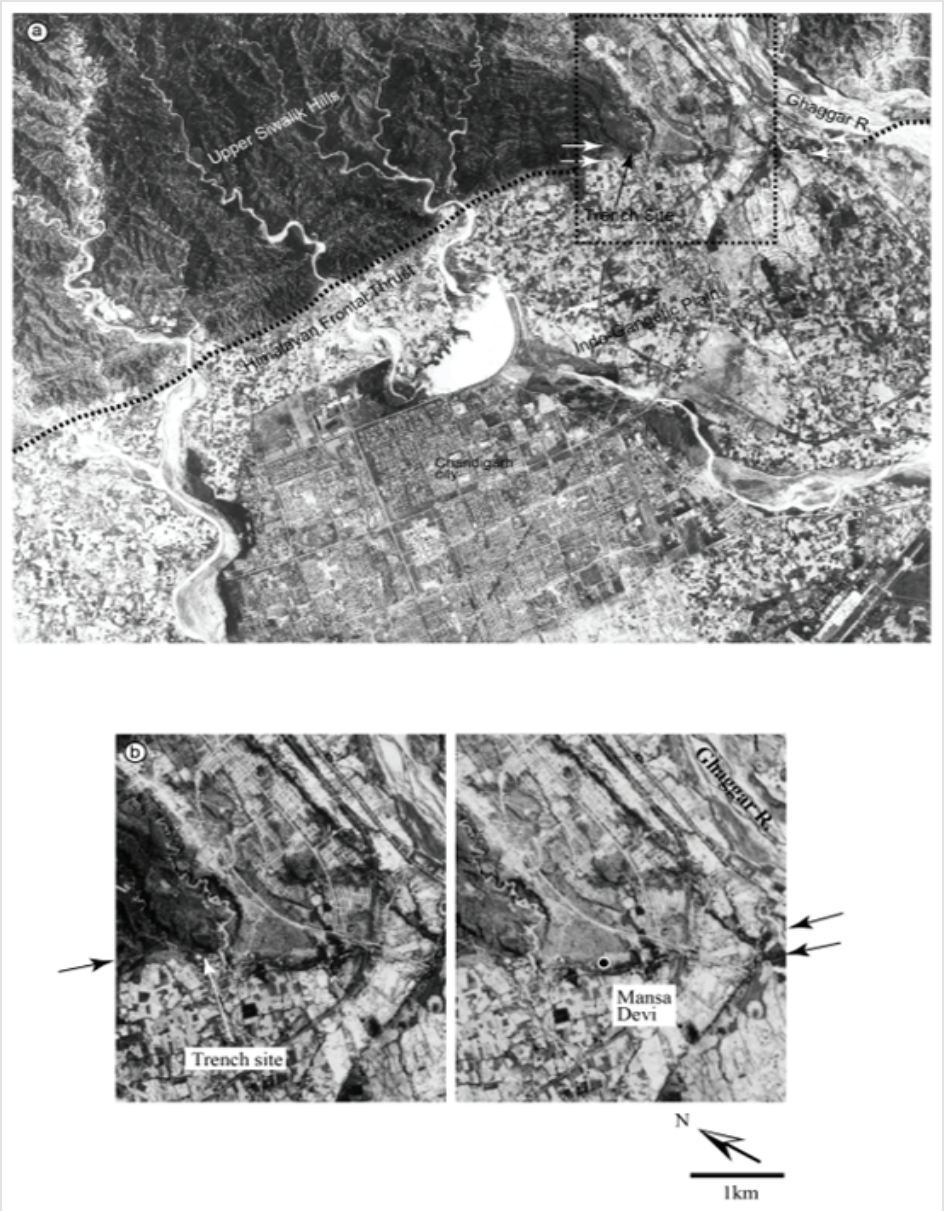


Fig. 10a-b: CORONA satellite photo of the study area around Chandigarh along Himalayan foothill zone. The photo shows thickly populated city of Chanidgarh located in the Indo-Gangetic Plain. Black dotted line represents the Himalayan Frontal Thrust (HFT), which marks the boundary between the Upper Siwalik Hill Range and the Indo-Gangetic Plain. Active fault traces are marked by white arrows. The box with dotted line marks the location of figure 10b.

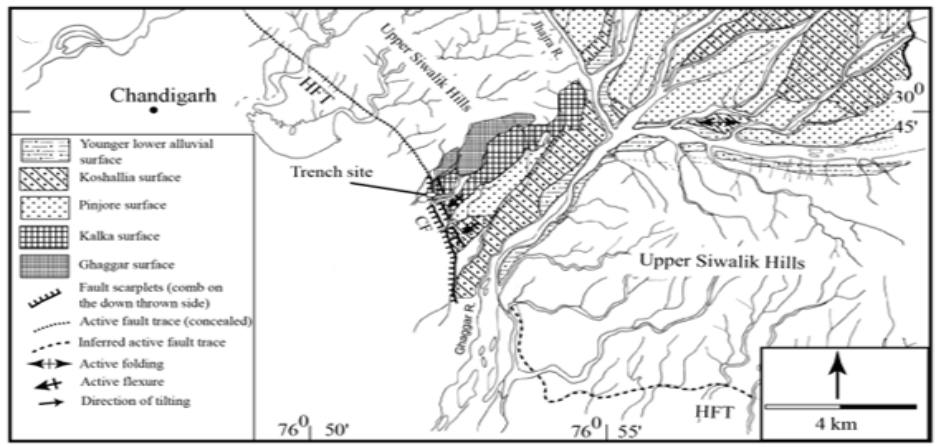


Fig. 11: Distribution of terraces and active fault traces along northwestern Himalayan Foot Hill Zone around Chandigarh along right bank of the Ghaggar River. White box shows location of the trench site. CF- Chandigarh Fault; HFT- Himalayan Frontal Thrust (after Malik & Nakata 2003).



Fig. 12a: A view of Chandigarh fault scarp (branching-out fault of HFT) near Mansadevi Temple, fault trace shown by red arrows and location of the trench. Foreground is the Indo-Gangetic Plain.



Fig. 12b: A view of Chandigarh fault scarp, fault trace shown by white arrows and location of the trench.

Paleoseismic study across the Chandigarh Fault (a branch of HFT)

A 14 m long, 2 to 4 m deep and 4.5 m wide E-W trench was dug at the base of a 16-20 m high fault scarp across the Chandigarh fault. The succession in the trench was divided into 7 different lithounits, from A (oldest) to G (topsoil) (Figs. 12a-b). A and F units are made up of loose matrix (very fine gravel + medium- coarse sand + silt) – supported pebble-cobble-boulder clasts of sandstone derived from Dagshai, Kasauli and Subathu (?) formations of Lower Tertiary age. These were transported and deposited by the river from the north debouching into the Gangetic Plain. The external geometry of unit F shows a slightly erosive contact with respect to the adjacent (to the left) units C and D and with the underlying unit B and concave-up lower-bounding surface representing shallow channel-fill geometry. Units B and D represent massive medium-coarse sandy facies. The unit C comprises fine gravel clasts as seen in A and F units and shows pinching out morphology representing a channel bar. The unit E is made up of medium- fine gravel similar to unit C, which represents slope deposit, deposited after the seismic event. Finally, the succession is capped by topsoil cover (unit G).

The fault strand identified, displaces units A, B and F and extends for about 6.5 m with variable dips ranging from 20° to 46° due northeast. The fault is marked by steeper dip of about 46° near the surface in the western portion of the trench, which decreases to about 20° towards east. In the central segment, the dip of the fault is low (4° to 8°), and becomes steeper in the lower part. The fault plane is distinctly marked by 10 to 12 cm thick crushed zone of angular gravel where it passes through the B unit (Figs. 13a-b and 14a). Further up, the fault contact between B and F shows prominent shear-fabric marked by discoidal pebbles aligned along their long axes oriented parallel to the fault-plane (Figs. 13a-b and 14b). The internal arrangement of the gravelly clasts in unit F and gravelly lens in unit B are indicative of slight folding-related to faulting, which resembles the folding near the tip of the fault.

Reconstruction of exposed displaced units in the trench suggests that one major large magnitude earthquake has struck this region in the historic past, which post-dates the channel-fill deposit – unit F (Fig. 13a-b). A total displacement of about 3.5 m was measured in the field, taking into account the lower-bounding surface between B and F units, which marks the prominent piercing point and contact that has been displaced along the fault. The maximum displacement (To = 3.5 m) and average angle of the fault (θ=25°) were used to determine other parameters like vertical slip (Vm) and horizontal shortening (Sh). This gives Vm = 1.47 m and Sh = 3.17 m for one event. The vertical displacement measured directly in the trench from the top of unit B gives Vm = 1.33 m, which is more or less consistent with the value calculated from palinspastic construction. This vertical displacement of 1.33 m for one event should have been reflected by the scarp height. However, the present scarp height of 1.2 m is a little less than the expected/calculated displacement, indicating erosion of the scarp after faulting.

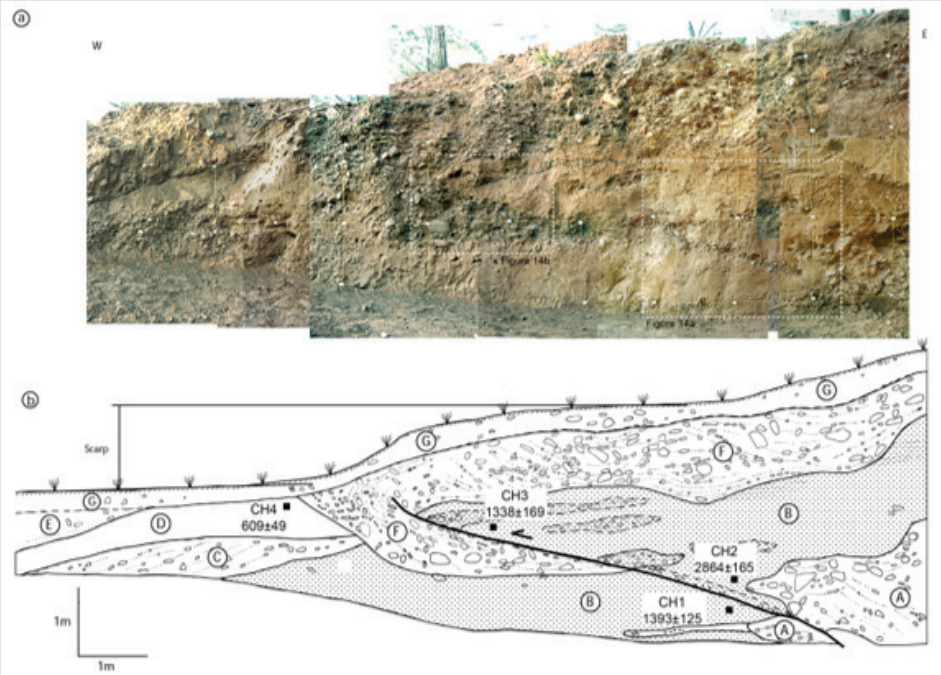


Fig. 13: (a) North-wall view of E-W trench at the base of Chandigarh fault scarp near Mansa Devi (refer to figure 10a and 11 for location). Thread on the wall shows grid on 1 m x 1 m. Detailed trench log of north-wall. Bold line marks the trace of low angle thrust fault, which has displaced A, B and F units. Unit A – older channel deposit; B and D – massive sand deposit; C – channel bar; E – fine gravel slope deposit; F – channel deposits and G – topsoil. The total amount of displacement (3.5 m) has been measured between the displaced B and F units taking into consideration the lower-bounding surface between them. The boxes with white dotted line show location of Figs. 14a and b.

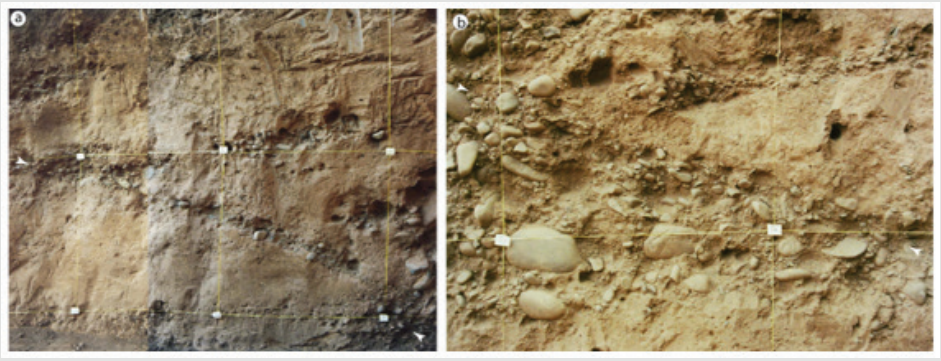


Fig. 14: (a) Close-up of the fault plane. The fault contact between unit B and F is marked by prominent shear-fabric defined by aligned discoidal pebbles along their long axes oriented parallel to the fault-plane contact (for location refer to Fig. 13a), (b) Close-up of the fault plane distinctly marked by 10-12 cm thick crushed zone comprising angular gravel where it passes through the B unit (for location refer to Fig. 13a).

Traces of active faults near Chandigarh, in the northwest Himalaya, indicate that the frontal portion has ruptured during the historic past. The two active fault traces are indicative of imbricated fault splays branching out from the main HFT, suggestive of propagation of tectonic activity towards the foreland (Figs. 11-12a). The variable heights of scarps ranging from 15 to 38 m suggest continued long term deformation, which is also supported by 3.5 m displacement recorded in a trench near Chandigarh. The OSL age from unit D (609±66 yr) is the deposition age, where this unit was eroded by later depositional phase marked by unit F – which got displaced during the latest event. Since we do not have the age from the uppermost lithounit, it is rather difficult to pin-point the event age. However, the available dates suggest that the event postdates the age of unit D. Thus, we are of the opinion that the event must have occurred sometime during the 15th or 16th century. Paleoseismic investigation ~ 150 km to the southeast from the present site around Kala Amb suggests occurrence of two large rupture earthquakes during the past 650 years at round 1423 AD and 260 AD (Kumar et al. 2001). The surface rupture of large magnitude event during 1400- 1500 AD extended for about ~150-200 km towards NW of Kala Amb, where displacement of 3.5 m was registered along the Chandigarh fault. Available historic data does not have record of such an event from this area, however, several events including the 1505 (M=8) Kabul and the 1505 Mw=8.2 Kumaon earthquakes have been reported from the western Himalaya (Ambraseys & Jackson 2003). Therefore, the question arises whether we are looking at one of these events whose location is uncertain as mentioned in the present earthquake dataset, or a major earthquake that occurred during 1400 AD but remained unrecorded during historic times.

Day-2, STOP 2: Khetpurali Taksal Fault [Thapli]

Paleoseismic studies in the last two decades confining to the HFT have partially enriched our knowledge on active tectonic deformation along the Himalayan arc (Arora and Malik, 2017; Wesnousky 2020; Bilham, 2020). Moreover, a very few surface ruptures of recent, historical, and pre-historic earthquakes have been identified. Also, little emphasis has been given on identifying signatures of paleo-earthquakes on the hinterland faults, and fault segmentation to understand their relationship with the ongoing tectonic deformation in the Himalaya (Fig. 2).

We report evidence of an active fault system that runs transverse as well as parallel to the Himalayan arc, hereafter called Khetpurali Taksal Fault (KTF), which has displaced and deformed the Sub-Himalayan and overlying Quaternary successions (Fig. 2). Based on deformation and displaced geological succession a strike-slip fault near Khetpurali was reported by Kumar and Tandon (1985). Geomorphic signatures marked by offset of Khusalia River near Parwanoo town indicated right lateral strike-slip movement along the Taksal Fault (TF) (Nakata, 1989). Later, study by Malik and Nakata (2003) suggested that the Taksal Fault (TF) extends for >45 km in northwest (Figs. 2, 15a-b). The KTF act as an out-of-sequence oblique-thrust with prominent dextral slip extending north from the Himalayan front through Pinjore Dun along Taksal Fault, Sundernagar Basin, and across Kangra Valley to join Kangra Valley Fault (KVF) (Malik and Nakata, 2003; Malik et al., 2015) (Figs. 2, 15a-b). We further present evidence of three paleo-earthquakes occurred during historic and pre-historic times on KTF. We argue that the KTF possibly represents the surface manifestation of a segment boundary in the NW Himalaya supported by several evidence such as

paleo-earthquakes, micro-seismicity, obliquity of convergence, arc- parallel shearing, strain partitioning, focal mechanisms, topographic anomaly and gravity anomaly. Although the KTF alone may not be responsible for a major/great Himalayan earthquake, but it has been observed to have moved during a major earthquake of 1400-1500 CE along with HFT, hence, could possess a future seismic threat in NW Himalaya.

