Chapter 6

Luminescence Chronology of Fluvial Archives: Paleoclimatic and Paleoseismic Implications

6.1 Flash flood and Terrace deposits

Vulnerability of the Himalayan watersheds is attributed to the continued compression caused by the northward movement of Indian plate. This has given rise to rapid upliftment and high incision (Burbank et al., 1996). Aided to this, the region is dominated by southwest monsoon. The central Himalaya has high annual rainfall (1500 mm) and the majority of the precipitation (~80%) occurs during the summer month from the southwest monsoon (Hasnain, 1999). The inherent vulnerability of surface sediments coupled with high rainfall leads to the landslide and debris flow that occasionally create temporary lakes on the river courses. These lakes can last for longtime and eventual breaching of such lakes cause flash floods with catastrophic discharge and sediment load. There are numerous examples of such floods from the Himalayan region. During such unusual events, rivers tend to transport sediments flux that exceeds the annual supply from denudational processes (Cornwell, 1998; Shroder, 1998). In addition to this, flash floods in Himalaya are also reported to have been caused by earthquakes and glacial lake outburst (Monecke et al., 2001). Considering that sizeable number of our population lives on the lower Ganga plain, it is important to ascertain the frequencies of these unusual events in the Himalaya for evolving a mitigation planning. This thesis attempted this by, (i) the identification of paleoflood deposits and (ii) ascertaining their chronology.

In the present study, these aspects were addressed. The age estimate for the known flood event that occurred during 1970 was dated at various places from the origin of the flood to the farthest location at the point of emergence of the Ganga River near Rishikesh. The ages obtained using the least 10% of the paleodoses varied from 0.5 ± 0.1 ka to 7 ± 2 ka (Table 6.1). In view of the short-lived nature of the flash flood, the above ages indicate that sediment bleaching was inadequate to erase the geological luminescence. Considering that 0.5 ± 0.1 ka was obtained from a flood plain deposit located proximal to the origin of flash flood site (at Kaleshwar), it can be suggested that luminescence dating of flood plain sediment can provide reliable ages.

With the above observation, paleoflood history of the Alaknanda River was reconstructed from a flood plain sequence at Srinagar (Fig. 6.1). These deposits are exposed on the left and right flank of the Alaknanda River. Compared to the left flank (Terrace T_1), where four paleoflood deposits of increasing magnitude were identified, the right flank had preserved only one event that is too of lesser magnitude (Fig. 6.1). Using the average of least 10% paleodose, the four paleoflood events on the left flank (from bottom upward) were dated to 6.3 ± 0.8 ka, 2.7 ± 0.7 ka, 0.8 ± 0.1ka and 0.5 ± 0.1 ka. A lone paleoflood event on the right flank was dated to 0.3 ± 0.1 ka. The reliability of luminescence ages is ensured by the fact that they are obtained on, (i) flood plain sediment; (ii) stratigraphically consistent and (iii) the younger age 0.5 ± 0.1 ka is obtained on the flood sediment on which 400 year old Keshav Rai temple was constructed.

In the monsoon dominated Alaknanda basin, the above flood events would in principle imply enhanced southwest monsoon. Paleomonsoon reconstruction based on pollen studies from the adjoining Bhagirathi valley identified three events of enhanced southwest monsoon between 6000 – 4500 cal years BP, 3000 – 1000 cal years BP and 800 cal years BP to present (Phadtare, 2000). These events accords well with the chronology of paleoflood records. The progressive increase in the flood magnitude from 6 ka to 0.5 ka would imply either increasing monsoon strength or gradual increase the magnitude of landslide-induced flash floods in the basin. The present study shows that

Table 6.1. SAR ages based on least 10% of the paleodoses from the samples of 1970's flood and terrace T_1 in Srinagar, Uttaranchal state.

Sample	U (ppm)	Th (ppm)	K (%)	Dose rate (Gy/ka)	Paleodose	SAR age (ka)
KL-1	2.2 ± 0.8	12.3 ± 2.8	1.3 ± 0.1	2.3 ± 0.3	9 ± 1	3.8 ± 0.5
KL-3	2.5 ± 0.7	12.4 ± 2.6	1.2 ± 0.1	2.3 ± 0.3	1 ± 0.3	0.4 ± 0.1
MVW-9	2.5 ± 0.4	7.7 ± 1.3	1.5 ± 0.1	2.2 ± 0.2	9 ± 2	4.2 ± 0.8
MVW-10	4.2 ± 0.6	14.3 ± 2	1.8 ± 0.1	3.2 ± 0.3	0.8 ± 0.2	0.3 ± 0.1
MVW-11	4.4 ± 0.8	12.7 ± 3	1.9 ± 0.1	3.2 ± 0.3	23 ± 4	7 ± 2
MVW-12	4.5 ± 0.9	17.6 ± 3.3	3.1 ± 0.2	4.5 ± 0.4	7 ± 1	1.5 ± 0.2
OTS-1	2.8 ± 0.7	9.7 ± 2.3	1.8 ± 0.1	2.9 ± 0.3	20 ± 1	6.3 ± 0.8
OTS-2	5.5 ± 1.1	11.8 ± 3.8	1.7 ± 0.1	3.6 ± 0.4	3.4 ± 0.5	0.8 ± 0.1
OTS-3	4.4 ± 0.5	24.1 ± 7.2	1.9 ± 0.1	4.4 ± 0.6	18 ± 0.5	2.7 ± 0.7
OTS-4	3.0 ± 0.8	10.2 ± 2.7	1.2 ± 0.1	2.5 ± 0.3	9 ± 3	3.4 ± 1.5
OTS-5	3.4 ± 0.7	14.9 ± 2.4	1.9 ± 0.1	3.5 ± 0.3	1.7 ± 0.1	0.5 ± 0.1
BN-6	6.6 ± 1.1	24.8 ± 3.8	1.6 ± 0.1	4.1 ± 0.4	18 ± 5	4.3 ± 1

