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PALAEOFLOOD RECORDS FROM UPPER KAVERI RIVER, SOUTHERN INDIA: EVIDENCE FOR DISCRETE FLOODS DURING HOLOCENE

VISHWAS S. KALE[1], HEMA ACHYUTHAN[2], MANOJ K. JAISWAL[3] and SOMASIS SENGUPTA[1]
[1]*Department of Geography, University of Pune, Pune 411 007, India*
[2]*Department of Geology, Anna University, Chennai, 600 025, India*
[3]*Department of Earth Sciences, Indian Institute of Science Education and Research (IISER), Kolkata 741 252, India*

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Abstract: A record of six discrete middle Holocene floods has been established based on sedimentological and stratigraphical studies in the upper Kaveri catchment at Siddapur. The flood events are represented by six discrete, sharp-bounded, sand-silt couplets. Texturally and geochemically the suite of couplets is quite distinct from the overlying and underlying structureless fluvial deposits. Based on OSL ages the suite of couplets cover the Holocene from ~8 to ~2 ka. Such evidence is not present or reported from any other river originating in the Western Ghat in the Indian Peninsula. We argue that the six couplets represent short-term, high discharge events or flash floods. The initiation of this phase of flash floods broadly corresponds with the southward migration of ITCZ and a gradual decline in Indian summer monsoon precipitation starting at ~7.8 ka. Comparison of the elevation of the highest couplet with the high flood level (HFL) of the 1961 extraordinary flood on Kaveri demonstrates that the 20th century flood was higher than the mid-Holocene palaeofloods.

Keywords: palaeofloods, Holocene, monsoon, OSL, Kaveri River.

1. INTRODUCTION

Fluvial systems are the most sensitive elements of the landscape. For this reason, any shift in climate and environmental conditions instigates a rapid response from the fluvial systems. The fluvial archives, therefore, hold the potential for developing a detailed record of river responses to climatic and environmental changes on different spatio-temporal scales. In the last few decades detailed studies of the fluvial records occurring along some of the Deccan Peninsula rivers (DPRs) have helped in unraveling the history of climatic and environmental changes during the late Quaternary (Kale, 2007; Fleitmann *et al*., 2007 and the references therein).

One of the major environmental changes within the last ~10 ka in the Deccan Peninsula as well as in other parts of the Indian subcontinent was a sudden and significant increase in the monsoon rainfall and river discharges in the early Holocene and a noteworthy shift in the hydrological conditions in the middle Holocene, demonstrating a link with the global-scale climatic variations (Kale, 2007). It has been suggested that the intensification of the monsoon during the early Holocene had a dramatic and profound impact on the fluvial systems of the Indian subcontinent, because of an abrupt and immense increase in the wet monsoon flows (Kale *et al*., 2003a). Flood chronologies developed for several regions of the world have demonstrated that times of rapid or even modest climate change have a tendency to be associated with more frequent occurrences of large and extreme floods (Knox, 2000). Sedimentary records of large-magnitude floods during the early to middle Holocene have been reported from a few monsoon-fed rivers, such as the lower Ganga (Goodbred and Kuehl, 2000), the Huanghe (Yang *et al*., 2000), the Changjiang (Yu *et al*., 2003), the Narmada and Tapi (Kale *et al*., 2003b) and Mahi River (Sridhar, 2007). It is therefore, reasonable to assume that the major rivers of the Deccan Peninsula heading in the Western Ghat might have also responded to the Holocene climate changes much in the same way. However, there is no direct and definite sedimentological or stratigraphical evidence of multiple individual large floods on any of the DPRs that originate in the Western Ghat.

During the course of geomorphic investigations in the upper Kaveri Basin, evidence of several discrete flash

Corresponding author: Vishwas S. Kale
e-mail: vskale@unipune.ac.in OR vskale.unipune@gmail.com

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floods was located at Siddapur. The main objective of this paper is to report the evidence of multiple large Holocene palaeofloods on the Kaveri River, roughly estimate their duration and relative magnitude and understand their hydro-climatic significance.

2. THE SIDDAPUR SITE ON KAVERI

The Kaveri (also Cauvery) River is the largest river in South India. It is 800 km long and drains a catchment of 81,155 km^2 composed of various lithologies including gneissic, charnockitic and granitic rocks of Archaean age. The river originates at Talakaveri in the Brahmagiri Ranges of the Western Ghat at an elevation of 1341 m ASL. From Talakaveri to Sivasamudram Falls, the Kaveri River flows over the Mysore Plateau, before descending down to the Tamil Nadu Plain (**Fig. 1A**) via a ~95 km long gorge developed in Biligirirangan Hill Ranges.