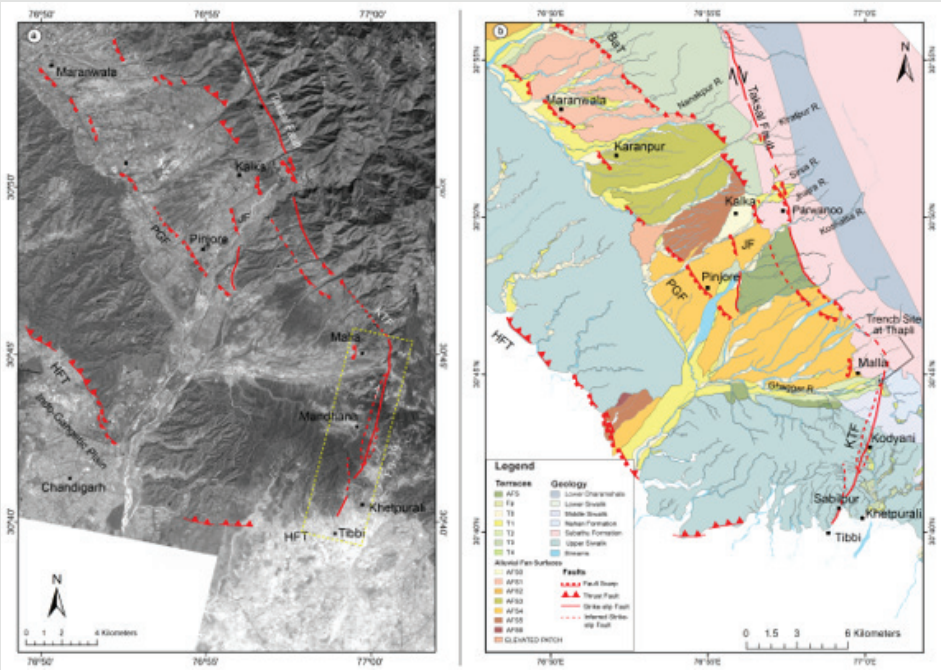


Fig. 15: (a) CARTOSAT-I image showing the distribution of active fault trace around Chandigarh-Pinjore region. Box with broken line marks the location of Fig. 2, (b) Detailed geomorphic map of the study area showing the distribution of active faults and associated landforms. The map shows six levels of terraces (T0-T5) and seven alluvial fan surfaces (AFS0-AFS6). The solid red line marks the fault traces, and combs indicate the down-thrown side along the scarp. PGF-Pinjore Garden Fault, JF-Jhajra Fault, KTF-Khetpurali Taksal Fault, BaT- Barsar Thrust, HFT-Himalayan Frontal Thrust.

The Khertpurali Taksal Fault (KTF), an out-of-sequence oblique-thrust with prominent right lateral strike-slip, was traced for ~250 km, extending north from the Himalayan front through Pinjore Dun along Taksal Fault, Sundernagar Basin, and across Kangra Valley along Kangra Valley Fault (KVF) (Fig. 2, 15a-b). The KTF is oblique to the Himalayan front with an NNE-SSW strike between Tibbi village in the frontal portion, and Thapli in the hinterland. The fault extends for 8.5-9.0 km displacing Sub-Himalayan (Upper Siwaliks) succession with prominent right-lateral (dextral) movement (Figs. 2, 15a-b, 16a-e). It bends to the NNW-SSE direction and merges with NNW-SSE striking Taksal Fault (TF) near Thapli village (Fig. 15a-b). Between Tibbi and Sabilpar, it exhibits a single fault strand. Further north, it splays out in multiple faults marked by E-W trending 0.5-15 km wide fault zone, consisting of several subparallel faults ranging in length from 1.5 to 3.0 km (Fig. 15a-b, 16a-e). These faults also

show distinct right-lateral strike-slip geomorphic features such as deflected streams, offset ridges, sag ponds, shutter ridges, and east and west facing fault scarps (Fig. 2, 15a-b, 16a-e). Prominent deflected streams, the offset of ridges, and sag ponds were observed west of Dundhgarh and near Kodyani villages (Fig. 15a-b, 16a-e). A right step-over fault west of Dundhgarh has resulted in the formation of ~100 m long sag pond (Fig. 16a-c). Near Kodyani village, more than one faults have displaced Upper Siwalik successions along with young fluvial terraces marked by south-facing fault scarps (Fig. 15a-b, 16a-d).

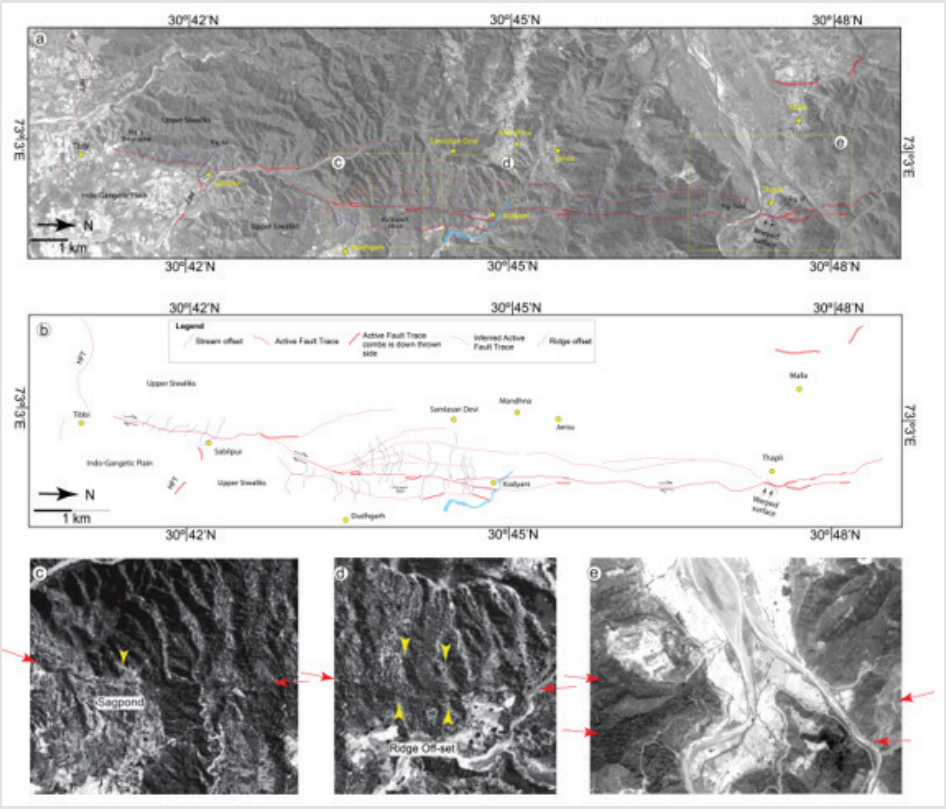


Fig. 16: (a) CARTOSAT-1 image (with reduced contrast) showing traces of the Khetuprali Taksal Fault (KTF), cutting through the Sub-Himalayan succession (Upper Siwalik) along with Quaternary deposits. KTF runs NNE-SSW between Tibbi in the south and Thapli in the north. Yellow boxes indicate the location of Fig. 16c-e. For the location, refer to Fig. 15a, (b) Trace map extracted from Fig. 3a, showing the distribution of active fault trace marked by a single fault between Tibbi and Sabilpur, bifurcates in multiple fault splays. Further north of Sabilpur up to Kodyani, it is marked by a 0.5–1.5 km wide fault zone. These fault strands along the strike have displaced streams and ridges, resulting in the formation of pressure ridges and sag pond, (c) Shows fault trace marked by red arrows. Right-stepping of the fault trace has resulted in the formation of a sag pond. Sag pond is marked by the yellow arrow, (d) Shows trace of fault (marked by red arrows), and offset of ridges marked by yellow arrows, (e) fault traces around Thapli marked by displaced river channel along with young fluvial terraces and associated warping with WNW facing 0.5–1.0 m high fault scarp. For a detailed map, refer to Fig. 17c and Fig. 18a-b for field photos.

A detailed topographic survey was conducted near Sabilpur and Thapli villages using Real-Time Kinematic (RTK) GPS. Digital Elevation Map (DEM) prepared shows a distinct 22 m right-lateral offset of the Dangri River near Sabilpur village, and 10 m stream offset along the fault trace at Thapli village (Fig. 15a-b, 16a, 17a-d). Another well-preserved exposure of faulting (a shear zone) was observed along the right bank of the Ghaggar River near Thapli village (Fig. 15a-b and 16a-b). The exposure shows a 2.5-3 m wide shear zone striking NNE-SSW, marked between Lower Siwalik grey sandstone in the downthrown block (left side) and red sandstone in the upthrown block (right side) (Fig. 18a-b). Here the fault has vertically displaced the overlying young Quaternary terrace deposits (strath terrace) comprised of sand and gravelly succession, resulting in 0.5–1.0 m high northwest facing scarp (Fig. 15b, 16a and e, 17a-b). Based on the number of observations of surface expression found along the trail (Figs. 15-18) discussed earlier, we infer the KTF to be a continuous transverse-oblique to parallel (to the Himalayan deformation front) oblique-thrust with distinct dextral strike-slip fault system (~250 km) which is connecting the constituent fault segments from Khetpurali to Taksal Fault continuing up to the Kangra Valley Fault (KVF).

Paleoseismic study across the KTF

A shallow trench (8 m long, 2 to 2.5 m deep, and 3.5 m wide) was excavated across the KTF, exposing footwall and hanging wall (Figs. 15a-b, 17a, 18b, 19, 20). Here the active fault trace (0.5–1 m high) is well preserved on the T3 terrace surface on the right bank of the Ghaggar River (Fig. 18a-b). Also, the incised cliffy bank shows prominent shearing and the presence of a vertical fault (Fig. 18a). The east and west trench walls were gridded at a 1 m ×1 m scale. We identified six sedimentary units based on grain size, color, and contacts. Unit F is the oldest, and Unit A is the youngest capping the sequence (Figs. 19, 20). Fault strands were demarcated with a cross-cutting relationship between the exposed sedimentary units.

We interpreted that Event-I occurred along F1a strand after the deposition of Unit-F, i.e., after 7520–4780 BCE, around 6719–4081 BCE (Fig. 21: Stages 1 and 2). Displacement resulted in developing an ideal site for ponding conditions, which allowed the formation of humus-rich soil after the deposition of Unit-E on the footwall (Fig. 21: Stage-2); followed by the deposition of Unit D capping the whole sequence on both the walls (Fig. 21: Stage-3). Deposition of Unit C initiated on footwall partially eroded Unit E, as marked by undulating or erosive contact.

The deposition of Unit C continued for longer period, with a thin cap on the hanging wall, also, indicated by higher thickness on footwall side (Fig. 21: Stage-4). Event-II occurred after the deposition of Unit-C and before the deposition of Unit-B, displacing Units F, E, D, and C along F1b and F1a along with subordinate fault strands – F2a and F2b (Fig. 21: Stage-5).

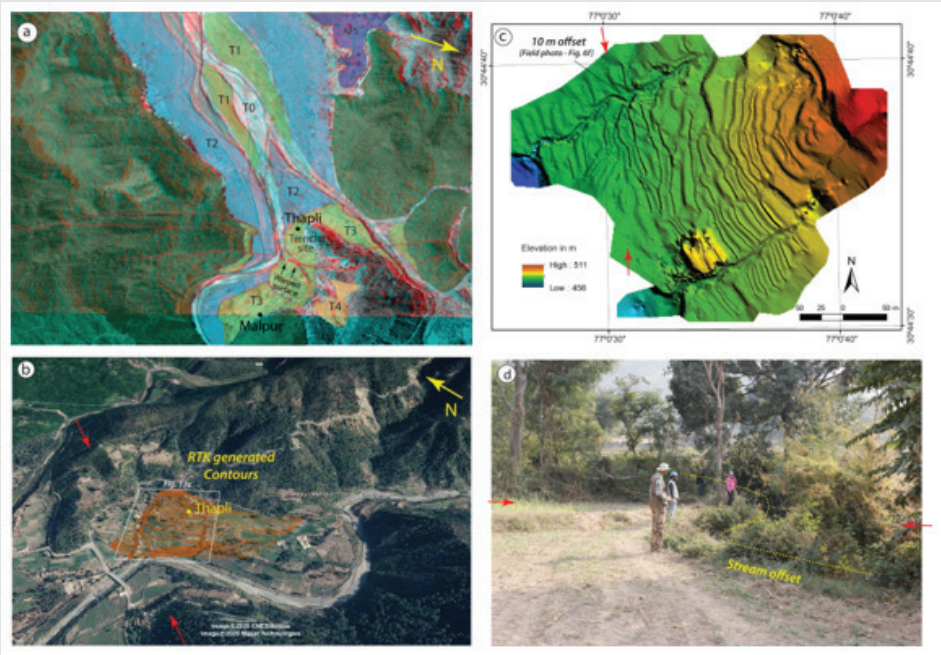


Fig. 17: (a) Anaglyph showing the area near Thapli village where fault enters the Pinjore Dun valley deforming terraces of the Ghaggar River, (b) Google Earth image with an overlay of contours generated by RTK-GPS survey. Red arrows mark a fault trace, and the white box shows the area of DEM generated in Fig. 16e, (c) DEM generated from the RTK-GPS survey around Thapli. The stream is offset right-laterally by 10 m along the fault trace, (d) A view of 10 m right-lateral stream offset at Thapli.

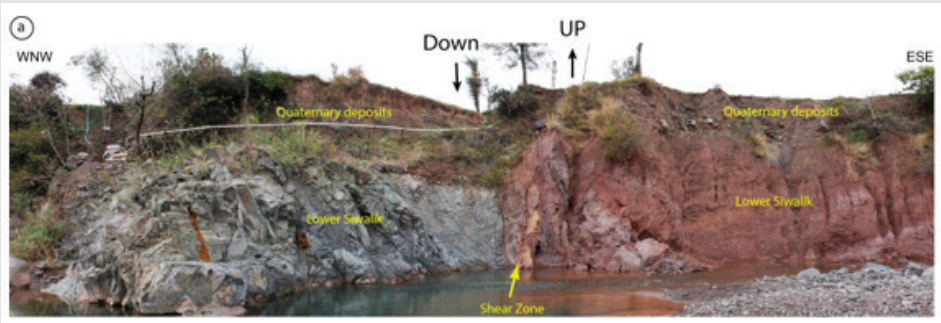




Fig. 18: (a) Field exposure of the KTF along the right bank of the Ghaggar River near the Thapli village. The fault has deformed, displaced, and juxtaposed the red-sandstone (on the right side) and the Lower Siwalik - grey sandstone (on the left side). Almost vertically stacked beds mark the shear zone in between the two formations. The fault has also displaced overlying young Quaternary deposits, exposed in the form of a strath terrace. The right-hand block (with red sandstone) marks the uplift. (b) WNW facing 0.5–1.0 m high fault scarp striking NNE-SSW.

Considering the minimum age from Unit-C and maximum age from Unit-B, we infer that Event-II occurred between 1064 and 1223 CE and 1346–1457 CE, most likely around 1400 CE. The event was followed by the phase of deposition of Unit-B on both walls (Stage-6). The Most Recent Event (MRE) – Event-III took place after the deposition of Unit-B, between 1731 and 1841 CE and 1862–1955 CE (Fig. 21: Stage-7). The event displaced Units F, C, and B along F2a and F2b strands. Displacement was also observed along F3 - a thrust fault that warped and displaced Units F, E, C and B. Finally, the sequence is capped by Unit A (Fig. 21: Stage-8). Considering the bracketing ages of these three events, we infer as follows (Fig. 9a-b, 10a-b, and 21): (a) Event-I occurred between 7520 and 4780 BCE and 5300–3730 BCE, around 6719–4081 BCE; (b) Event-II 1064–1223 CE and 1346–1457 CE, which occurred during 1141–1421 CE; (c) Event-III between 1731 and 1841 CE and 1862–1955 CE, might have occurred during 1767–1926 CE, probably 1800 CE event or possibly the 1905 Kangra earthquake (Mw 7.8) that breached the surface along the KTF.

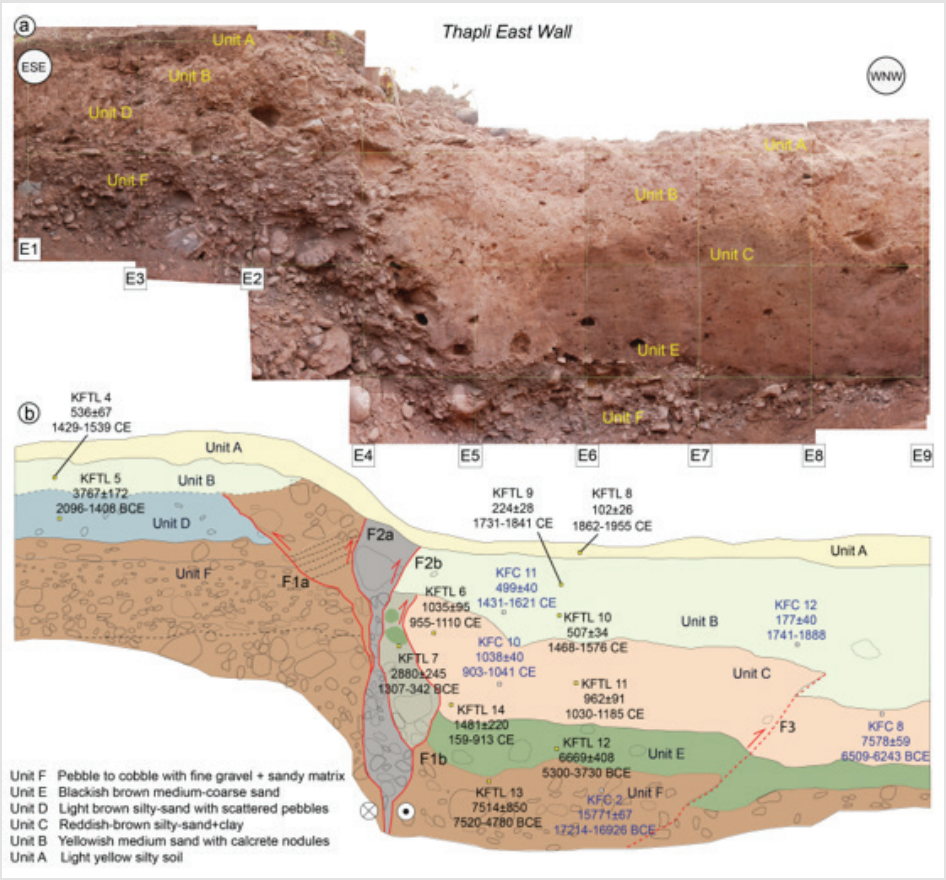


Fig. 19: (a) Mosaic of the east wall of the trench excavated across NNE-SSW striking fault scarp along the Khetpurali Taksal Fault (KTF) at Thapli village. The exposed stratigraphy in the trench reveals six sedimentary units. Unit F oldest and Unit A youngest. (b) At least three fault strands, F1 to F3 were identified. Three paleoseismic events were identified based on the cross-cutting relationship between sedimentary units and the orientation/alignment of pebbles (indicative of shear zone) - Event-I along F1a, Event-II along F1a and F1b (also slip was taken-up along F2a and F2b), and Event-III F2a, F2b and F3. F1a, F1b, F2a, and F2b are vertically oriented faults (mark the shear zone) with the strike-slip component, whereas F3 is a thrust fault developed in the foreland side. Bold red lines mark fault strands. Yellow squares show the location of OSL samples, and white squares are the locations of charcoal (14C AMS) samples. Based on the ages and cross-cutting relationship of the sedimentary units, we bracketed the events: Event-I occurred between 7535 and 4792 BCE and 5293–3726 BCE; Event-II was between 1056 and 1219 CE and 1341–1451 CE; and Event-III between 1744 and 1879 CE and 1864–1957 CE.