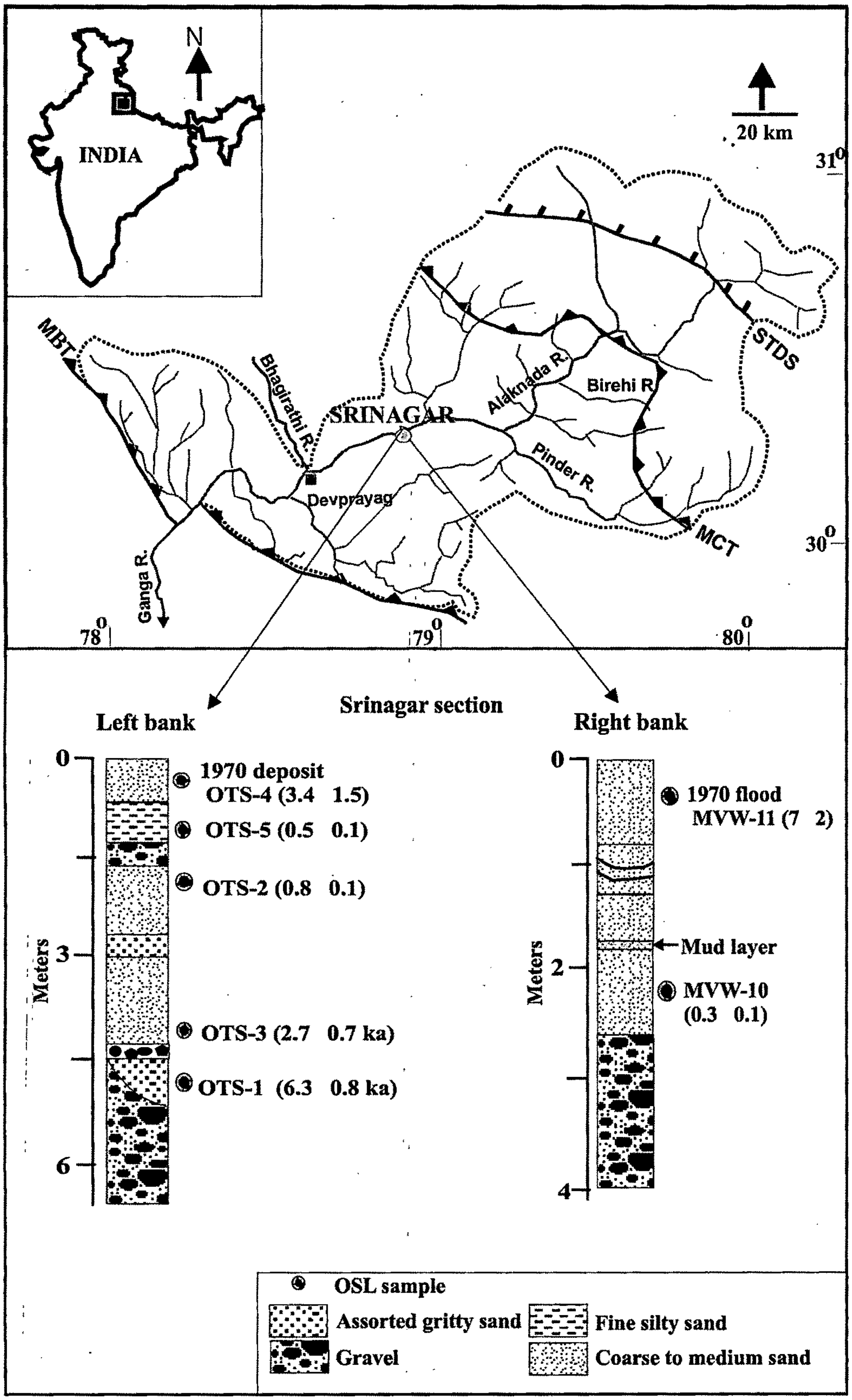

Fig. 6.1. SAR ages obtained from terrace T1 at Srunagar on either bank of the river.

the 1970's flood was of the highest magnitude that was ever recorded in the Alaknanda basin since last 6 ka.

In the last fifty years, increasing deforestation in the upper Alaknanda basin was identified as the cause of the 1970's flash flood (Kimothi and Juyal, 1996). However, considering the tectonically active Himalaya ranges, it has been suggested that deforestation has minimum impact on flash floods (Ives and Messerli, 1989). Due to the paucity of scientific data on paleoflood deposits in the Alaknanda basin, the above debate remained inconclusive. An attempt was made for the first time to reconstruct the geological record of past floods from the Alaknanda basin and ascertain the causes of past floods.

In the present study luminescence dated paleoflood deposits were analyzed for the identification of sediment provenances. This was done using the rare earth tracer ϵ_{Nd} (France-Lenard et al. 2000). The study indicates the paleoflood sediments 6 ka to 0.5 ka (except 0.8 ka) had source in the Higher Himalayan Crystalline (HHC) (Table 6.2) This area lies north of the Main Central Thrusts (MCT), which is a zone of high relief and high physical weathering. Compared to this, during the 1970's flood, majority of the sediment originated from low relief Lesser Himalayan (LH) watersheds (Wasson et al., submitted). This zone is also known as the southern mountain front (Hodges et al., 2004) and had records of deforestation during the recent time. It was observed that the past floods were caused by the natural processes, where as the recent flood was triggered by anthropogenic activity.