The study site (12.30º N and 75.87º E) is located downstream of a bridge on the Kaveri River (**Fig. 1B**) between Siddapur and Nellihundhikeri towns, about 50 km downstream from the source at Talakaveri. The upstream catchment area is ~772 km^2 or < 1% of the total basin area. The average annual rainfall at Kodagu (~10 km from Siddapur) is about 2750 mm.

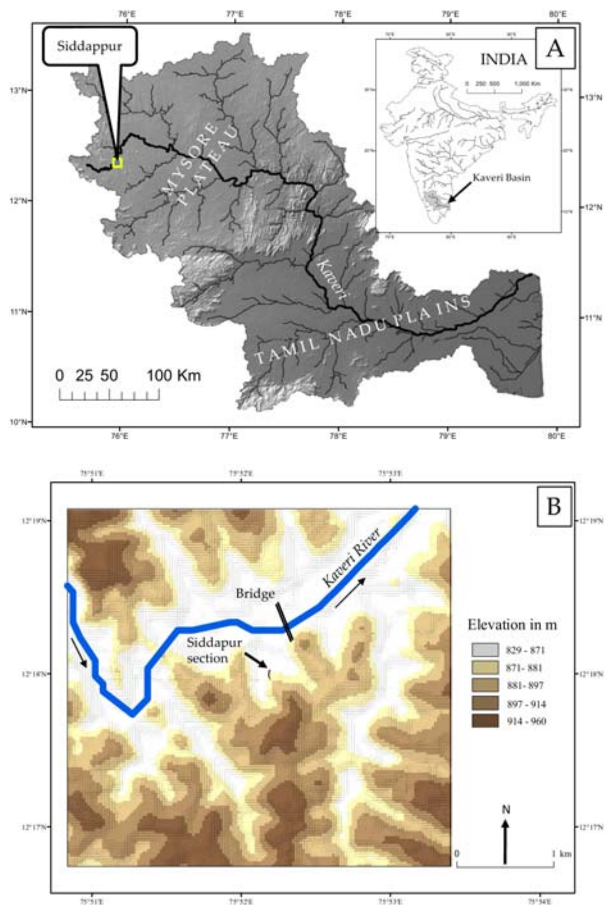

Fig. 1. *(A). Physiography of the Kaveri Basin based on SRTM-DEM. The location of Siddapur site is shown. The inset map shows the location of the Kaveri Basin in India. (B). ASTER-based DEM of the Siddapur locality.*

The river at this site has a, more or less, straight course, but upstream the river course through hills is highly sinuous. Downstream of the study reach, hills again come close to the river. The valley floor in this reach is slightly wider, providing favourable geomorphic setting for the deposition and preservation of fluvial deposits. Thick fluvial deposits are inset in a wide inlet-like valley carved by a small tributary. These deposits have yielded evidence of half-a-dozen large individual floods that occurred within the Holocene.

3. METHODOLOGY

Stratigraphical studies were carried out at the Siddapur site by taking a step-trench in the ~6 m thick deposits. Samples from each sedimentary unit were collected for textural and geochemical analysis. Grain size measurements were done using a Sedigraph particle size analyzer and the elemental composition was obtained by XRF. The geochemical data were used to calculate the CIA (Chemical Index of Alteration) following Nesbitt and Young (1982). The trace elemental data were used to calculate the metal/Al ratios for all the units. Three samples were dated by OSL. In addition, the 30-m ASTER data were used to generate digital elevation model (DEM) of the area around Siddapur.

4. SIDDAPUR STRATIGRAPHIC SEQUENCE

On the basis of stratigraphical and sedimentological characteristics, the deposits at Siddapur could be divided into three broad units ─ the upper (U-1), middle (U-2) and lower (U-3) (**Fig. 2** and **3A**). The U-1 is about 1.45 m thick and yellowish-brown in colour. The unit is dominated by poorly sorted coarse silt (mean φ=4.6). The percentage of clay is ~15%. The skewness is positive (sk=~2.0), indicating excess of fine sediments. The unit is structureless. The lower most unit (U-3) is ~3.0 m thick and dark-brown in colour. This unit is identical to U-1 in terms of texture and sorting. The mean φ varies between 4.7 and 5.1. The sediments are very poorly sorted (3.1 to 3.5) and positively skewed (sk=0.65 to 0.73). This unit is generally massive without distinct stratification. The top ~1.9 m is characterized by mottles and a few light-coloured, thin sandy lenses. The lower ~1.1 m is more reddish in colour. Lack of structures in these two units indicates rapid deposition through the deceleration of flows characterized very high suspended sediment load (Collinson and Thompson, 1989).