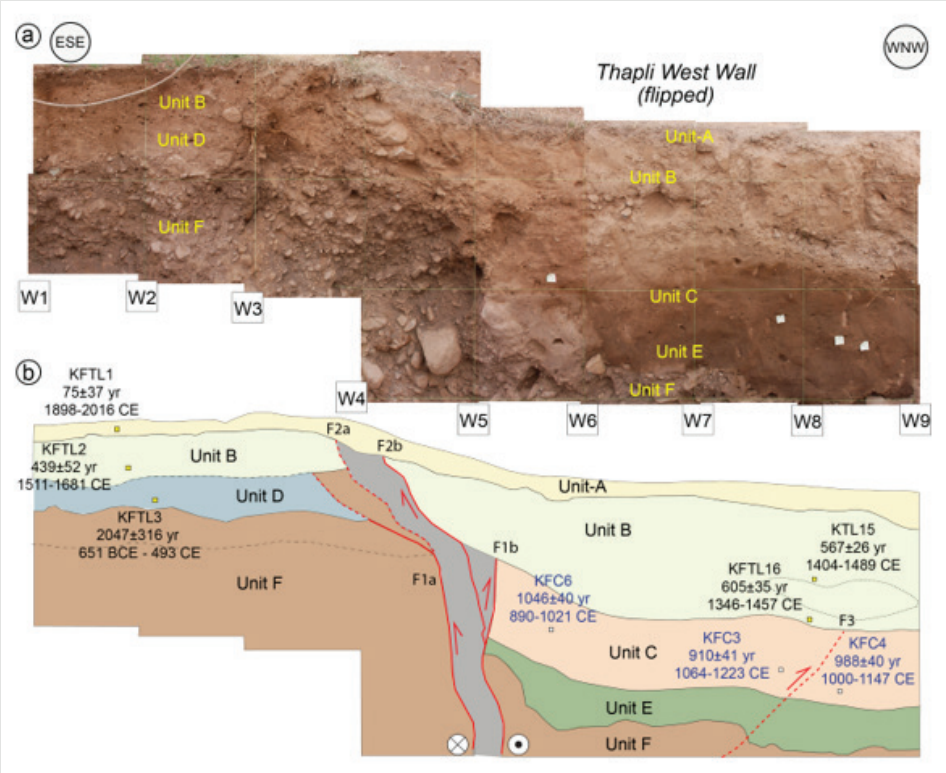


Fig. 20: (a) Mosaic of the west wall of the trench excavated across NNE-SSW striking fault scarp along the Khetpurali Taksal Fault (KTF) at Thapli village. (b) Trench log prepared from the mosaic. For further details on sedimentary units, refer to Fig. 19a-b.

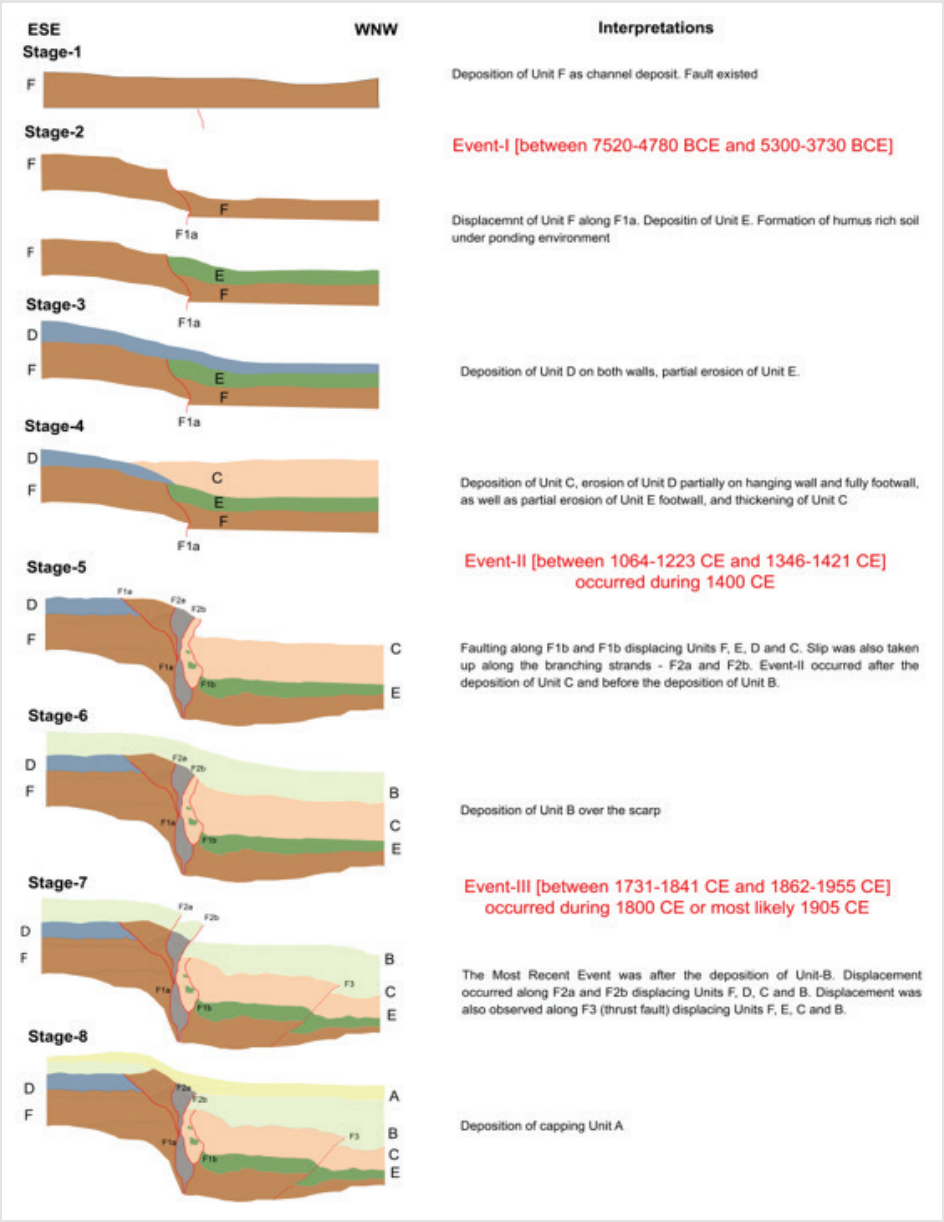


Fig. 21: Schematic diagram showing faulting process and events along KTF. Event-I occurred between 7535 and 4792 BCE and 5293–3726 BCE, around 6700–4080 BCE; (b) Event-II 1056–1219 CE and 1341–1451 CE could be an event that occurred during 1120–1410 CE; (c) Event-III between 1744 and 1879 CE and 1864–1957 CE, that might have happened during 1800 CE, or most likely 1905 CE.

Day-3

We will be visiting the historical places/monuments that were affected by the 1905 Kangra earthquake. STOP 1: St. John Church McLeodganj, Baijnath Temple and the Kangra Fort (Fig. B).

Day-4

Visit around Tangroti: Tectonic Geomorphology showing evidence of right lateral movement along Kangra Valley Fault (KVF) and related signatures marked by offset of streams, displaced and uplifted terraces. Trench excavation across the KVF near Pathyar and Dadh (Fig. B). Detailed discussions on trench walls.

Day-5

Visit to Sihunta valley: Distinct fault scarps, offset of streams with younger displacements and rotational movement along KVF (Fig. B). Visit to Dal Lake (Sag Pond), Naddi.

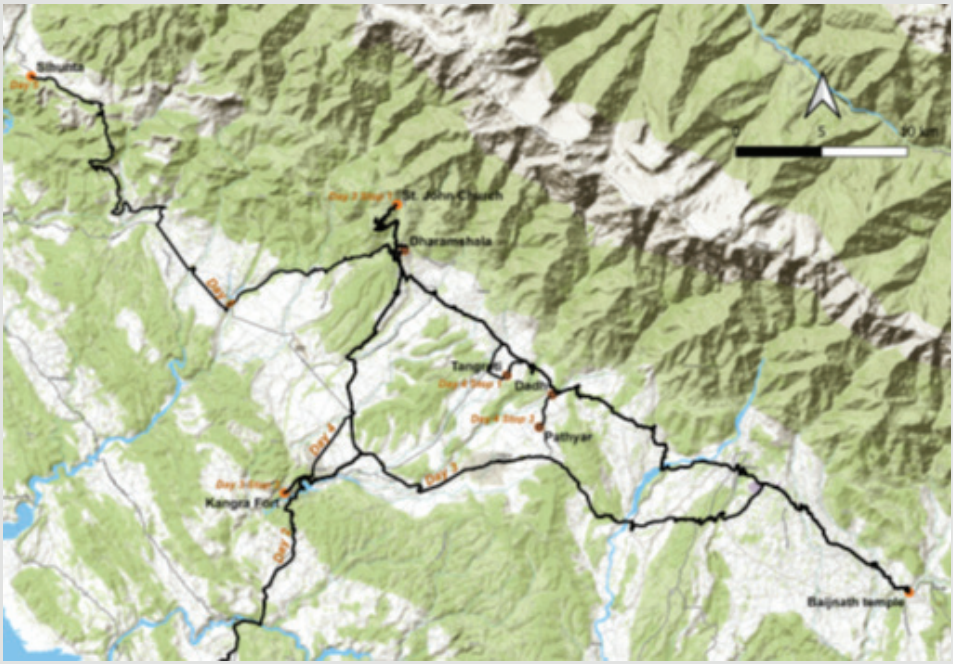


Fig. B: Locations to be visited during the Day 3 to 5.

Geoheritage, UNESCO Heritage, Archaeological sites in the vicinity

Day-3, STOP 1: St. John Church McLeodganj



Fig. 22: Famous St. John Church of McLeod Ganj (a). Cracks and displaced walls (b-d).

St. John in the Wilderness is an Anglican church situated at Forsyth Ganj on the way to McLeod Ganj amidst beautiful deodar trees (Fig. 22). The church was dedicated to Saint John the Baptist and was constructed in 1852. The Church is a historic monument and one of the oldest churches in the region. It is built in Neo-Gothic architectural style. The church was built with grey stone and is one of the few buildings still in existence in the town from the British era. In 1905 an earthquake destroyed the bell tower of this church. According to the records, the church's spire and bell tower were completely destroyed, while the main stone structure remained intact due to its robust construction; however, one of the remaining structures was twisted on its base. The complex structure which adds to the memory of the Earl of Elgin in 1863 had all the upper parts fallen whilst the lower part was shattered. The three horizontal courses of stone making up the body of Lord Elgin's tomb had shifted differentially, generally towards NW indicating a thrust of the shock from NW-SE. Of the gate posts, one was twisted on its base, similarly to the Lord Elgin's tombstone. The greatest breaking down had occurred to the South wall, which corresponds to the direction of the free edge of the steep slope below the churchyard. The tower and east end wall were fissured diagonally, showing strains due to the rocking about its long axis, and drag of the falling long walls (Memoirs of the Geological Survey of India: Volume XXXIII).

Day-3, STOP 2: Baijnath Temple

Baijnath Temple is situated on the foothills of the Dhauladhar ranges on the left bank of the river Binwa. This temple was built in 1200 AD. The Baijnath Temple in Kangra, an architectural marvel dedicated to Lord Shiva, endured significant structural damages due to the 1905 Kangra Earthquake (Fig. 23).



Fig. 23: Old photograph of Baijnath temple which was partially damaged during 1905 Kangra earthquake (a). Present photograph of the temple (b) having cracks developed (c) and repaired walls.

The devastating earthquake that shook the entire region of Kangra on 4th April 1905 also caused damage to the shrine, which has been reported by J. Ph. Vogel and has since been repaired (Fig. 23).

At present the temple is a protected monument under the Archaeological Survey of India. There are cracks and displacements in the temple's shikhara (spire), weakening its vertical integrity. The mandapa (pillared hall) witnessed partial collapses, with fractures in several supporting pillars. Intricate stone carvings adorning the temple were affected; some carvings detached or shattered due to the thrust's directional shaking. The boundary walls and foundations of surrounding shrines were severely impacted, with visible fissures and alignment shifts attributed to the fault thrust's dynamic energy (Memoirs of the Geological Survey of India: Volume XXXIII).

Day-3, STOP 3: Kangra Fort

The Kangra Fort, one of the most iconic historic remains, suffered extensive collapses in outer wall and bastions with large sections of masonry dislodged due to the intense seismic activity (Fig. 24). The earthquake also devastated the inner chambers and temples within the fort complex, including the Lakshmi Narayan Temple and the Ambika Devi Temple, which were integral to the fort's cultural and religious significance. The old cemetery near the NE gate of the fort suffered few damages. Few tombs had horizontal cracks, and one flat slab of stone had shifted 0.25 inches towards E 3° S with trace of twisting.



Fig. 24: Photograph of the historic Kangra Fort, Kangra (Source: Internet).

Day-4, Pathiyar – Tangroti Transect

The Pathiyar-Tangroti segment along the Kangra Valley Fault (KVF) is a geologically and geomorphologically significant zone, offering insights into the tectonic activity and sedimentary processes associated with the 1905 Mw 7.8 Kangra earthquake (Figs. 25-27).

Geologically, this segment lies between the Main Boundary Thrust (MBT) and Jawalamukhi Thrust (JMT), reflecting active slip partitioning due to oblique convergence in the Northwest Himalaya. The sedimentology of the region is characterized by alluvial deposits, fluvial terraces, and fan surfaces, which exhibit lateral and vertical offsets due to fault activity. These offsets range from 10 m to 340 m for streams (Figs. 28-29), with smaller offsets indicative of single-event displacements, while fault scarps range in height from 1.2 m to 14 m (Figs. 30-32). Stratigraphically, the region comprises unconsolidated sediments overlying older lithologies, with evidence of deformation in the form of warped and displaced layers. The distinctive "Y"-shaped branching at the fault trace endpoints suggests complex rupture dynamics, influenced by stepping and branching mechanisms (Fig. 25). Two rupture scenarios are proposed: unidirectional propagation from Pathiyar-Malan towards the west or bilateral propagation originating centrally at Miniama.

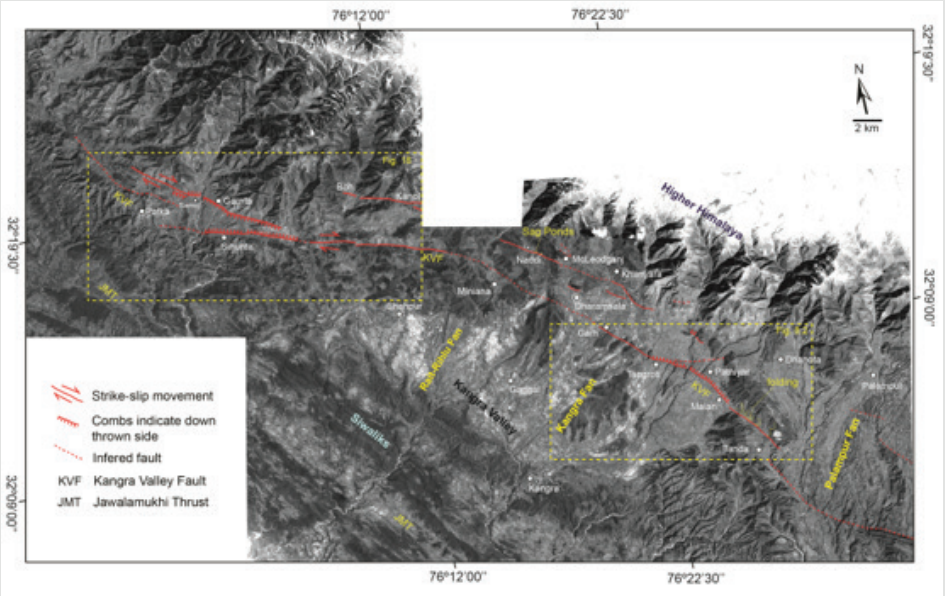


Fig. 25: CARTOSAT-1 photo mosaic showing landscape around Kangra-Dharamsala. The Kangra valley is comprised of alluvial fan sediments deposited by Rait-Rihlu, Kangra and Palampur Fans (coalesced fan). Active fault trace/s striking NNW-SSE and WNW–ESE with prominent right-lateral strike-slip movement, named as "Kangra Valley Fault" (KVF) has cut through the Kangra Valley – displacing young alluvial fan surfaces and fluvial terraces. The fault trace extends for about 60 km between Garnta village in NW and Tanda village in SE. Yellow boxes marks the area of the fault portions showing prominent manifestation of active fault topography.