6.2 Slack water Deposit

Gangetic plain, a unique geomorphological entity is drained by many large rivers and inhabited by 250 million people. Large and small floods also affect this region during the monsoon. Therefore, an understanding of past floods and their recurrent frequencies is important for better land use and land management strategies. Floods in the Ganga River are associated with the southwest monsoon. The upper catchments of the Ganga River viz. the Alaknanda and Bhagirathi witness high precipitation during June to September (Hasnain, 1999). Though there is limited data on the downstream (Ganga plain), recent studies have demonstrated that majority of the sediment as far as the eastern Ganga plain have source in the higher Himalayan region (Sinha, 2005). Majority of the sediments are transported during the monsoon that are scavenged from the Himalayan watershed by surface runoff and landslides (Wasson, 2003). At times, river courses are blocked temporarily, breaching of such blockades cause flash floods in the lower reaches such as the 1970's flood (Weidinger, 1998). A recent study suggests that 90% of the total sediment that are transported by the Ganga River originates from the Himalaya (Wasson, 2003).

Evidence of past floods at Raiwala, where 14 vertically stacked flood couplets (slack water deposits) suggests that the upper catchments of the Ganga River in central Himalaya witnessed high magnitude floods in the past. Luminescence chronology using least 10% of paleodoses that are obtained on 8 samples collected from three pits (Pit-1 to Pit-3) suggests that the flood occurred during 2.6 ± 0.6 ka (Fig. 6.2, Table 6.3). This event was observed in both Pit-1 and Pit-2 (Fig. 6.2) and also seen in the Alaknanda basin at Srinagar. Following this a maximum of 6 floods of high magnitude occurred between 2.6 to 1 ka and during 1 ka to 0.8 ka, presence of 8 flood couplets suggests significant increase in flood frequencies. Absence of flood couplet above the 0.8 ka event suggests that flood magnitude since then decreased. Occurrence of 10 couplets during 2.6 to 1 ka suggests the recurrent interval of 260 years for high magnitude flood. However between 1 ka to 0.8 ka, a significant rise in the frequencies of high magnitude flood that comes out to be once in every 25 years. Since floods are associated with high rainfall event, which in our case is the southwest monsoon, thus, it can be suggested that the paleoflood sequence represent fluctuating southwest monsoon during the last 2.6 ka. Evidence based on the peat bog from the central Himalaya indicate a stepwise increase in southwest monsoon after 3000 cal. yrs. BP culminating at 1000 Cal. yrs. BP (Phadtare, 2000). This periods broadly compares well with the event corresponding to 6 flood couplets that were deposited between 2.6 ka and >1 ka. Between 1 ka and 0.8 ka 8 flood events of increasing magnitude suggests frequent flash flood events suggesting stronger monsoonal condition. Speleothem record from Nepal Himalaya (Denniston, et al., 2000) and peat bog data indicate strengthening of southwest monsoon after 1500 year that persisted until >0.8 ka. This period culminated into cold and dry phase around 0.8 ka (Phadtare, 2000) this is