Sandwiched between the two structureless units is the middle unit (U-2). The ~1.1 m thick unit is composed of six discrete couplets (**Fig. 2B**) which are typically observed in vertically stacked sequences of slackwater flood deposits (Kochel and Baker, 1988; Ely *et al*., 1996). The couplets are made up of a thicker basal layer (~8 to 30 cm) of slightly light coloured fine sand (mean φ=2.7 to 3.9; clay 7 to 9%) grading into an upper thin layer (1-2 cm) of darker fine sand and silt (mean φ=3.1 to 5.0). The percentage of clay is significantly higher in these darker layers (15 to 20%). The sediments are relatively better sorted. The upper boundaries of the dark layers are very sharp. Flood couplet-3 shows highly irregular upper

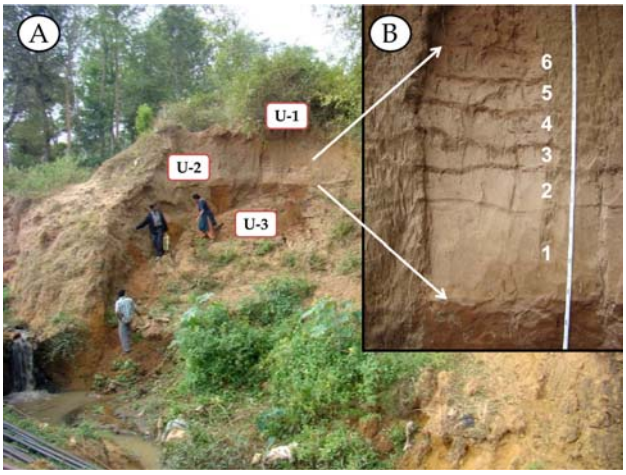

Fig. 2. *(A). Photograph showing the general view of the alluvial deposits exposed on the left bank of the Kaveri River at Siddapur. (B) Enlarged view of the six flood couplets (1-6) seen in the middle unit (U-2) in A.*

boundary (**Fig. 2B**). The textural characteristics (**Fig. 3B**) and the couplets indicate that these are undoubtedly slackwater deposits associated with discrete floods (Ely *et al*., 1996). The basal unit of the first (and the oldest) couplet is very thick (~30 cm) and coarser indicating higher magnitude of associated flood (Kochel and Baker, 1988). The repetitive sand-to-silt couplets represent deposition from short-term, high discharge events (Ely *et al*., 1996) or flash floods.

Geochemical data clearly brings out the distinctive nature of the middle unit. Chemical Index of Alteration (CIA) (Nesbitt and Young, 1982) values reveal a very distinct change in U-2 (**Fig. 3C**). The CIA values are relatively lower for the middle unit composed of the suite of couplets (CIA=74.6–90.2) than the upper and lower structureless units (CIA=87.5–91.6) indicating that the suite of couplets is composed of less weathered sediments, most likely brought and deposited by flash floods. Metal/Al ratios (Zn/Al, Pb/Al, Na/Al, Ca/Al and Fe/Al) (plots not given) also show a marked change in U-2. As the CIA value for the overlying younger unit is higher, it appears that the differences are related to weathering at source and not at the present site.

5. LUMINESCENCE DATING

To constrain the timing of the suite of six large flash floods recorded at Siddapur, samples were collected for OSL dating from the bottom of the upper (U-1), middle (U-2) and lower units (U-3) (**Fig. 3A**). Because of the highly disturbed nature, no samples were collected for dating from the top of U-1.

The three sediment samples were collected in galvanized iron tubes. The sediment was sequentially treated with 10% HCl and 30 % H_2O_2 to remove carbonates and organic material, then sieved to obtain 90-150 µm size