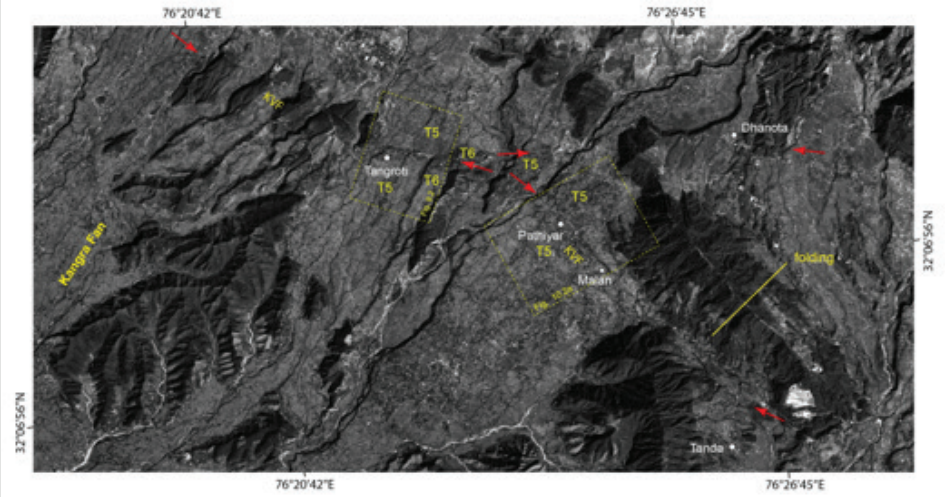


Fig. 26: CARTOSAT-1 photo showing landscape around the Pathiyar-Tangroti portion along KVF. The KVF has displaced the Kangra Fan surface (T5) and older surface (T6) resulting into north facing active fault scarp. Active fault trace shows slightly variable strike from NNW-SSE between Tanda and Pathiyar villages, WNW–ESE between Pathiyar and Tangroti villages and to NNW-SSE further north to Tangroti village. For location refer yellow box marked in Fig. 25.

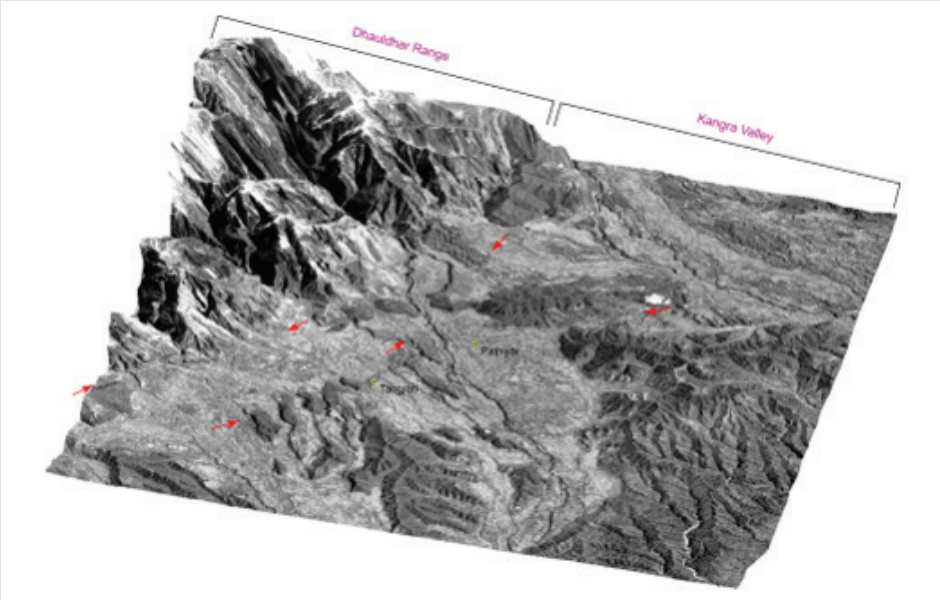


Fig. 27: A 3D perspective view of the landscape around Pathiyar and Tangroti villages showing the trace of KVF. CARTOSAT-1 ortho-kit image (2.5m spatial resolution) draped over DEM extracted from after and forward images. The red arrows show the active fault traces.

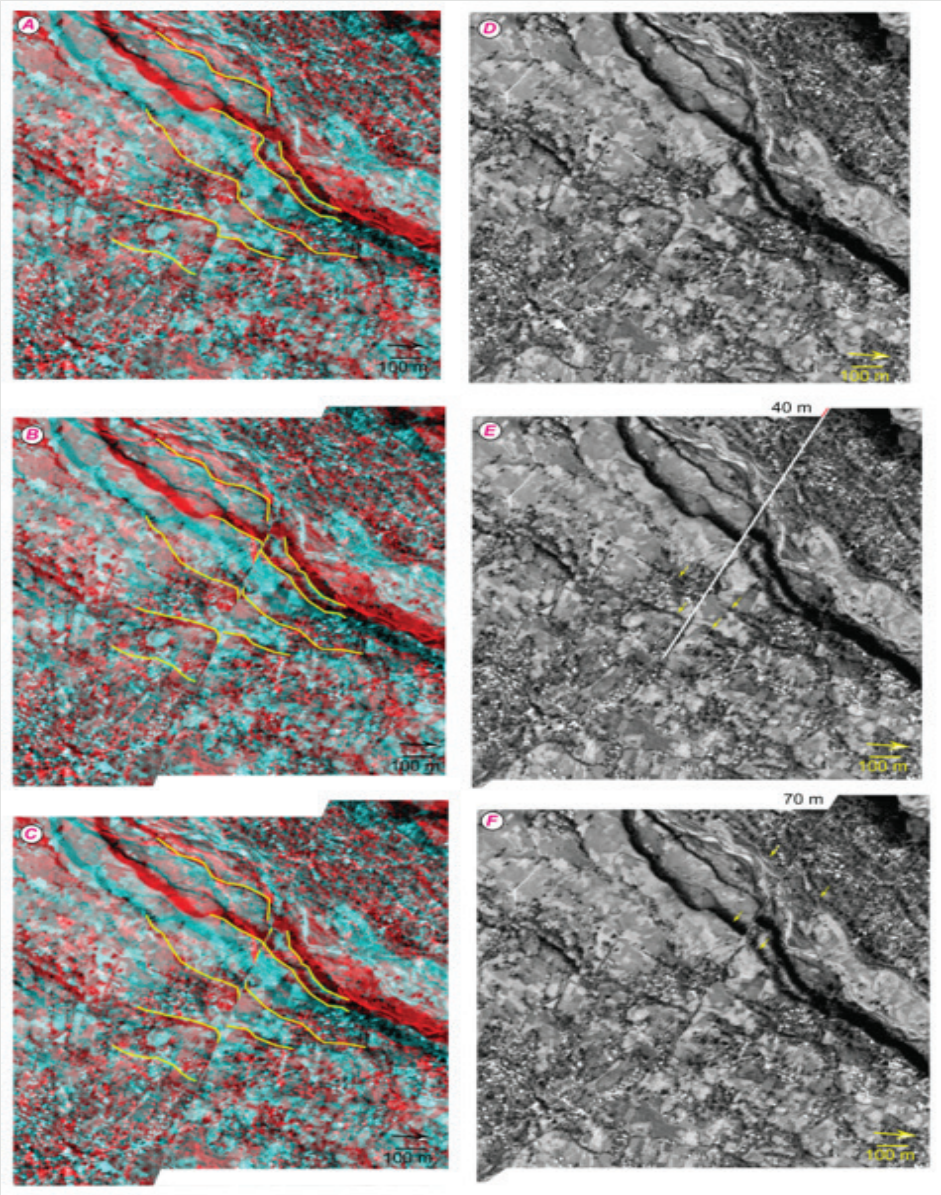


Fig. 28: (a-c) Anaglyph prepared from CARTOSAT-1 data of the area around Pathiyar village to measure the offset. Yellow lines mark the boundary of terrace risers and bank of river channel, (d-f) CARTOSAT-1 photos of the area around Pathiyar village showing best fit between blocks offset along the fault matching the terrace risers, first match shows offset of 40 m and second shows 70 m. This also suggests a young deformation along this segment of KVF.

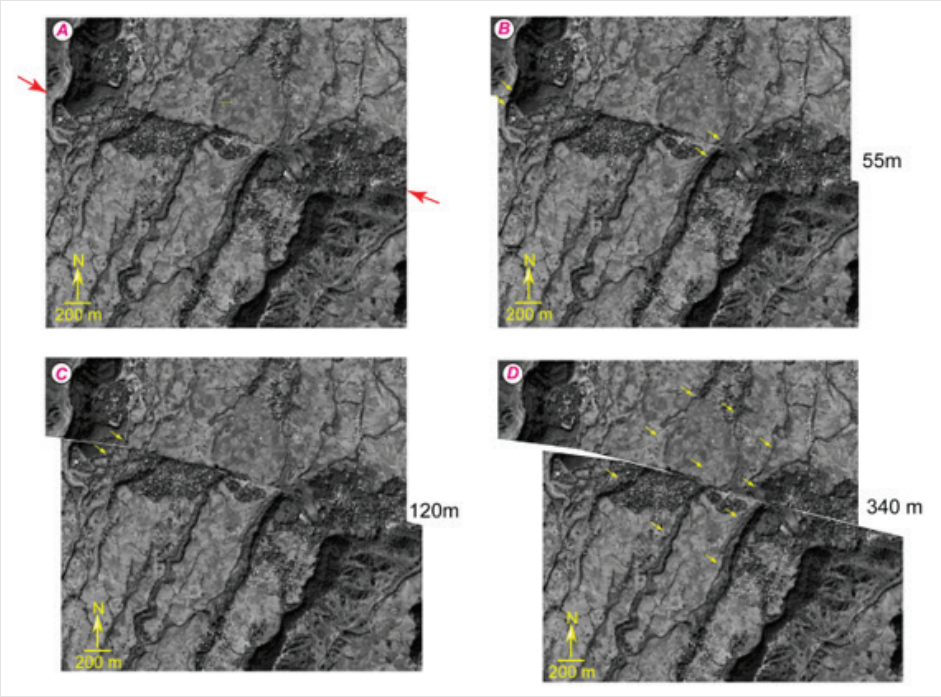


Fig. 29: (a) CARTOSAT-1 photo showing right lateral offset of alluvial fan surface and streams along KVF near Tangroti village in Kangra valley, (b) Best fit between blocks offset along the fault matching the landform and streams showing offset of 55 m. Vertically displaced alluvial fan surface and fluvial terraces has resulted in formation of north facing fault scarp, (b) matching eastern edge of the mound in the left side of the photo as well as streams suggested slip of 120 m, and (c) matching of west edge of the mound in the right side of the photo shows maximum displacement of 340 m. Yellow arrows indicated the matching landforms or streams.

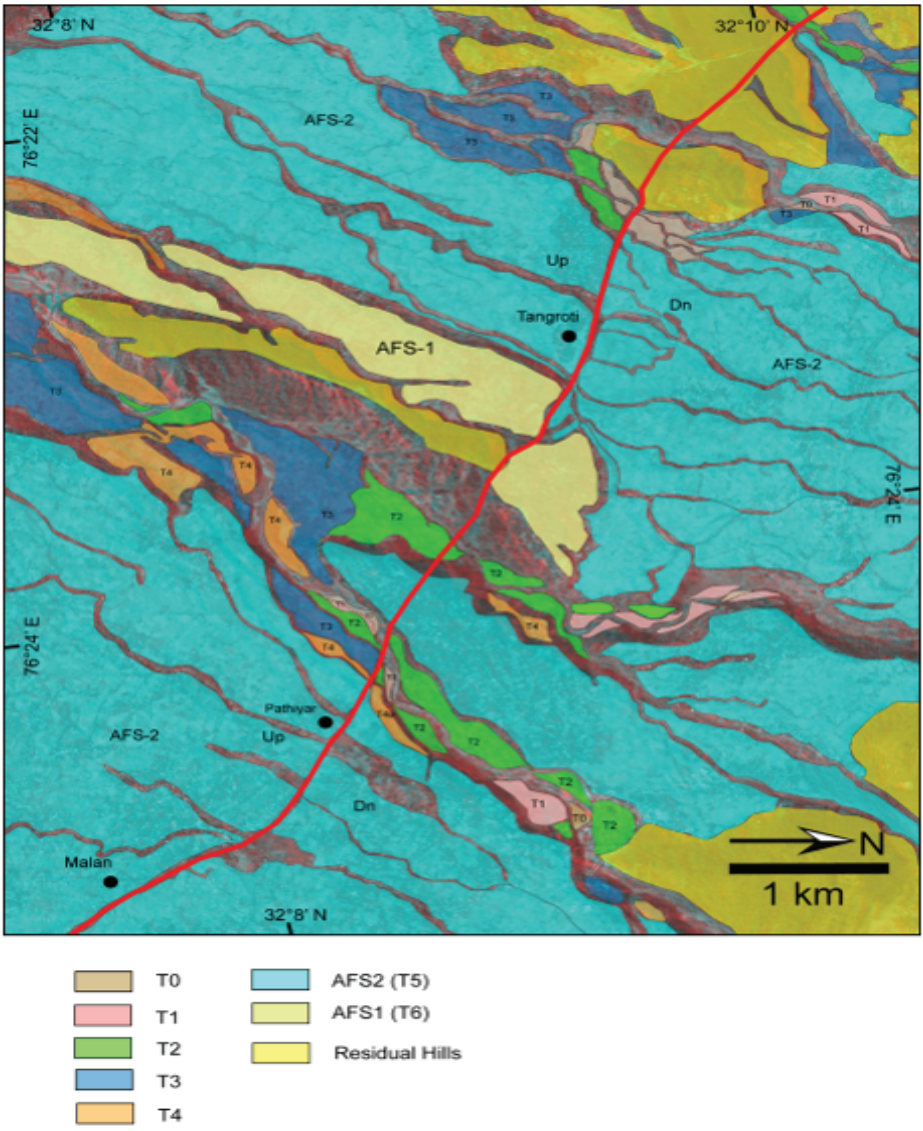


Fig. 30: A detailed geomorphic map of the study area around Pathiyar and Tangroti villages, showing distribution of different levels of terraces along Buner Khad and Iku Khad. Map traced on CARTOSAT-1 satellite image. At least 05 levels of terraces have been identified (T0 to T4) – these terraces are confined along the valley close to the fault line. Alluvial Fan Surface AFS1 is the older fan surface and AFS2 represent comparatively younger. The AFS2 shows extensive occurrence. The fault trace cutting through and displacing the terraces show and "S" shape pattern with NNW-SSE around Malan village, strike change to WNW-ESE between Pathiyar and Tangroti village and again follows the strike of NNW-SSE further west of Tangroti.

Day-4, STOP 1: Tangroti

The fault trace is more pronounced and linear on the surface near Tangroti Village. Both younger and older landforms have been displaced by the fault's vertical migration. The fault displaced older residual hills comprised of sandstone, shale, conglomerate of Siwalik-Dharamsala formation. Two levels of alluvial fan surfaces and younger fluvial terraces resulting into formation of north facing fault scarp with a scarp height of 2.5 m (Figs. 31-32).

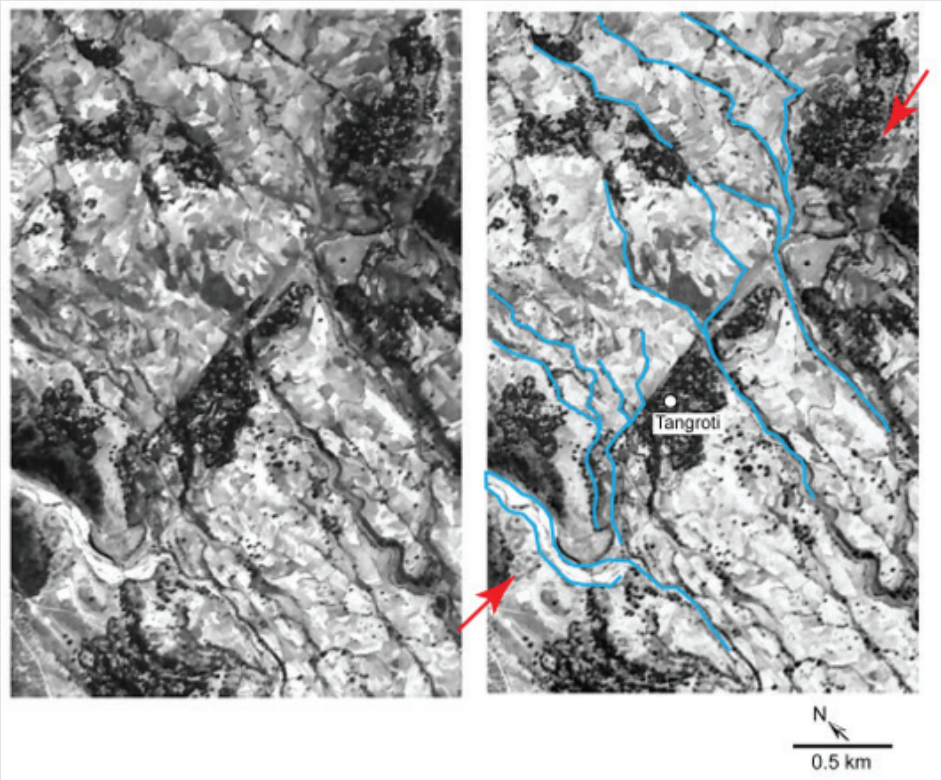


Fig. 31: Stereo-pair of high-resolution Corona satellite photos showing active fault traces (marked by red arrows) of study region (refer Figure 25 for location of active fault traces) near Tangroti village, Kangra.