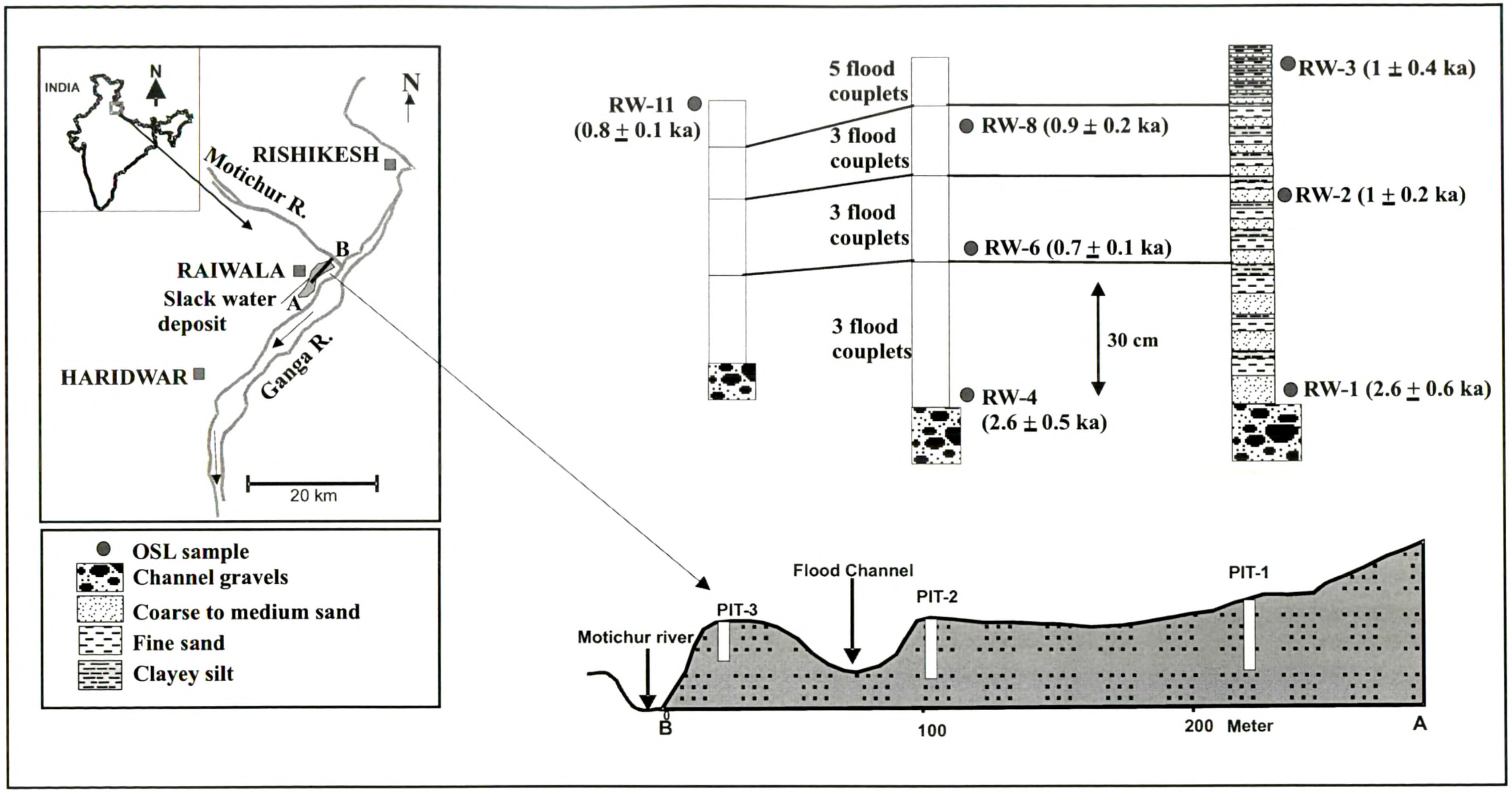

Fig. 6.2. SAR ages from slack water deposit at Raiwala, Haridwar. Ages are suggesting ameliorating monsoon during 2-1 ka, however, the monsoon strength was highest during ~1 ka as suggested by high frequency paleoflood record.

Table 6.2. The sediment contribution from High Crystalline Himalaya (HCH) and Inner Lesser Himalaya (ILH) to the sediment at Srinagar terrace T_1 (after Wasson et al., submitted)

Serial no.	Sample	HCH%	ILH%
1	OTS-1	78	22
2	OTS-2	52	48
3	OTS-3	86	14
4	OTS-4	45	55
5	OTS-5	86	14
6	Modern	64	36

Table 6.3. SAR ages from slack water deposit at Raiwala

Sample (pit no.)	U (ppm)	Th (ppm)	K (%)	Dose rate (Gy/ka)	Paleodose (SAR)	SAR ages (ky)
RW-1 (1)	3.6 ± 0.7	14.2 ± 2.4	1.9 ± 0.1	3.1 ± 0.3	8.2 ± 1.6	2.6 ± 0.6
RW-2 (1)	5.0 ± 0.8	12.1 ± 2.8	1.3 ± 0.1	2.7 ± 0.3	2.7 ± 0.5	1.0 ± 0.2
RW-3 (1)	3.9 ± 0.9	15.1 ± 3.1	1.7 ± 0.1	3.0 ± 0.3	3 ± 1	1.0 ± 0.4
RW-4 (2)	5.4 ± 0.5	26.1 ± 5.6	2.2 ± 0.1	4.3 ± 0.5	11 ± 2	2.6 ± 0.5
RW-6 (2)	2.2 ± 0.6	19 ± 5.7	2.5 ± 0.2	3.6 ± 0.4	2.5 ± 0.3	0.7 ± 0.1
RW-8 (2)	3.9 ± 1	20.3 ± 7.8	2.4 ± 0.2	3.9 ± 0.6	3.5 ± 0.8	0.9 ± 0.2
RW-11 (3)	4.4 ± 0.8	16.8 ± 2.8	1.7 ± 0.1	3.2 ± 0.3	2.5 ± 0.4	0.8 ± 0.1

manifested in the absence of high magnitude flood after 0.8 ka at Raiwala indicating weakening of the southwest monsoon in the upper catchments of the Ganga River.

6.3. Mega alluvial and Piedmont fan

Srivastava et al., (2003) provided the preliminary luminescence chronology for the mega fan formation. Based on MAAD technique the event of mega fan aggradation was bracketed between 26 - 22 ka. Similarly, the ages on piedmont fan ranged from 8 – 3 ka. Considering the poorly bleached nature of fan sediments, MAAD ages are likely to be overestimate of the real age. In the present study SAR technique was employed for age estimation. Clarke (1996) and Jain et al., (2004) have demonstrated that for older samples, mean paleodose can be considered for age estimation. Because in such samples the unbleached luminescence is insignificant compared to the acquired luminescence during the burial. This is further supported by the low relative standard deviation (20 – 30%) and normal distribution of paleodoses (Fig. 5.6, chapter 5). However, in case of the younger piedmont fan sediments, least 10% paleodose was used for age estimation.

In the field, three events of mega fan aggradation were identified. Due to inaccessibility three samples were dated one from lower episode-I and two from the upper episodes-III. One sample was dated from the upper 3 m sheet deposit (NN-8) (Fig. 6.3). Due to lack of coarse quartz fraction in sample NN-8, MAAD fine grain technique was used. The lower most fan aggradation (episode-I) was dated to 14 ± 3 ka (NN-1, Table 6.4). Initiation of the upper most phase of fan aggradation began at 9 ± 1 ka and terminated at 8 ± 1 ka (Fig. 6.3). The overlying sheet flood deposit occurred after the deposition of the upper most fan sequence was dated to 8 ± 2 ka (Srivastava, 2003). Considering the uncertainty associated with this age, it can be argued that event of surface modification began around <9 ka. In piedmont fan two events were identified in the field stratigraphy. Chronology of these events was ascertained using the least 10% of the paleodoses. Thus ages obtained are 2 ± 0.2 ka for the older episode and 1 ± 0.2 ka for the younger episode (Fig. 6.3).