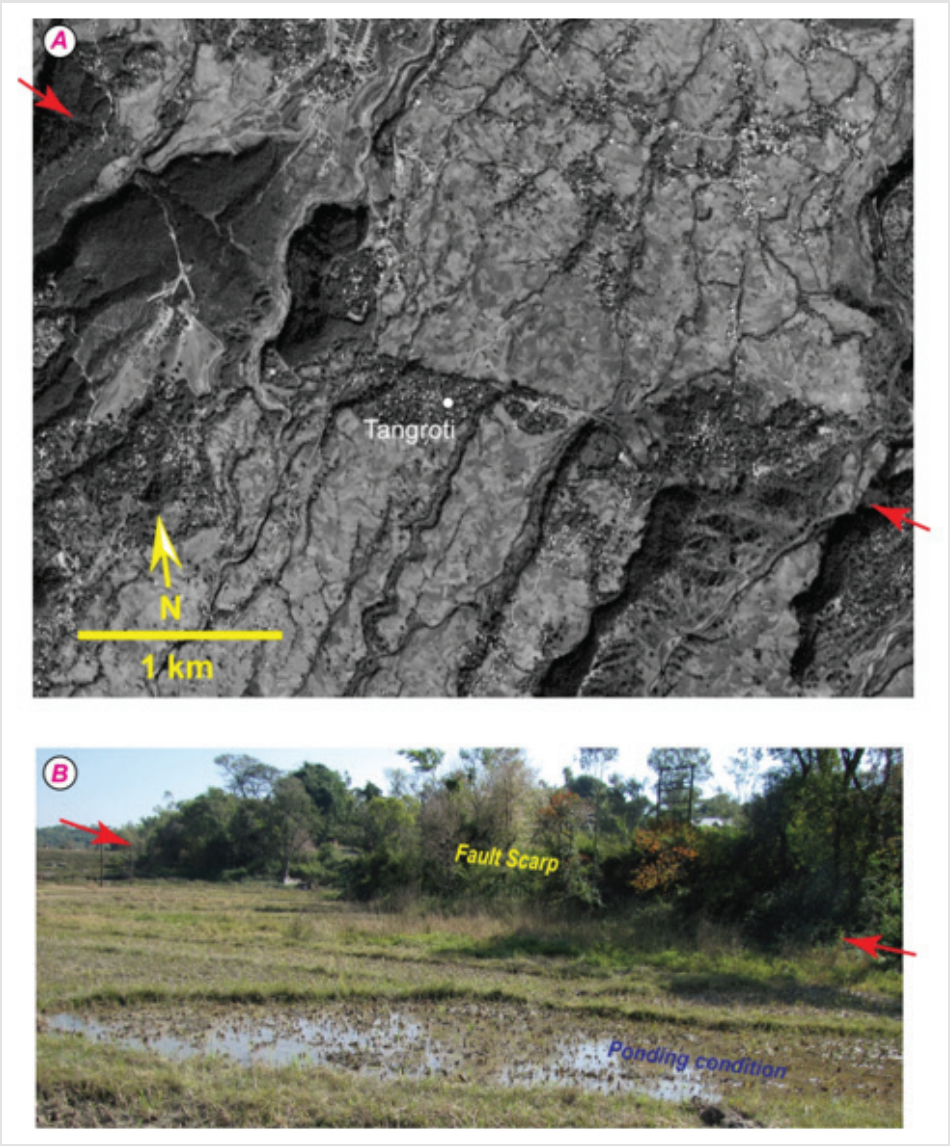


Fig. 32: (a) CARTOSAT-1 photo showing right lateral offset of alluvial fan surface and streams along KVF near Tangroti village in Kangra valley. Vertically displaced alluvial fan surface and fluvial terraces has resulted in formation of north facing fault scarp, (b) North facing scarp has resulted into ponding condition along the scarp.

Day-4, STOP 2: Pathiyar

A prominent active fault trace was observed at Pathiyar and Tangroti villages in Kangra valley (Fig. 31) in this window the fault is oriented in WNW-SE direction and extends for 6.5 km. Along the left bank of Buner Khad in Pathiyar Village, prominent terrace risers that were vertically displaced and right lateral were visible. The displacement of alluvial fan surfaces led to the development of these north-facing scarps, and the height of the fluvial terraces varies from 1.0 m on the southeast side at Pathiyar to 10 m on the northwest side along the bank of Buner Khad (Figs. 33). Granitic boulders that range in size from 1.5 to 2.0 meters in diameter make up the scarp.

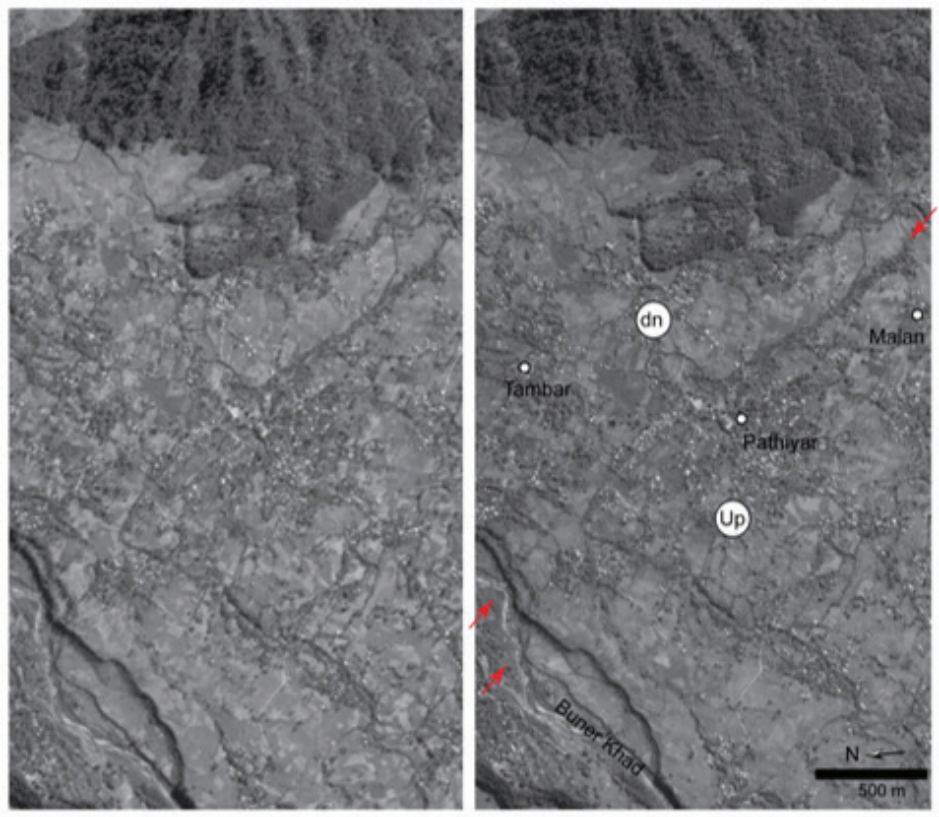


Fig. 33: Stereo photo of CARTOSAT-1 data of the area around Malan and Pathiyar villages. A prominent north facing fault scarp striking NNW-SSE is seen displacing the alluvial fan surface as well as terraces of Buner Khad stream. The height of the fault is higher of about 5-6 m around Malan and west of Pathiyar village near Buner Khad, whereas, about 1.5-2.0 m in the central part near Pathiyar. Right lateral offset of terrace risers was also noticed along the fault. The fault trace bifurcates near Buner Khad.

The fault trace in the southeastern portion between Malan and Pathiyar was marked with a distinct continuous linear valley (Figs. 33-34). The offset streams flow into a linear valley that follows the fault path for almost 1.5 km. Near Pathiyar village, a total offset of 40 m indicated by displaced terrace riser was measured (Fig. 28). However, towards Buner Khad, the entire offset increased to 70 m with a scarp height of 5–6 m.

Paleoseismic investigation

Based on the 2D and 3D GPR profiles collected across a young 1.5 to 2.0 m high north facing fault scarp, appropriate site was selected to excavate trenches to know (a) the pattern of deformation along KVF, (b) paleoseismic history and (c) the most recent event (MRE) occurred during recent historic past.Two trenches were excavated in the eastern segment of KVF. Trench-PT1 about 16 m in length, 2-2.5 m in depth and 2.5-3.0 m wide was excavated across NNW-SSE striking 1.2 m high fault scarp near Pathiyar Village, whereas trench-PT2, with dimension 15 m in length, 1-2.5 m in depth and 3.0 m wide was excavated within a low-lying depression located 160 m west of PT1 near Dadh Village (Figs. 35a-b). To have better correlation of displaced-deformed lithounits, sedimentary succession on hanging as well as foot walls were exposed. The sedimentary succession exposed in the trenches were classified based on their (a) physical properties i.e., color, texture (b) grain size, and (c) contact-bounding surfaces with respect to overlying and underlying lithounit (erosional or gradual). Based on these criteria the exposed lithounits in both the trenches were classified in total 11 number of lithounits, with Unit-a, be the youngest and Unit-k be the oldest (Figs. 35a-b; 36a-b,38b).

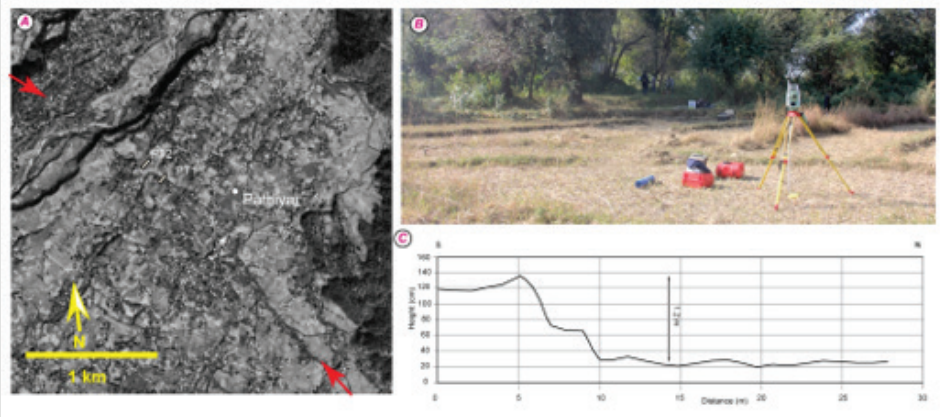


Fig. 34: (A) CARTOSAT-1 photo showing a trace of active fault striking NNW-SSE around Pathiyar village. The red arrows indicate active fault trace. (B) Field photo showing north facing active fault scarp near Pathiyar village, (C) Topographic profile collected with total station across the fault scarp. The height of the scarp is 1.2 m.

Sedimentary units

Litho-units exposed in both the trenches were observed and mapped to understand the overall depositional sequence and its relation to the tectonic deformations along KVF. All litho-units exposed in hanging wall as well as footwall were compared (Figs. 35a-b; 36a-b; 38b).

Unit-a is the youngest uppermost litho-unit representing the present day grayish yellow brown (10YR 6/2) clayey soil. It is exposed in both the trenches (PT1 and PT2) (Figs. 36a-b, 38b). The unit is only observed on the northern part of the trenches with thickness ranging from 15-25 cm. However, no trace of this unit was noticed on the upthrown side comprised of boulder deposits. In the northern part of the trench, at the base of the scarp unit-a caps the fault strands which have displaced the underlying lithounits during the latest event. It is marked by gradual contact with underlying unit-b but looks distinct because of colour contrast. This unit shows a typical mottled nature suggestive of deposition under clam environment.

Unit-b is a dull yellowish red colour (10 YR 6/4) unit made up of fine silty-sand. It shows gradual and undulating contacts with underlying and overlying units. This unit is exposed in both PT1 and PT2 trenches (Figs. 36a-b, 38b). Thickness varies from 15-25 cm, only exposed in the footwall side. Unit-c, is dull yellowish brown (10 YR 5/4) silty-sand unit with comparatively more content of clay. The contact is gradual to sharp with the under unit-d. The sharp contact with unit-d was observed in central and northern parts of the trench. It is marked by a concave bounding surface with underlying unit, suggestive of a shallow channel trough. Thickness of the unit varies from 10-60 cm, where the thicker part represents the deeper part of the channel trough. It is suggested that this channel flowed parallel to the scarp after the earthquake.

Unit-d, is light brown (10 YR 5/6) silty-clay soil marked by a diffused contact with underlying Unit-f. In the northern part of the trench this unit caps a shallow channel comprised light yellowish brown clayey deposits Unit-e. The thickness of Unit-d varies from 20-40 cm. This unit is displaced along the fault strand F1, and scattered fragments and vertically squeezed layers are noticed in the faulted zone in the southern part of the trench.

Unit-e, is light yellowish brown (10 YR 5/2) clayey channel-fill deposit. It is marked by prominent channel trough, with irregular-sharp contact with underlying Unit-f. The maximum depth of the channel is about 0.8 m. The deposits clearly suggest a very clam and low energy condition. Based on the orientation of channel-trough in WNW-ESE trend it can be suggested that a shallow channel developed after the earthquake event that flowed along the base of the north facing fault scarp (Figs. 36a-b; 37a). This unit was only exposed in trench PT1.

Unit-f, is the most prominent brownish black (10 YR 3/2) unit exposed in both the trenches (PT1 and PT2). It is made up of medium-fine sand in trench PT1 and fine gravel with coarse sand matrix in PT2. It also comprises whitish caliche nodules. Thickness varies from 0.5-1.0 m, with lesser thickness to the southern side on the hanging wall and thicker in the northern part of the trench. The brownish black colour of Unit-f indicates that the soil unit is humus rich and was formed under a reducing environment. It is further suggested the uplift and

lateral displacement along fault resulted into damming of the south flowing drainage. This unit was deposited after the earthquake event in a marshy environment (Figs. 36a-b; 38b).

Unit-g, 10 YR 3/3- Dark brown clayey unit underlying Unit-f. This unit also shows presence of scattered fine caliche nodules. It is exposed in both the trenches and marked with a gradual contact with overlying unit. This unit indicates deposition under calm environment due to blocking of drainage along the north facing scarp.

Unit-h, represents matrix supported debris deposits exposed on the hanging wall in the southern side of the trench, and observed in both the trenches (Figs. 36a-b; 38b). The fragment size in this unit varies from 15-20 cm to 1.5-3 m in diameter (Figs. 36a-b; 37a-b; 38b). It rests over a 10-15 cm thick greyish green colour medium to coarse sand Unit-i. The underlying Unit-j is reddish color fine silty unit. It is massive in nature with sharp contact with overlying unit. This reddish unit indicates warm phase and represents the older alluvial fan surface. From the stratigraphic sequence exposed in the trenches it is suggested that the boulder Unit-h mark the alluvial fan aggradational phase. Unit-k, is the oldest unit exposed in the trench. This unit comprises coarse sand.



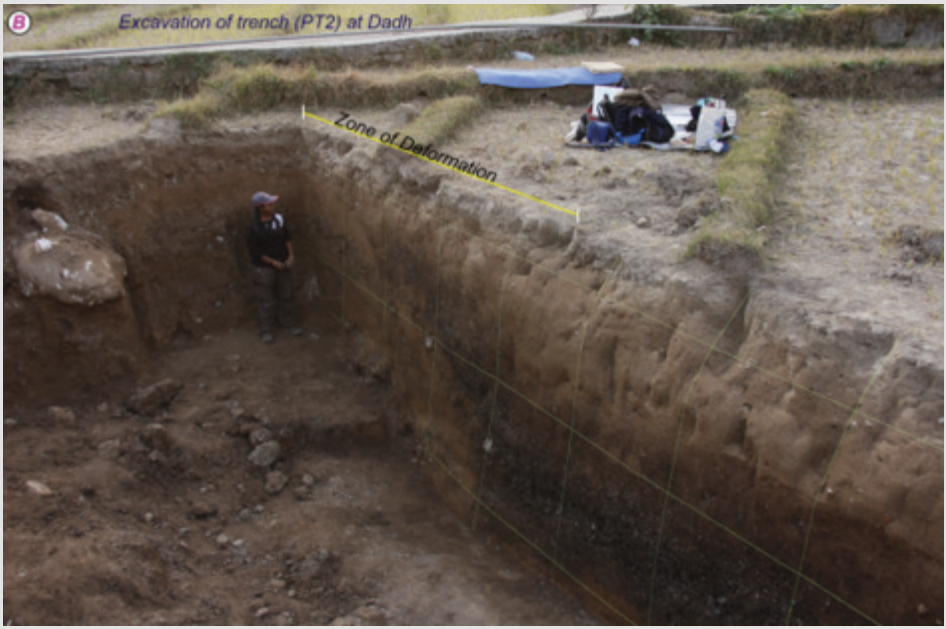


Fig. 35: (a) The excavated trench (PT1) across KVF near Pathiyar village, (b) Trench PT2 excavated at Dadh village.

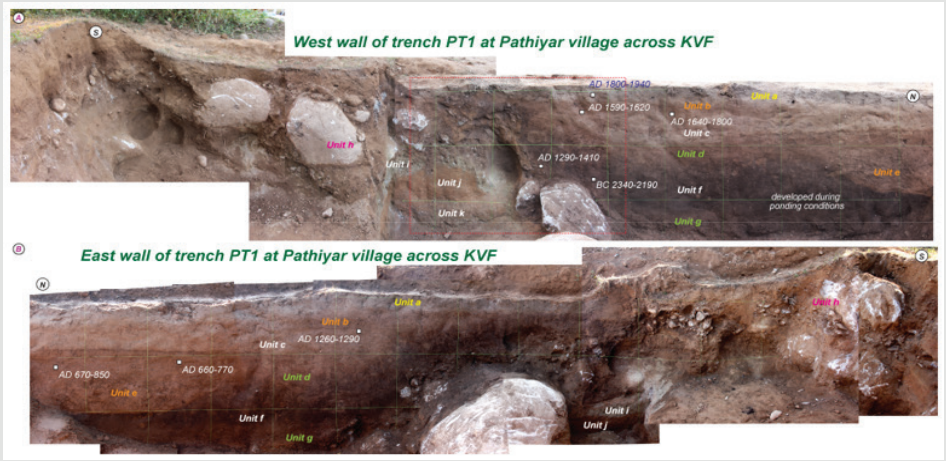


Fig. 36: (a) Photo mosaic of the west wall of PT1 trench. Based on the physical properties the exposed sediment succession was divided into 11 units, Unit a, is the youngest and Unit k represents older. Fault zone comprised of vertical to sub-vertical faults splaying out towards top has displaced Units b to k. Fault zone is extended for about 5 m. Charcoals from exposed litho-units from west and east walls yielded ages of BC 2340-2200 from Unit f, AD 1290-1410 obtained from Unit f (from fault zone), AD 1590-1620 and AD 1640-1800 from Unit b, AD 1800-1940 from Unit a. (b) Charcoals from the east wall yielded ages of AD 670-850 and AD 660-770 from Unit d, AD 1260-1290 from Unit c.

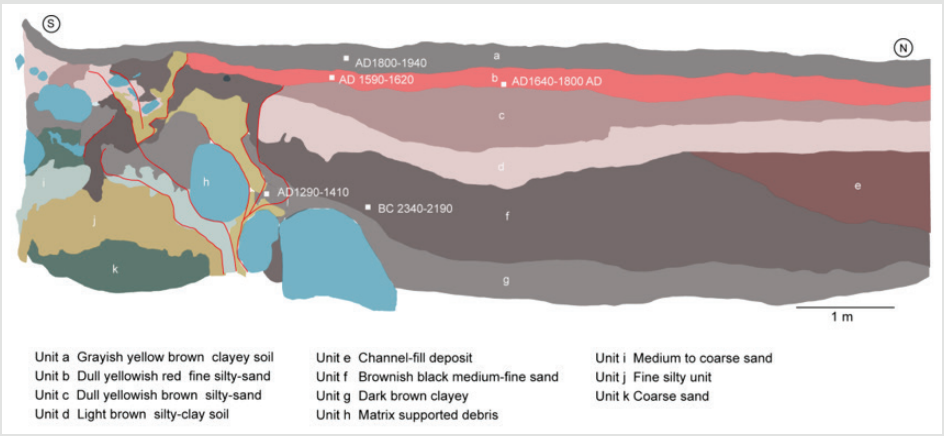


Fig. 37: (a) Trench log of west wall (PT1) showing litho-units exposed on hanging wall and footwall. A typical positive flower structure is seen on the southern side marked by vertical to sub-vertical branching out fault strands. All these fault strands merge or converge down into a narrow fault zone.

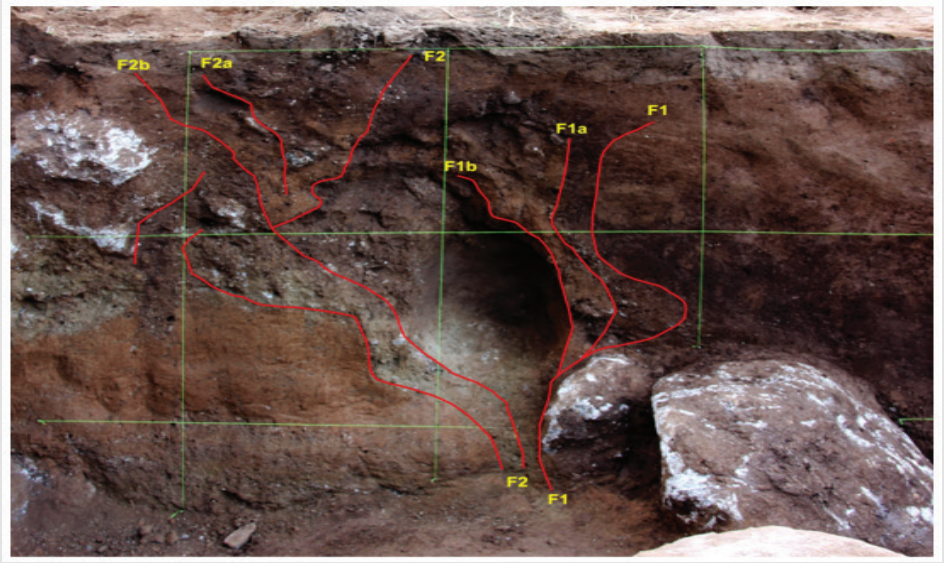


Fig. 37: (b) Close-up view of rupture zone exposed in a trench – PT1 excavated across KVF at Pathiyar village. From the pattern of displacement, it is suggested that most recent event occurred along F2 and penultimate along F1 displacing Units f to b and finally capped by Unit a. Displacement along F1 strand stops at about 40 cm from the surface. It has displaced Units c, d, f and g, putting Units f and g are vertically stacked along the fault zone – clearly indicated by squeezed units between F1a and F1. It is suggested that Units c, d, f and g were faulted during penultimate event, the event occurred after Unit c and before the deposition of Unit b. Similarly, the most recent event displaced and squeezed almost all units – Units b-k, finally capped by Unit a (present day soil). For location of this figure refer Figure 26.

Sr. No.	Sample Number	Lab. Sample Number[a]	Trench and wall	Unit[e]	Material	Location	$\delta^{13}C(o/\infty)$[d]	Conventional Age(BP)[b]	Radiocarbon Age (BP)	Calibrated Age(2σ)[c]
1.	JNMPC10	350428	PT1 West Wall	A	Charcoal	Foot wall	-24.1	120 ± 30	110 ± 30	AD 1800-1940
2.	JNMPC11	350429		B	Charcoal	Foot wall	-24.9	400 ± 30	400 ± 30	AD 1590-1620
3.	JNMPC13	369146		B	Charcoal	Foot wall	-23.1	230± 30	200± 30	AD 1640-1800
4.	JNMPC9	350427		F	Charcoal	Fault zone	-22.9	610 ± 30	580 ± 30	AD 1290-1410
5.	JNMPC12	350430		F	Charcoal	Foot wall	-24.6	3810 ± 30	3800 ± 30	BC 2340-2190
6.	JNMPC8	350426	PT1 East Wall	C	Charcoal	Foot wall	-26.6	730 ± 30	760 ± 30	AD 1260-1290
7.	JNMPC4	350425		D	Charcoal	Foot wall	-22.6	1260 ± 30	1220 ± 30	AD 670-850
8.	JNMPC7	371327		D	Charred material	Foot wall	-25.7	1310± 30	1320± 30	AD 660-770
9.	JNMPC18	350432	PT1 West Wall	B	Charcoal	Fault zone	-24.0	2700 ± 30	2680 ± 30	BC 900- 800
10.	JNMPC19	353031		C	Charcoal	Fault zone	-11.2	580 ± 30BP	350 ± 30	AD 1300-1420
11.	JNMPC24	369148		C	Charcoal	Foot wall	-27.8	390± 30	440± 30	AD 1590-1630
12.	JNMPC21	371328		F	Charred material	Fault zone	-25.6	2810± 30	2820± 30	BC 1020-900

[a]Samples were processed and measurements were carried out at Beta Analytic Radiocarbon Dating Laboratory, Miami, Florida, USA.

[b]Conventional Radicarbon Age (CRA) was calculated according to Stuiver and Polach (1977) and it represents the Measured Radiocarbon Age (MRA) corrected for isotopic fractionation, calculated using δ13C.

[c]"Calibrated" or calendar ages were calculated using "INTCAL09" database (Stuiver et al., 1993, Heaton et al., 2009, Reimer et al., 2009)

[d]δ13C was calculated relative to the PDB-1 standard.

[e]Refer Figure 36a-b,38b for sample locations.

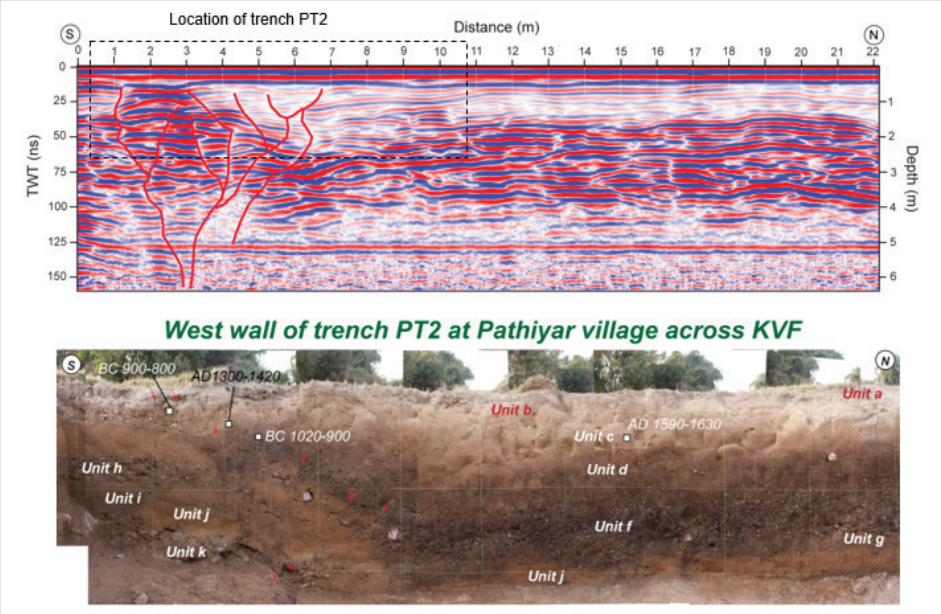


Fig. 38: (a) GPR profile collected with 200 MHz antenna near Dadh village (b) Photomosaic of west wall of trench PT2 at Dadh. Zone of deformation extends for 4.5 m in the southern side of the trench. The fault zone has displaced Units b to k. The detrital charcoal from faulted zone yielded ages of BC 900-800, BC 1020-900 and AD 1300-1420, and AD 1590-1630 from Unit c. Black box with broken line shows location of trench.

Chronology

Detrital charcoals collected from exposed litho-units in trenches PT1 and PT2 yielded ages ranging from BC 2340-2200 to AD 1800-1940 (Table 2; Figs. 36a-b, 38b). The charcoal from west and east walls of PT1 yielded ages of BC 2340-2200 from Unit f, AD 1290-1410 obtained from fault zone, AD 1590-1620 and AD 1640-1800 from Unit b, AD 1800-1940 from Unit a (from footwall). Charcoals from the east wall yielded ages of AD 670-850 and AD 660-770 from Unit d, AD 1260-1290 from Unit c. The detrital charcoal from PT2 trench from faulted zone yielded ages of BC 900-800, BC 1020-900 and AD 1300-1420, and from footwall AD 1590-1630 from Unit c.

Deformation and Paleoseismic events

The characteristics of litho-units on the hanging wall and footwall as well as cross-cutting relationship within the fault zone, helped in understanding the pattern of deformation along the KVF. The GPR profiles marked by warped and displaced reflections, and the displaced-deformed litho-units mapped in trenches (PT1 and PT2), clearly revealed the reverse as well as lateral components along KVF due to oblique movement (Figs. 36a-b; 37a-b; 38a-b). The pattern of fault strands observed in GPR profiles and in exposed trench walls resemble a typical positive flower structure commonly observe in a strike-slip duplexes

(Figs. 37a-b; 38a). It also suggested that if the vertical component is reverse, the branching out splay faults have a tendency to be convex upward, with gentle dips at the surface. This pattern of deformation will usually cause uplift of the area, resulting into formation of pressure ridges. These splays converge down into a main fault.

Based on the AMS dates obtained from PT1 and PT2, and cross-cutting relationship of respective litho-units with one another it can be suggested that at least four major earthquake events have occurred along KVF during recent historic past. From the pattern of displacement observed in PT1, it is suggested that most recent event occurred along F2 and penultimate along F1 displacing Units f to b and finally capped by Unit a (Fig. 37b). Displacement along F1 strand stops at about 40 cm from the surface. It has displaced Units c, d, f and g, putting Units f and g are vertically stacked along the fault zone – clearly indicated by squeezed units between F1a and F1. It is suggested that Units c, d were faulted during penultimate event, the event occurred after Unit c and before the deposition of Unit b. Similarly, the most recent event displaced and squeezed almost all units – Units b-k, finally capped by Unit a (present day soil). An attempt has been made to resort the displaced unit at different stage during different events. The whole deformation based on the present trenches is presented in five stages (Fig. 39).

Stage I

During this stage due to occurrence of Event-I the alluvial fan surface sloping towards south was displaced resulting in north facing active fault scarp along the fault trace (Fig. 39). The stream flowing across this area before fault got blocked or deflected due to vertical displacement of fan surface. The two Units f and g abut against the north facing fault scarp. The Unit g is clayey, and the overlying Unit f is black humus reach soil. This clear indicates that vertical displacement resulted into development of ponding condition due to blocking of south flowing stream. The organic reach black soil was formed under marshy environment. The detrital charcoals from Unit f (fault zone) in trench-PT1 yielded an age of AD 1290-1410 and BC 2340-2190 (Table 2 and Fig. 36a). Therefore, considering the ages from Unit f and fault zones observed in PT1 and PT2 it is suggested that Event-I might have occurred before BC 900. Whereas ages comparatively younger than BC 2300 ranging from BC 900-800 and BC 1020-900 were obtained from the fault zone of trench PT2 (Table 2. and Figure 38b). Also, another sample from the fault zone from PT2 gave much younger age of AD 1300-1420 (Fig. 38b). However, if we consider the ages yielded by Unit d (capping the channel deposit Unit e) from east wall of PT1 ranging from AD 670-850 and AD 660-770, it is quite logical to infer that Event-II may have possibly occurred between BC 900 and AD 850 (Figs. 36b and Table 2).

Stage II and III

During Stage-II, the basin started filling up and deflected stream flowed along the scrap incising the Unit f (Fig. 39). This is well revealed by a shallow channel (Unit e). Further the overbank deposition of finer deposits marked by Units d and c. Taking into account the ages from Unit d of AD 670-850 and AD 660-770 (from east wall of PT1), and AD 1260-1290 from Unit c, it suggested that the deposition of these units continued up to or later than AD 1290.

Stage IV

This stage suggests lateral as well as vertical displacement of all units (i.e., Units g to c), with Unit c as event horizon (Fig. 39). The Event-III occurred after the deposition of Unit-c and before the capping Unit b. This event occurred along fault strand F1. Based on the ages from Unit c AD 1260-1290 (from east wall PT1) and AD 1300-1420 (from fault zone PT2), and the ages of AD 1590-1620 and AD 1640-1800 from Unit b (footwall east wall PT1) it is suggested that Event-III occurred during AD 1600-1800.

Stage V

Stage V represents the present-day condition in which all the lithounits except Unit-a, are folded, displaced and intermixed in the fault zone (Fig. 39). Displacement during most recent event (MRE) occurred along F2, displacing again all units, with Unit b as event horizon. Finally, the fault strand F2 along with other splays are F2a and F2b are capped by Unit a. Considering the ages of AD 1640-1800 from Unit b and age of AD 1800-1940 from Unit a, it is suggested that the MRE, Event-IV occurred during AD 1800-1940, i.e., after Unit b and before Unit a.

The paleoseismic investigation carried out along KVF helped in understanding the pattern of deformation and occurrence of earlier events those occurred during recent historic past. Two trenches excavated across KVF near Pathiyar and Dadh revealed the paleoseismic history of faulting between BC 900 and 1940. Based on the characteristics of the sedimentary units, deformation pattern and cross-cutting relationship between the exposed units along the fault strands it has been suggested that at least four major earthquake events have occurred along KVF during recent historic past. We suggest that Event I occurred before BC 900, Event-II took place between BC 900 and AD 850, this shows wide range which need to sort out with more dating of samples or dating these units with OSL technique. Event-III occurred during AD 1600-1800 and Event-IV (MRE) occurred during AD 1800-1940. Considering the AMS ages and displacement reaching up to the surface capped by present day soil, it is suggested the Event-IV can be correlated with the most devastating earthquake of 1905 Kangra earthquake (Mw7.8) so far experienced in Himalayan domain.

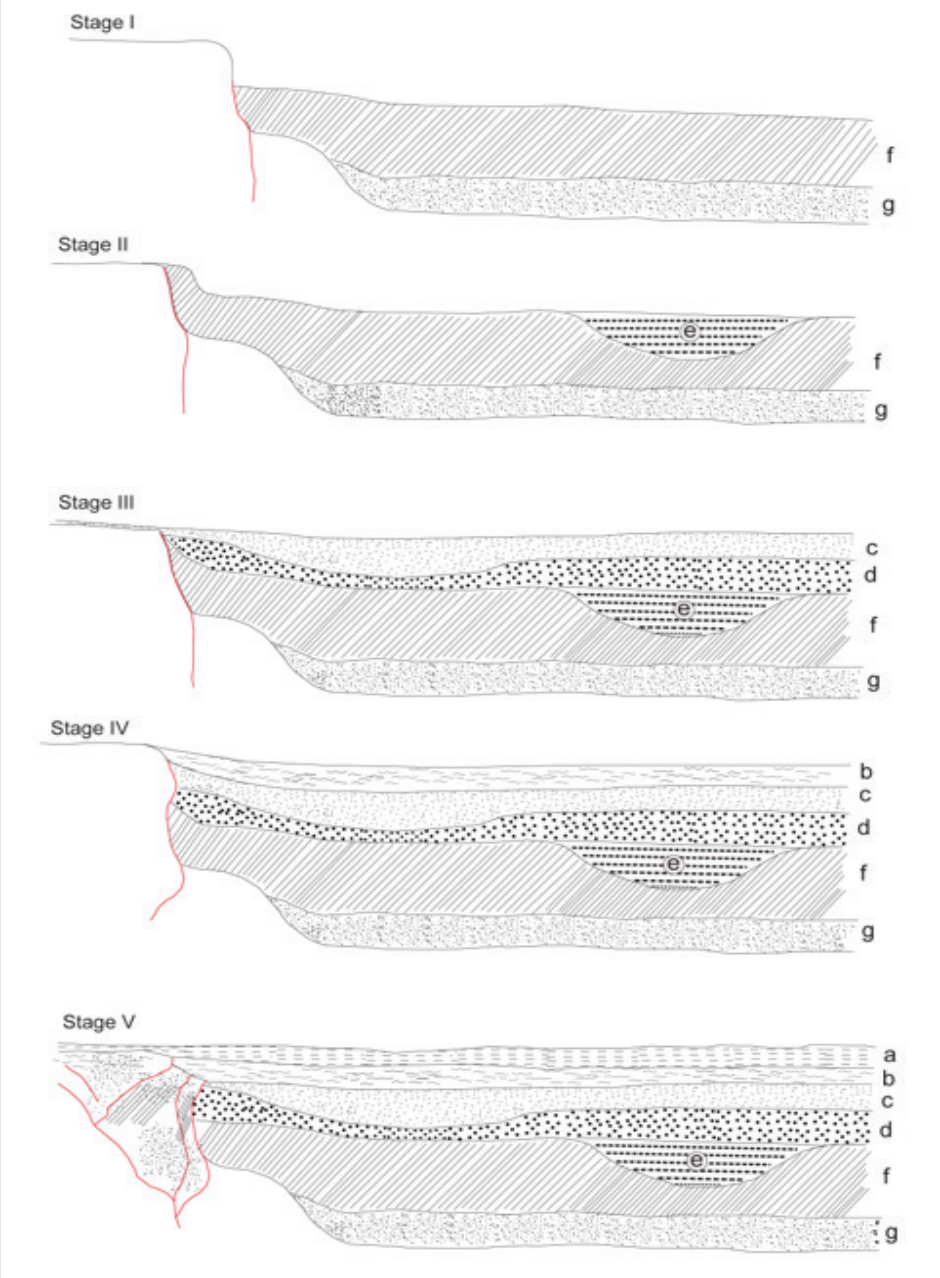


Fig. 39: Schematic view of trench log (PT1) showing sequence of faulting and depositional phases from Stage I to V.