Table 6.4. SAR ages of the mega and piedmont fan samples (Least 10% for sample KT-5 and KT-6 and mean paleodose were taken for samples NN-1, NN-5 and NN-6 respectively.

Sample	U (ppm)	Th (ppm)	K (%)	Dose rate (Gy/ka)	Paleodose (SAR)	SAR ages (ka)
NN-1	2.5 ± 0.8	10.6 ± 3	1.7 ± 0.1	4.6 ± 0.7	38 ± 11	14 ± 3
NN-5	3.6 ± 0.9	8.2 ± 3	1.7 ± 0.1	2.9 ± 0.3	25 ± 6	9 ± 2
NN-6	2.8 ± 1.1	14.8 ± 4	1.9 ± 0.1	3.3 ± 0.4	25 ± 8	8 ± 2
KT-5	1.8 ± 0.5	5.3 ± 2	0.8 ± 0.1	1.5 ± 0.2	2.6 ± 0.3	2 ± 0.3
KT-6	2.6 ± 0.9	9.6 ± 3	1.0 ± 0.1	2.2 ± 0.3	2.2 ± 0.8	1 ± 0.2

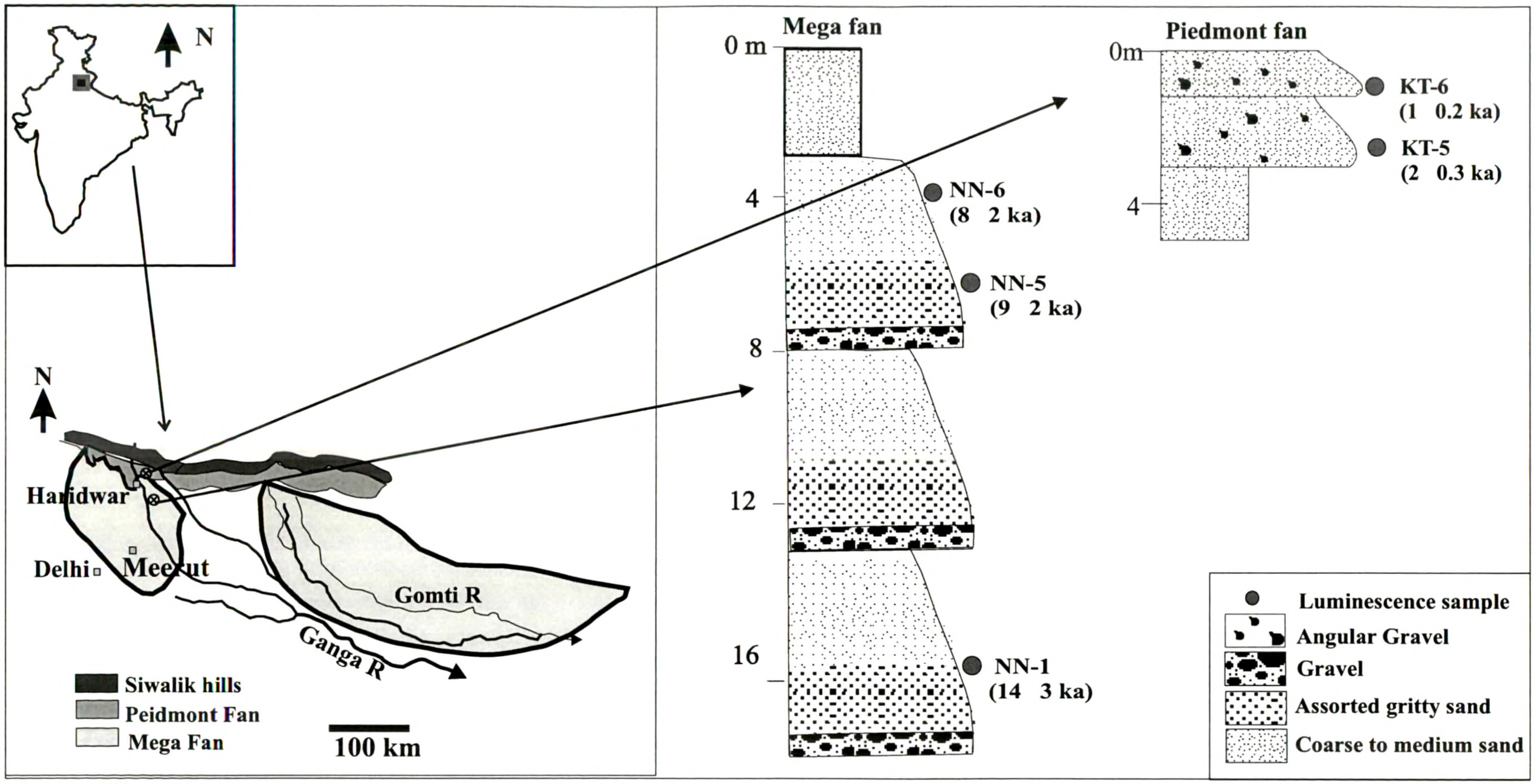

Fig. 6.3. SAR ages obtained for Yamuna Ganga mega and piedmont fan. The ages suggest that the mega fan sedimentation started ~14 ka and terminated ~8 ka. Piedmont fan formed in a short period of time ~2-1 ka. (After Srivastava et al., 2003)