Day-5, Sihunta-Garnta-Samot Transect

Day-5, STOP 1: Sihunta

The Sihunta Dun located west of Dharamsala is a small valley that extends for about 10-12 km in length between Mahetra and Patka Village (Fig. 25). It is marked by variable width of about 1.5-2.0 km in the east and west, and about 4.5 km in the central part (Figs. 40).

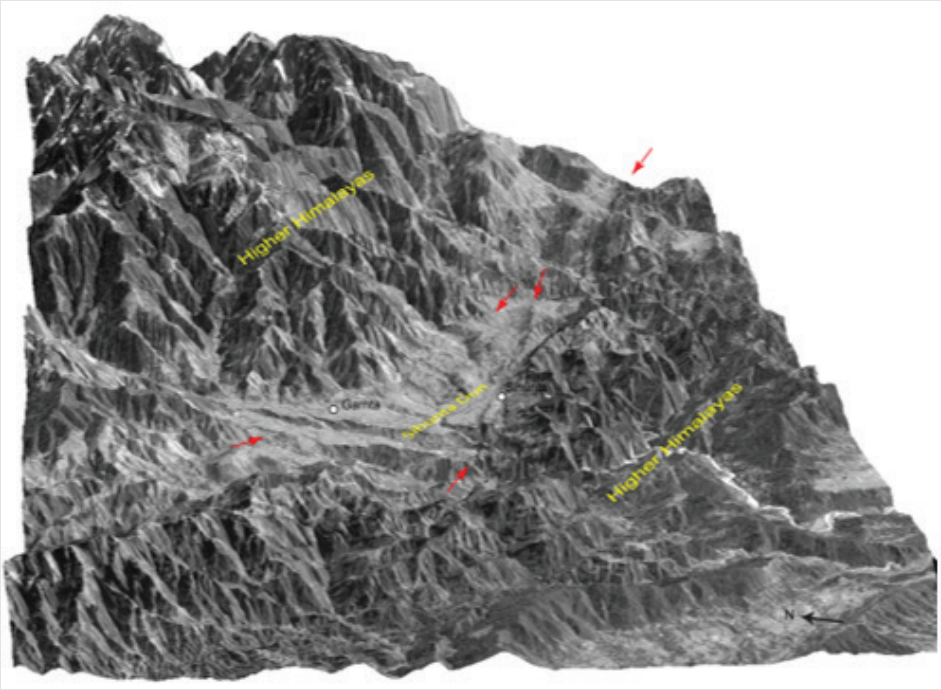


Fig. 40: 3-D perspective view of the terrain of the around Sihunta valley (Dun). The Sihunta valley is marked as "V" shaped valley – with a length of 10 km in east-west direction, 1.5-2.0 km width in eastern and western edge and about 4.5-5.0 km in the central part. The fault distribution is indicated by red arrows – forming a "Y" shaped pattern. The fault traces have displaced alluvial fan surfaces in their proximal, medial and distal part. The fault scarps near Sihunta are north facing, around Garnta and at the base of the mountain range is south facing.

The KVF after traversing the rocky terrain, runs through Sihunta Dun for about 10 km displacing the alluvial deposits between Sihunta and Garnta villages (Fig. 40). As observed in the eastern part i.e., around Pathiyar and Malan, the fault trace in Sihunta Dun bifurcates and branches out by stepping to right resulting into "Y" shape pattern (Fig. 25; 40; 41). The fault branches out from Mahetra village and changes its strike to NW-SE passing through Sarog, Garnta and Samot villages (Figs. 40; 41; 43; 44). Whereas it follows the strike of WNW-ESE between Mahetra and Sihunta, same as that of the main fault. Here the manifestation of 15-20 m high north facing scarp is a testimony to the long-term tectonic displacement along

this fault (Figs. 25-26). After bifurcation, the branch-out fault runs along the range front between Sarog and Garnta villages (Figs. 41-43).

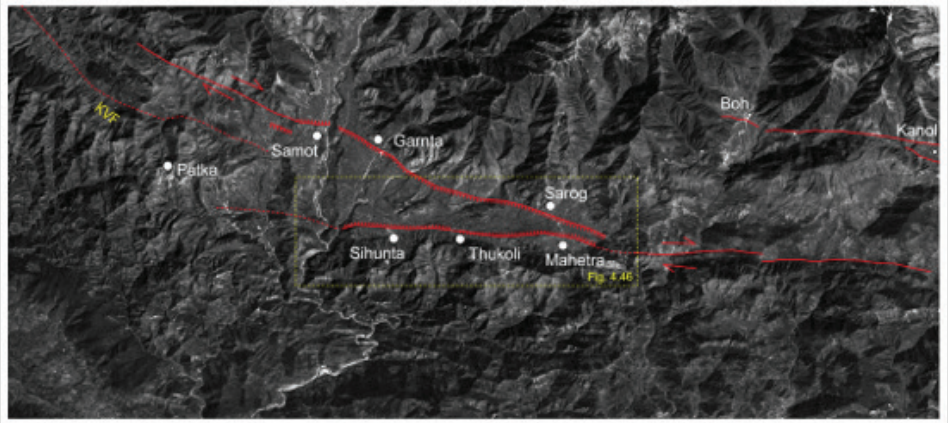


Fig. 41: CARTOSAT-1 photo showing landscape, fault topography and distribution of fault traces along KVF and its branching fault around Sihunta and Garnta villages in the western part in Sihunta valley. Here one of the splays of KVF shows stepover to right a few km before Mahetra village. The fault scarp around Sihunta is marked with north side down, whereas, after taking right step it shows south side down. For location refer yellow box marked in Figure 25.



Fig. 42: A panoramic view of the Sihunta valley (Dun) showing the Dhauladhar range in the north and extensive flat terrain representing the alluvial fan surfaces (AFS1 and AFS2). The active fault (trace marked by red arrows) has displaced older (AFS1) as well as younger (AFS2) surfaces resulting into north side up and south side down near Garnta side (with south facing scarp) and south side down and north side up (with north facing scarp) near Samot Village. The fault has displaced both AFS1 and AFS2. Photo taken from Sihunta looking towards Garnta and Samot.

The fault along with lateral offset of streams has vertically displaced the alluvial fan surfaces in their proximal part resulting into south facing fault scarps (Figs. 41-43). The branch-out fault has displaced the proximal and medial part of the alluvial fan surfaces (Figs. 41-43). Further, a typical characteristic pattern of vertical component along right-lateral strike-slip fault marked by upthrown side located on the north in the eastern section and downthrown side on the south in the western section was identified near Garnta-Samot located in the NW part of the fault trace (Figs. 45-48). The fault has displaced and offset higher (AFS1) and lower (AFS2) fan surfaces (Figs. 42; 45-48). This characteristic pattern of vertical slip distribution along the strike-slip fault may be used for identification of fault segments as suggested by Nakata et al., (2000).

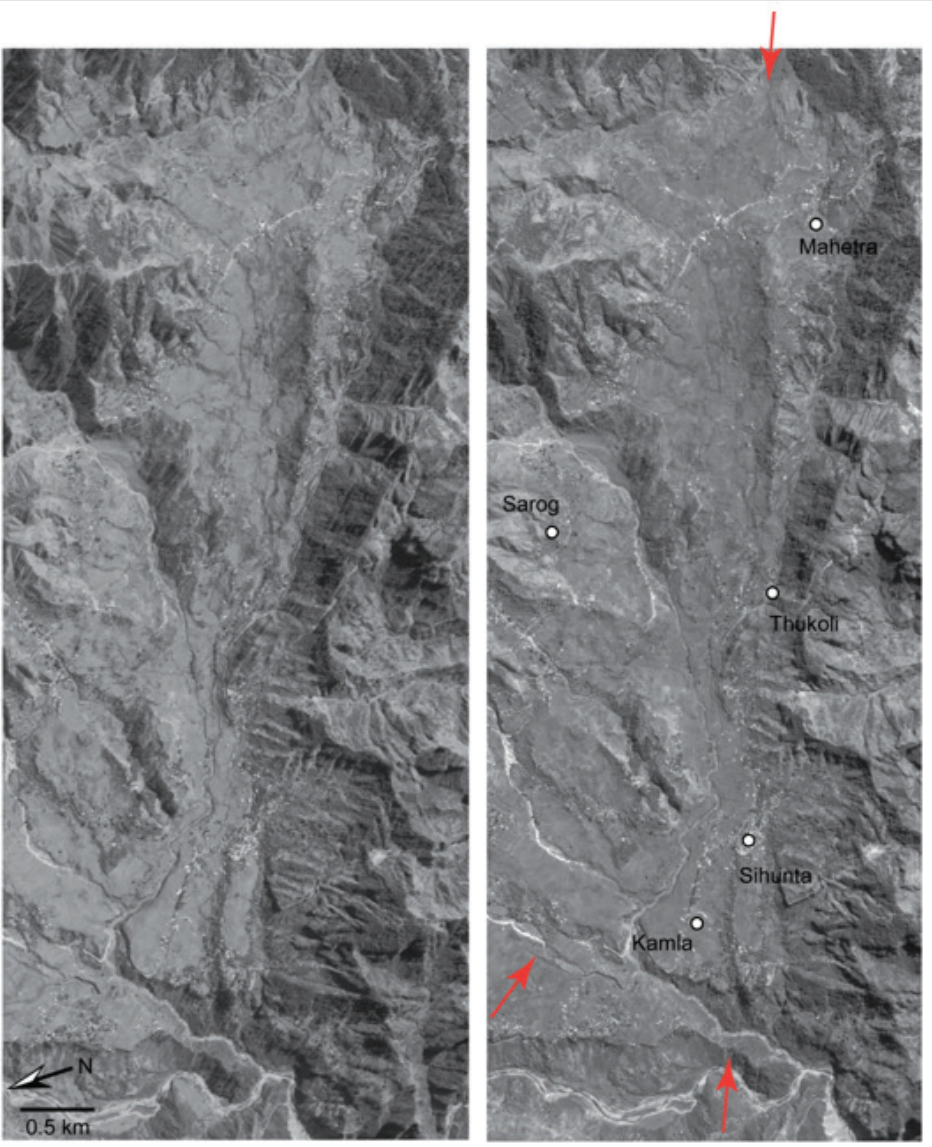


Fig. 43: Stereo-pair of CARTOSAT-1 data of the area in Sihunta Dun. The fault traces (marked by red arrows) show typical "Y" shaped pattern, branching out from Mahetra Village. The fault with strike WNW-ESE follows the southern edge of the Sihunta Dun displacing the distal part of fan surfaces giving rise to north facing scarps. Whereas the branched fault with NW-SE strike follows the range front along the northern edge for few km and then displace-offset the medial part of the alluvial fan surfaces as well as minor and major streams. A total offset of 10 m was measured in the field.



Fig. 44: A view of north facing fault scarp near Sihunta. The scarp height is about 15-20m.

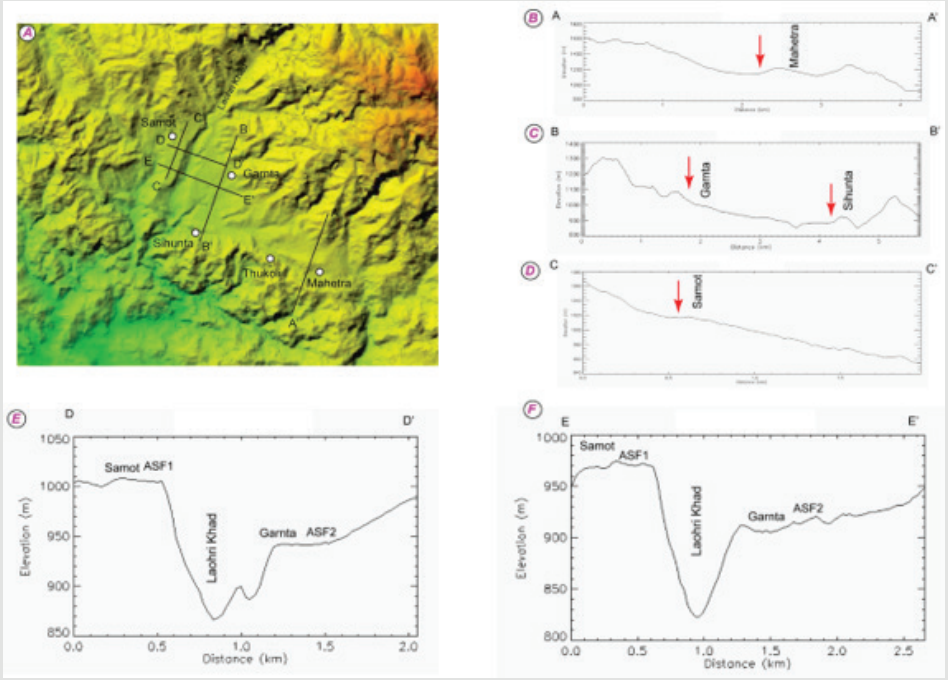


Fig. 45: (a) Shaded-relief map of Sihunta Dun. Lines are the location of topographic and cross-sectional profiles, (b, c and d) Topographic profiles extracted across the Sihunta Dun. Profile AA' shows north face scarp, BB' shows north facing scarp near Sihunta and south facing scarp near Garnta, (e and f) cross-sectional profile across Laohri Khad, the profiles show a deep incision and two level of surface – Older AFS1 and Younger ASF2. It shows incision of 150 m with respect to AFS1 and 90 m with respect to AFS2. Red arrows show location of fault traces.

The most prominent offset measured on satellite data and field was observed between Garnta and Samot (Figs. 46-49). This is well marked by a right-lateral offset along the left bank of Laohri Khad. A total offset of 10 m was measured in field (Figs. 46-49). The total vertical displacement probably represents evidence of long-term tectonic activity along KVF. However, looking to the lateral offset of 10 m may be indicative of displacement during one single event (Figs. 46-49). The oblique slip along KVF has given rise to 14 m high south facing fault scarp composed of granite boulders (Figs. 48a-b).

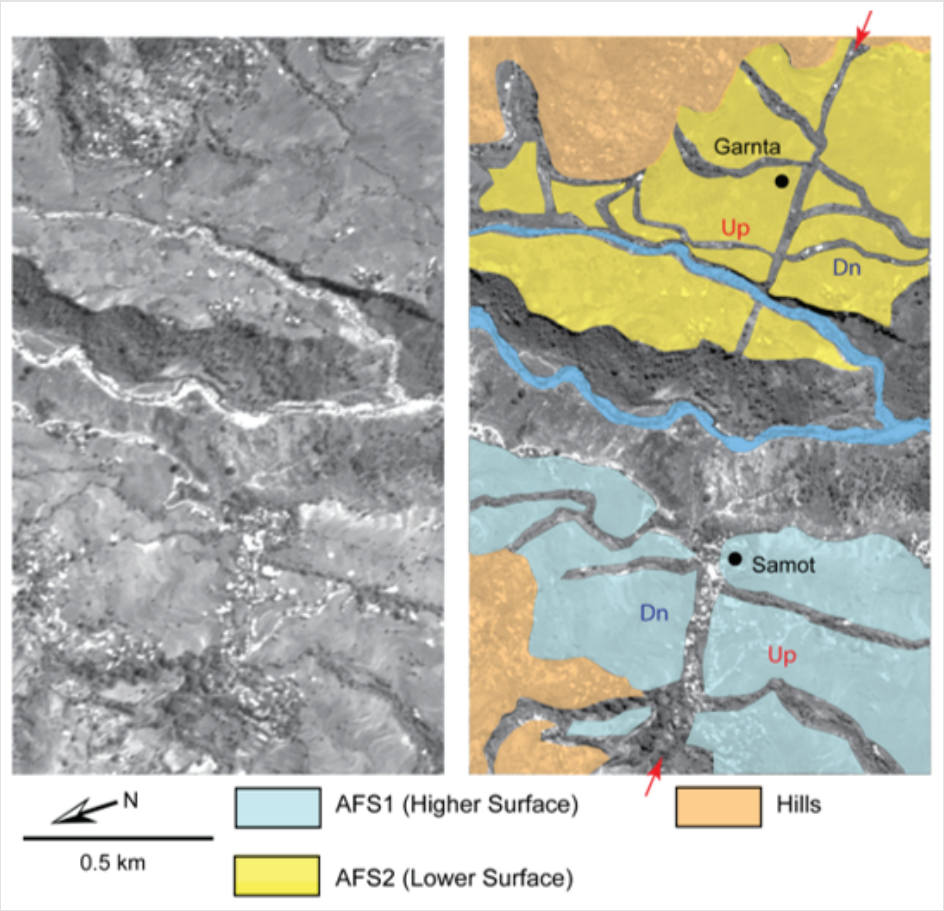


Fig. 46: The active fault (trace marked by red arrows) has displaced older (AFS1) as well as younger (AFS2) surfaces resulting into north side up and south side down near Garnta side (with south facing scarp) and south side down and north side up (with north facing scarp) near Samot Village. The fault has displaced both AFS1 and AFS2.

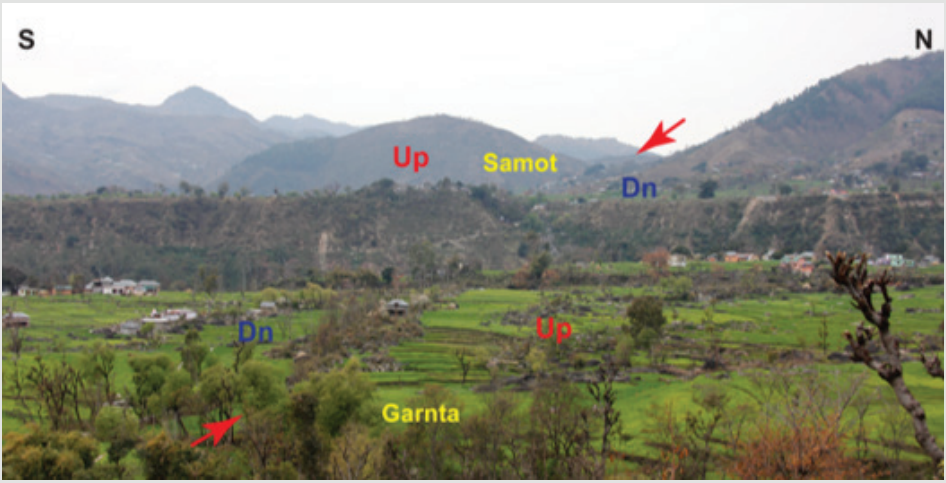


Fig. 47: A view of vertical component along right-lateral strike-slip fault marked by upthrown side located on the north in the eastern section and downthrown side on the south in the western section near Garnta-Samot located in the NW part of the fault trace. The fault has displaced and offset higher and lower fan surfaces.

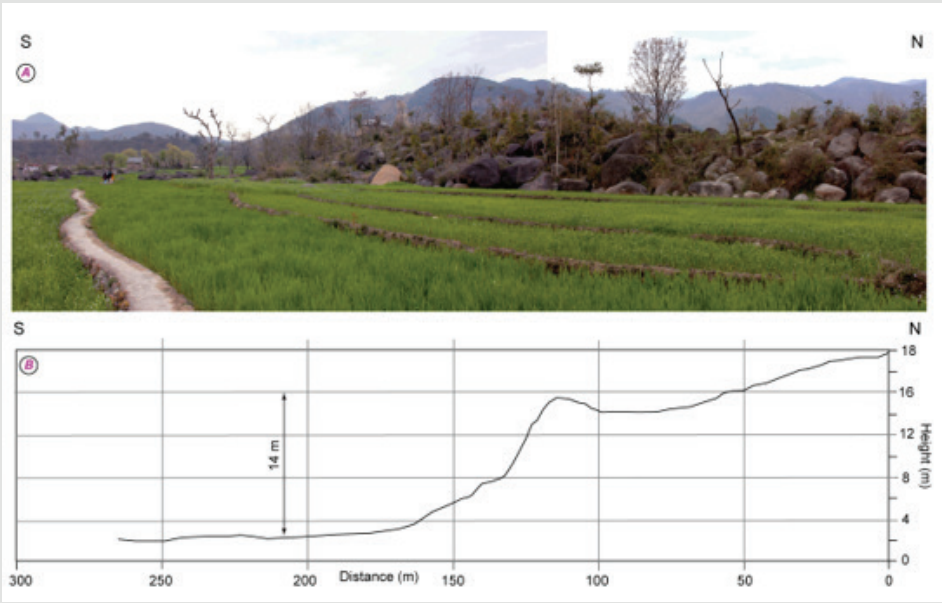


Fig. 48: (a-b) NW-SE striking fault scarp near Garnta. Vertical displacement along KVF has resulted into formation of 14 m high south facing fault scarp comprised of granitic boulders.

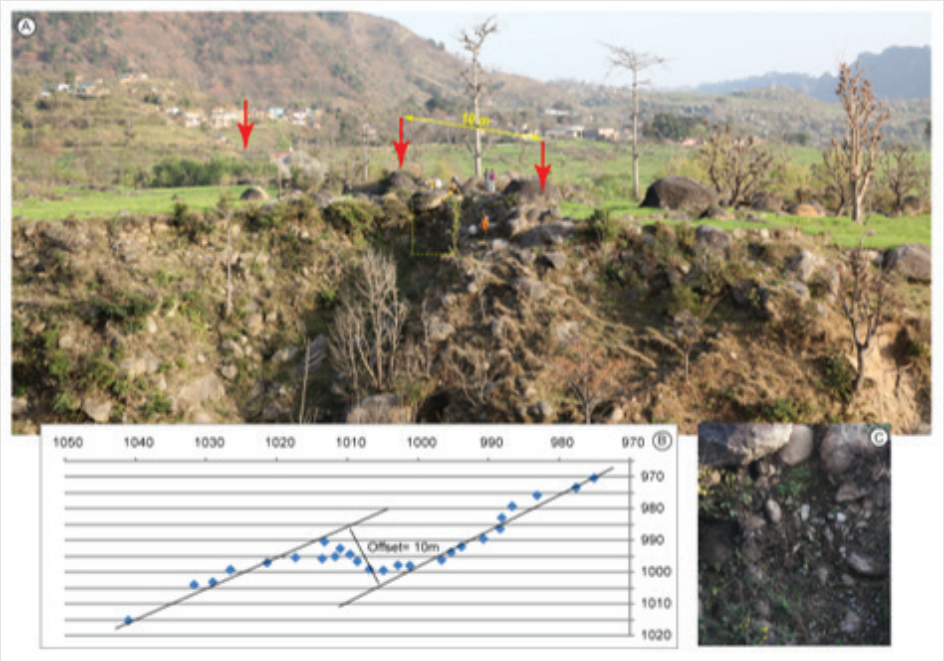


Fig. 49: (a) Right lateral offset of left bank of Laohri Khad. Offset measured in field is 10 m NW-SE. Fault trace is marked by red arrow, (b) Lateral offset measured in field, (C) Close-up view of shear zone marked by vertically stacked cobbles and boulders along the fault plane.

Day-5, STOP 2: DAL LAKE, NADDI

North of Dharamsala and NW of McLeodganj the displacement is well manifested by a very sharp linear fault trace and series of sag ponds (Figs. 50-51). The fault topography with north side down and sag ponds can be traced up to Naddi. One of the sag ponds is presently utilized as playground by local residents – TCV playground, whereas the other one – Dal Lake is an attraction for tourists in the McLeodganj area (Figs. 50-51). The Dal Lake is about 280 m long and 90 m wide. The fault trace further extends in NW through Naddi village. It extends further west of Naddi, takes a right step with same strike as mapped on satellite photo between Kareri and Kanol villages. This portion of the fault is also reported by Philip (2007). Near Kanol the fault again takes right step resulting into formation of depression or a valley.

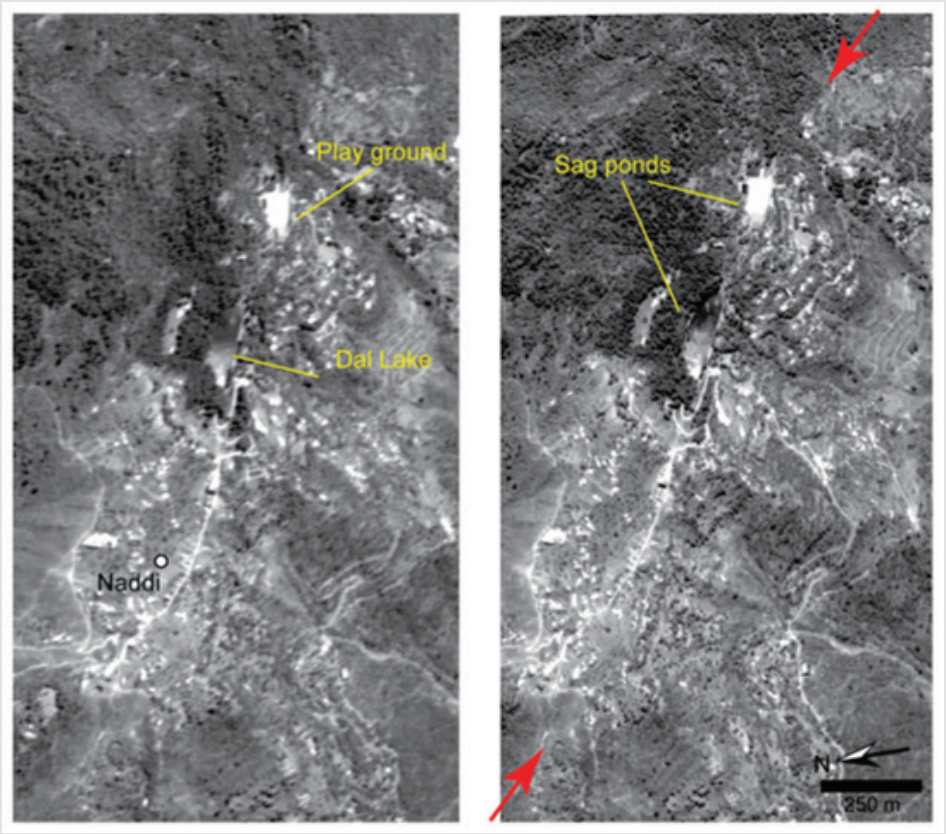


Fig. 50: The active fault scarp identified near Naddi village strikes ENW-WSE. Lateral as well as vertical displacement along this fault has resulted into vertically stacking of sedimentary sequence. The right-lateral movement has given rise to formation of a very sharp north facing scarp and two prominent sag ponds – TCV playground and Dal Lake.



Fig. 51: The active fault trace around Dal Lake. (a) The fault passes along the southern edge of Dal Lake and extends further west along a narrow valley (b).

Day-6

Return to New Delhi.

Local Conveniences



Fig. A1: Local hospital in and around Dharamsala.



Fig. B1: Local Police Stations in and around Dharamsala.

Conclusion

The proposed post-conference field excursion offers a comprehensive overview of the tectonic evolution, active faulting, and seismic hazards of the Northwest Himalaya through an integrated field transect spanning from HFT to the KVF. Participants will observe a wide spectrum of geological and geomorphological features, including active fault scarps, displaced river terraces, offset streams, sag ponds, fault-controlled landscapes, and paleoseismic trench exposures, together with historical monuments that preserve evidence of the devastating 1905 Kangra earthquake. This unique combination of modern active tectonic processes, Quaternary geology, paleoseismology, and historical earthquake records provides an exceptional opportunity to understand the relationship between crustal deformation, landscape evolution, and seismic hazard in one of the world's most active continental collision zones.

Beyond remarkable geological localities, the excursion emphasizes the importance of multidisciplinary approaches that integrate tectonic geomorphology, structural geology, Quaternary stratigraphy, geochronology, and historical observations to reconstruct earthquake histories and characterize active fault systems. The field discussions will provide insights into fault segmentation, strain partitioning, rupture propagation, and the role of both frontal and hinterland faults in accommodating ongoing India–Eurasia convergence. Such integrated observations are essential for improving our understanding of earthquake generation and refining seismic hazard assessments across the Himalayan arc.

By traversing a continuous tectonic profile from the Indo-Gangetic Plain to the Himalayan hinterland, this excursion transforms the landscape into an open-air laboratory where participants can directly examine the geological processes that have shaped the Northwest Himalaya over Quaternary time. It provides an invaluable platform for scientific exchange, discussion, and collaboration among researchers, early-career scientists, and students, while highlighting the broader significance of field-based investigations in advancing earthquake science and disaster resilience. The knowledge gained from this transect will not only enhance our understanding of Himalayan tectonics but will also contribute to the global effort to better characterize active fault systems and mitigate seismic risk in continental collision zones worldwide.

Where to Shop in Dharamsala-Kangra: Best Souvenirs, Apparel, and Markets:

Shopping in Dharamsala and Kangra is an enriching experience, blending the charm of local craftsmanship with the vibrant culture of the region. From bustling markets to small artisan shops, the valley offers something for every visitor.

• **Kotwali Bazar:** Located in Dharamshala, this bustling market offers a variety of local handicrafts, including Kangra paintings, pottery, and Himachali jewellery.

• **Kangra Main Market:** Situated near the Brajeshwari Devi Temple, this market is known for traditional items like woollen shawls, Kashmiri handicrafts, and Himachali artifacts.

• **Dolls4Tibet:** Specializes in Tibetan handicrafts and unique gifts, located in McLeod Ganj.

• **Palaco Handmade Crafts:** Offers a variety of handmade items, including jewelry and decor, with a focus on local craftsmanship.

• **Thankas and Gifts:** A gem in McLeod Ganj, offering carefully sourced Tibetan thankas and other unique items.

• **Divine Buddha Handicrafts:** Perfect for prayer flags, magnets, and other Tibetan-inspired gifts.

Help with stolen passport:

• Report to Local Authorities: Visit the nearest police station and file an FIR (First Information Report) for the lost/stolen passport. Get a copy of the FIR, as it is required for further procedures.

• Inform the Workshop Organizers: Notify the INQUA workshop coordinators or local hosts about the situation. They might assist in contacting local authorities or embassies.

• Getting a New Passport or Travel Document- Since there is no foreign embassy in Dharamsala, participants should contact their country's embassy in New Delhi.

• Arrange Temporary Identification: Use a digital copy of the passport (if available) or any other ID (student ID, Driver's license, etc).

References

- https://himachaltourism.gov.in/
- https://himachaltourism.gov.in/destination/dharamshala
- https://www.himachal.exploreindia.in/flora-and-fauna-of-himachal-pradesh.html

Annexure

Field Excursion Guidelines: Do's and Don'ts

To ensure the safety of all participants and to promote responsible scientific field practices, all participants are requested to adhere to the following guidelines throughout the field excursions.

Keep a valid passport (for international participants) or a government-issued photo ID (for Indian participants) with you at all times during the field excursion.

Do's	Don'ts
1. Follow the instructions of the excursion leaders, coordinators, and local authorities at all times.	1. Do not collect rocks, fossils, archaeological artefacts, biological specimens, or any other materials without prior authorization.
2. Remain with the group and inform the excursion leader before leaving the designated route.	2. Do not damage, deface, or remove material from geological outcrops, caves, monuments, heritage structures, or other natural features.
3. Wear appropriate field attire, including sturdy closed-toe footwear, full-length trousers, a hat or cap, and weather-appropriate clothing.	3. Do not wander alone or separate from the excursion group without informing the field leaders.
4. Carry sufficient drinking water, personal medications, sunscreen, insect repellent, and other essential field supplies.	4. Do not climb unstable slopes, cliffs, rock formations, or enter hazardous areas unless specifically instructed or supervised.
5. Keep a valid photo identification and your excursion registration details with you during travel.	5. Do not swim or enter rivers, lakes, lagoons, or coastal waters unless expressly authorized by the excursion leaders.
6. Respect local customs, religious sites, cultural heritage, and private property.	6. Do not consume alcohol, recreational drugs, or engage in unsafe or irresponsible behaviour during the excursion.
7. Follow the Leave No Trace principles by carrying back all waste and helping to keep field sites clean.	7. Do not operate drones or other restricted equipment without obtaining the necessary permissions.
8. Use designated trails and approved observation areas to minimise environmental disturbance.	8. Do not photograph restricted installations, sensitive locations, or local residents without prior permission.
9. Observe geological, ecological, archaeological, and cultural features carefully without causing any damage.	

10. Record field observations systematically and collect samples only with prior permission from the excursion leaders and the relevant authorities.

11. Exercise caution near cliffs, riverbanks, caves, unstable slopes, road cuts, and other potentially hazardous terrain.

12. Respect wildlife by maintaining a safe distance from animals, birds, reptiles, insects, and their habitats.

13. Immediately report any illness, injury, emergency, or hazardous situation to the excursion organizers.

14. Be prepared for changing weather conditions and comply with all safety advisories issued by the excursion leaders.

9. Do not create excessive noise or disturb local communities, religious activities, wildlife, or natural habitats.

10. Do not leave valuables unattended or rely solely on mobile phone connectivity in remote areas.

11. Do not undertake any activity that may compromise your safety, the safety of fellow participants, or the conservation of the area's geological, ecological, archaeological, or cultural heritage.

Disclaimer

Participation in the field excursions is entirely at the participant's own risk. While the Organising Committee and excursion leaders will make every reasonable effort to ensure participant safety and provide appropriate guidance, they shall not be held responsible for any personal injury, illness, loss of personal belongings, property damage, delays, or unforeseen incidents arising during travel or field activities. Participants are expected to act responsibly, follow all instructions issued by the excursion leaders, and comply with applicable local laws and regulations throughout the excursion.













Scan for
Field Guide Book

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