It has been suggested that mega fan aggradation in Ganga plain occurred during the time of the initiation of humid climate that was preceded by a long arid phase when huge amount of sediment from the Himalaya were transported into the Ganga plain (Singh, 1996). Chronology of the mega fan aggradations suggests that the older episodes (I and II) occurred after 14 ka and before 9 ka (Fig. 6.4). The older episode-I corresponds to the reestablishment of southwest monsoon (Sirocko et al., 1993; Overpeck et al., 1996) whereas, the episode-II was deposited after the Younger Drayas cooling event dated to 10.5 ka BP in the Ganga plain (Sharma et al., 2004). Evidence similar to this was obtained from the central Himalayan loess sequences suggesting three phases of loess accretion followed by a period of landscape stability between 16 - 12 ka, 9 – 7 ka and < 1 ka (Pant et al., 2005). The topmost sheet-wash sediments were deposited after 8 ka. Following this incision of the mega fan sediment was initiated in the study area. Observation similar to this was made by Godbred Jr., (2003), who has attributed this period to the hypsithermal event of intense humid climate. Climatically this period corresponds to regionally extensive humid phase that was observed in the central Himalaya (Phadtare, 2000; Sharama et al., 2004; Pant et al., 2005), Central India (William and Clark, 1984), Thar desert (Enzel et al., 1999; Deotare et al., 2004).

Chronology of the younger piedmont fan dated between 2 ka and 1 ka suggests that piedmont fan aggradation post dates the mid-Holocene aridity in the Ganga plain that was dated between 5000 – 2000 (^{14}C) years BP and then followed by ameliorating monsoon (Sharma et al., 2004). The event of piedmont fan aggradation suggests improved moisture regime associated with the improved southwest monsoon. Evidence for improved southwest monsoon is also suggested by the development of paleosol in the central Himalaya (Pant et al., 2005). From the western coast, improved southwest monsoon condition began after 2200 yr BP that continued till today (Caratini, 1994). In the present study it was observed that frequencies and magnitude of floods in the upper Ganga catchments began to increase after 2.7 ka. Thus it can be suggested that piedmont fans aggradation indicate reestablishment of the southwest monsoon after the mid Holocene aridity.

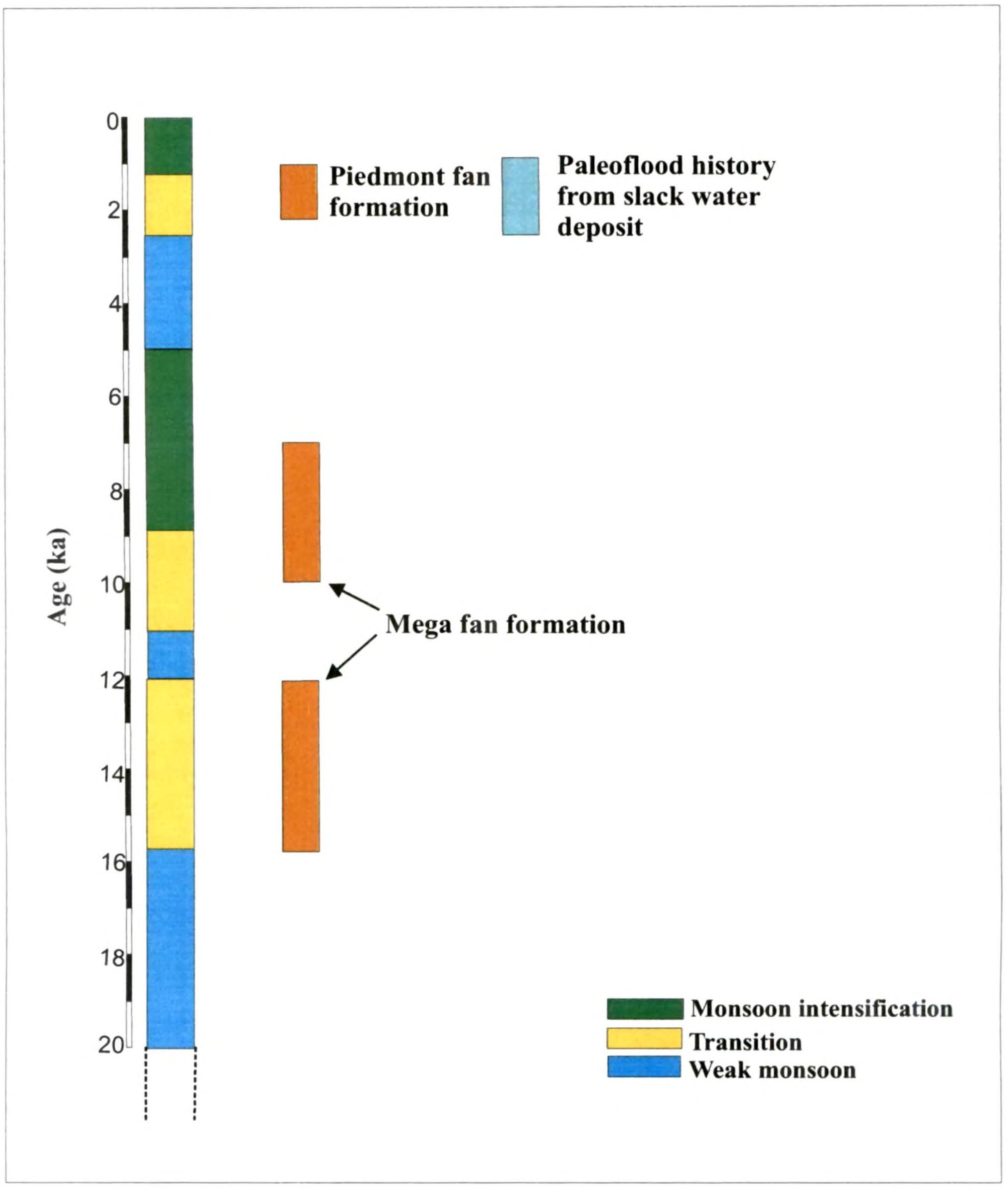

Fig.6.4. Chronology of Yamuna Ganga mega and piedmont fan and their correlation with paleoclimate record from Himalaya. The processess of fan formation accords well with paleocliamte record and also supported by paleoflood record at Raiwala, Haridwar studied in the present work (Phadtare, 2000; Srivastava et al., 2003 and Pant et al., 2005)

6.4 Fault gauge and incised terraces

The surface-breaking faults exhibit brittle deformation fabric. This allows Thermoluminescence (TL) dating of fault gouge (Singhvi et al., 1994) excavated from exposed fault zones in the terrace area. TL dating provides the most recent cataclysmic motion on the faults and assumes that the P-T conditions during faulting reduced the geologically acquired TL to zero or near zero value. TL dates fault gouges from the bounding faults viz. the northern South Kalijhora Thrust (SKT) and the southern Mountain Frontal Thrust (MFT). The fault gauge ages obtained on SKT was 42 ± 10 ka and on the MFT 45 ± 7 ka (Table 6.5). These ages are in conformity with the earlier study carried out in the lesser Central Himalaya (Banerjee et al., 1997) indicating that lesser Himalaya experienced a regional phase of tectonic activity around 40 ka. In addition to this one more sample that was dated from one of the imbricate faults (duplexes) located 0.5 km south of SKT gave TL age of 20 ± 6 ka (Table 6.5). Since the above ages are obtained on the fault gouge that was formed on the host rocks of greater than 2 Ma age (Middle Siwaliks) suggest that the basic premises of zeroing are adequately met for fault gouge samples.

Ages of the incised terraces were obtained using the least 10% paleodoses. The ages obtained are 7.7 ± 1 ka (T_5), 4.4 ± 1 ka (T_4), 1.4 ± 0.3 ka (T_3) and 50 ± 50 a (T_0) (Fig. 6.5). The youngest T_0 sample was collected from the present day Tista River, which has given age of modern sand suggesting that the incised terrace sediments were adequately bleached prior to the deposition. In addition to this, two samples that were collected from 1 km and 20 km south of the mountain (PRLT-3 and PRLT-5) were dated to 14.5 ± 2.4 ka and 6.0 ± 0.6 ka respectively (Fig. 6.5).

Five fluvial terraces of the Tista River are cut into the Siwalik rocks and overlying alluvium (Mukul, 2000). The upper most meter of the alluvium was sampled to date the latest aggradation after which the incision took place and in the process formed a terrace (Fig. 6.5). Terrace (T_5) (~40 m above the present water level) is dated to 7.7 ± 1 ka

Table 6.5. Age table of samples from Tista valley

Sample	U (ppm)	Th (ppm)	K (%)	Dose Rate (Gy/ka)	Paleodose (Gy)	Age (ka)
Raised Terraces						
T-5	5.3 ± 1.3	19.2 ± 8.4	2.9 ± 0.2	5.1 ± 0.7	40 ± 2	7.7 ± 1.1
T-4	6.4 ± 1.3	18.2 ± 8.9	2.7 ± 0.1	5 ± 0.7	22 ± 2	4.4 ± 0.8
T-3	7.0 ± 1.2	19.2 ± 11.4	2.1 ± 0.1	4.8 ± 0.9	7 ± 0.4	1.4 ± 0.3
T-0	3.6 ± 0.8	16.9 ± 6.4	2.2 ± 0.1	3.8 ± 0.5	0.2 ± 0.6	0.05 ± 0.05
PRLT-3	6.8 ± 0.8	20.2 ± 10.3	2.8 ± 0.2	5.3 ± 0.8	77 ± 5	14.5 ± 2.4
PRLT-5	4.7 ± 0.9	7.2 ± 3.1	3.4 ± 0.2	4.6 ± 0.4	28 ± 1	6 ± 0.6
Fault Zones						
SKT-1	5.3 ± 1.2	44.7 ± 19.5	4.2 ± 0.2	13.7 ± 2.4	578 ± 88	42 ± 10
PRLT-1	4.8 ± 1.2	10.9 ± 4.0	3.0 ± 0.2	7.4 ± 1.3	150 ± 38	20 ± 6
PRLT-4	2.9 ± 1.1	14.5 ± 3.6	2.6 ± 0.1	6.5 ± 0.7	293 ± 29	45 ± 7

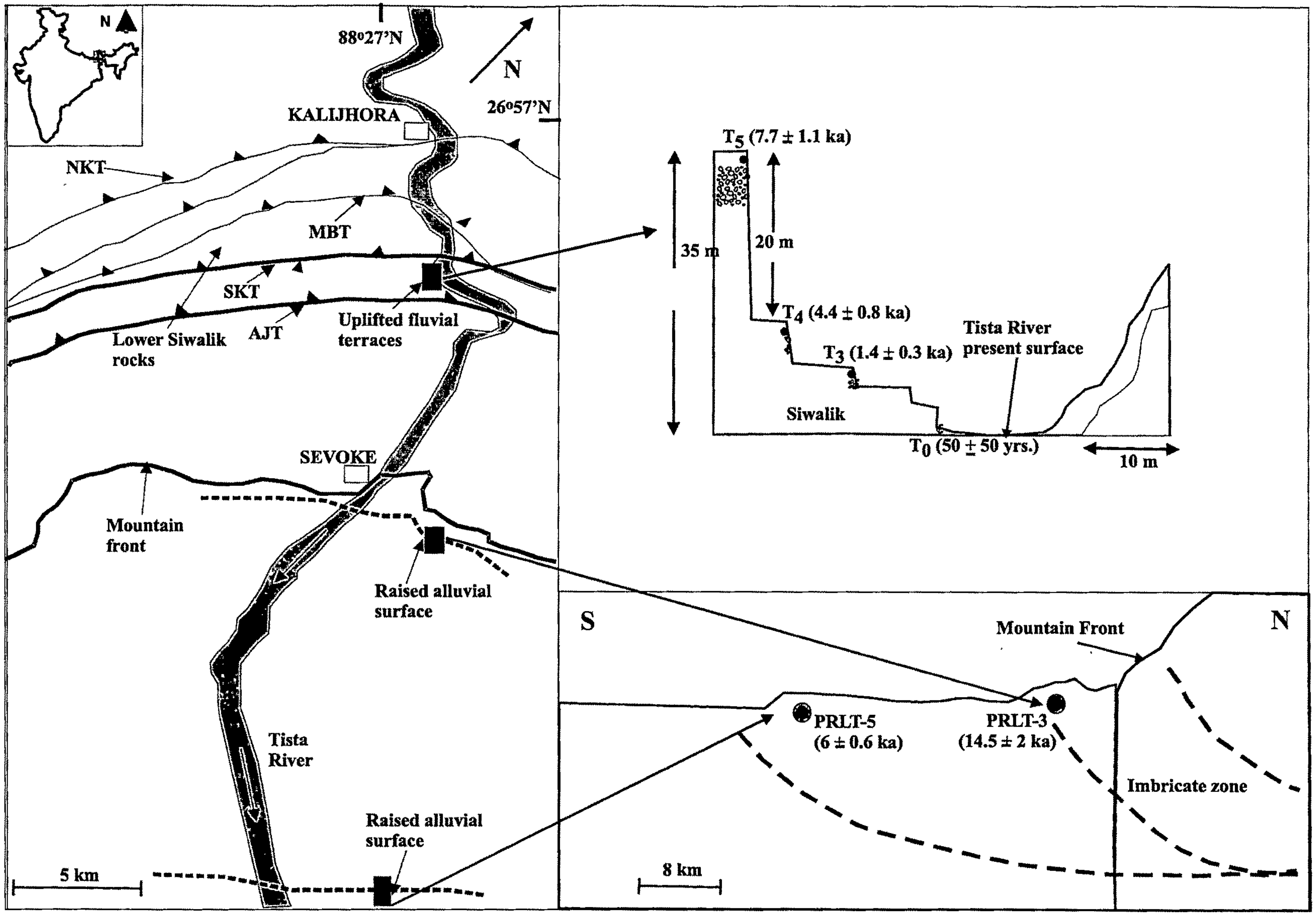

Fig. 6.5. SAR ages of fluvial terraces in Tista valley in the vicinity of MBT. Two raised surfaces (PRLT-3 and PRLT-5) were identified (SKT=South Kalijhora Thrust, NKT=North Kalijhora Thrust, MBT=Main Boundary Thrust, LS=Lower Siwalik, MS=Middle Siwalik, AJT= Anjherijhora Thrust)(After Mukul, 2000)

(Table 6.5). The lower two terraces T_4 and T_3 at ~25 m and ~13 m above the present water level were dated to 4.4 ± 0.8 ka and 1.4 ± 0.3 ka respectively (Table 6.5). The age (50 ± 50 a) of modern samples (T_0) implies that terraces T_2 and T_1, formed in the period between 1.4 ka – 0.3 ka. Given that the area is free from any human interference, and that T_2 and T_1 are practically unvegetated it is suggested that T_2 and T_1 were formed relatively recently. Further, T_3 was vegetated only by bushes whereas T_4, and T_5 were thickly vegetated by bushes and trees (Mukul, 2000). The spatial association of these terraces with the surface breaking imbricates allowed the estimation of the approximate lower (1.4 ± 0.3 ka) and upper (20 ± 6.2 ka) bounds of the age of the active deformation events.

The ages on T_0, T_4, and T_5 (Table 6.5) exhibit an inverted depth-age sequence typical of such fluvial terraces and the sequence $T_1<T_2<T_3$ (1.4 ± 0.3 ka) implies that the out-of-sequence structure has been active from 1.4 ± 0.3 ka till the present. These dates imply local incision rates of 3-10 mm yr^{-1} in the Lesser-Outer Himalaya and are comparable to the incision rates of ~5-10 mm yr^{-1} in the Higher Himalayas (Lave and Avouac, 2001) with higher relief.

Further evidence of blind thrusting south of the exposed mountain front is provided by the presence of fault scarps. Sediments from a scarp about a km south of the exposed mountain front gave an OSL date of 14 ka (PRLT-3; Table 6.5) and about 20 km south of this, sediments from another scarp was dated at 6 ka (PRLT-5; Table 6.5). The combined evidence above indicates that the deformation in the region stalled at the mountain front around 40 ka, and the active deformation front subsequently moved north of the mountain front to the footwall of the MBT around 20 ka. Subsequent deformation and topography building near the MBT then caused additional blind imbricates faults to develop south of the mountain front at 14 ka and 6 ka. The two active fronts may have, therefore, evolved in a coupled manner; with the building of a critical taper in the footwall (Dahlen, 1990) of the MBT driving blind imbrications south of the mountain front at around 14 ka and 6 ka (Mukul, 2005).

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