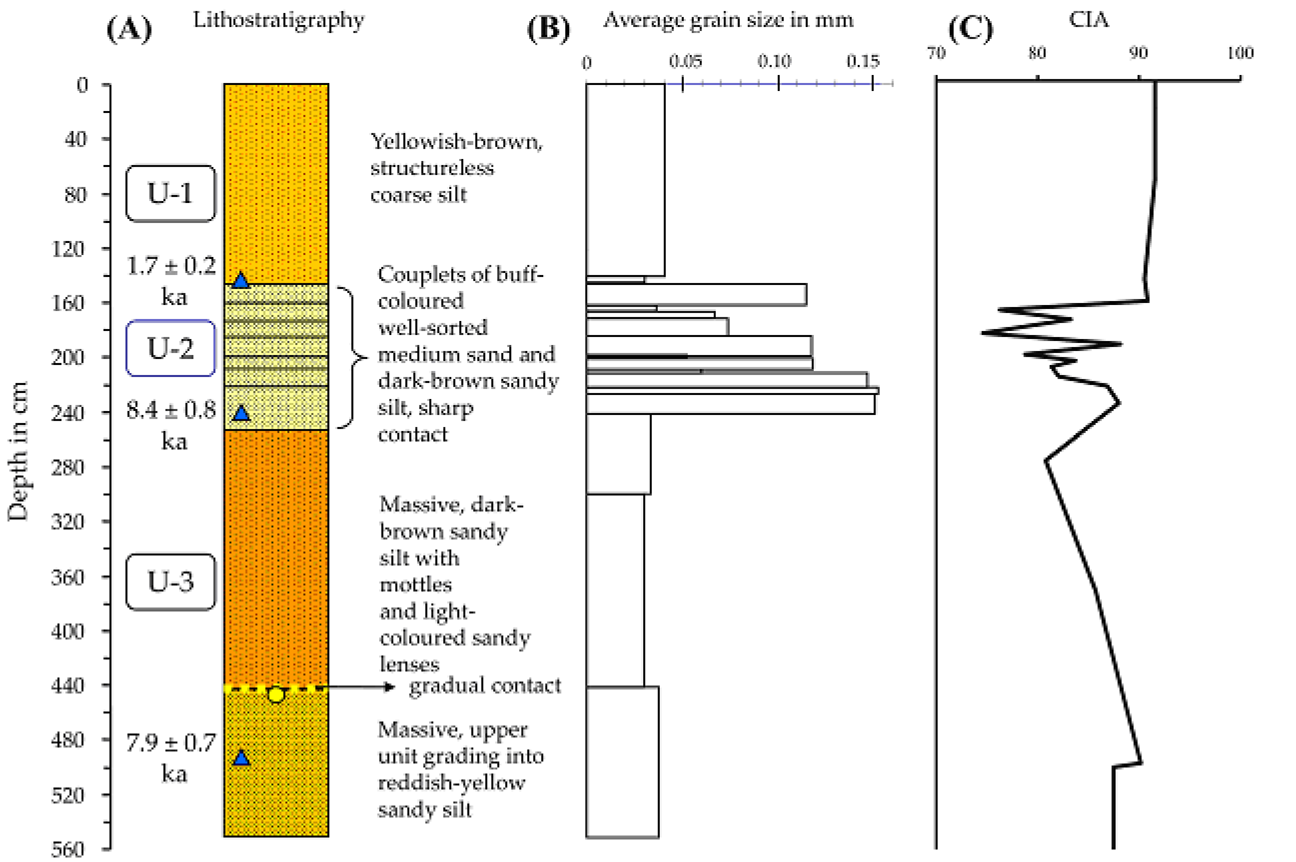

Fig. 3. *(A) Lithosection of the Siddapur section. The triangles represent the location of samples collected for OSL dating. (B) Variation in the mean grain size. (C) Plot of Chemical Index of Alteration (CIA).*

fraction. Heavy liquid density separation using sodium polytungstate solutions (density = 2.58 g/cm^3) was carried out to separate quartz and feldspar minerals. To remove alpha dosed outer layer (~10-15 µm) and also to get rid of feldspar grains contamination left, if any, the quartz grains were etched for 80 minutes using 40% HF acid followed by 40 minutes of 40% HCl acid to dissolve fluorides formed during etching. All the samples were checked for any contamination of feldspar using Infrared Stimulated Luminescence (IRSL) at 125^o C.

Standard SAR protocol (Murray and Wintle, 2000) was applied to obtain equivalent dose from each sample. Small aliquots of ~3 mm were prepared on a 10 mm diameter stainless steel disks. Blue light stimulated luminescence (BLSL) using blue light LED's (λ=470±30 nm; delivering 45 mW/cm^2 of energy) was measured for 40 seconds at 125^o C with a Risø TL-DA-15 reader equipped with EMI 9635 QA Photo multiplier tube (PMT). Detection optics comprised U-340 and BG-39 filter transmitting in the UV spectrum for photons detection. XRF and ICPMS analysis were done to measure radioactive elemental (U, Th and K) concentration, summarized in **Table 1**.

The photon counts were well above the detection limit and laboratory generated growth curves were linear in the range of natural dose (**Fig. 4A**). Initial OSL luminescence (0.8 seconds integral counts) was used after a background subtraction from last 4 seconds integral of the shine down (**Fig. 4A**).

To check the applicability of SAR protocol, a dose recovery check was made on the quartz from SDP-2 sample. The preheat temperature of 240^{o}C for 10 seconds and

Table 1. *Summary data for OSL ages. The measured water content was ~20% in all the samples and cosmogenic dose rate of 0.15 Gy/ka was assumed. The error on equivalent dose is standard error.*

Sample No.	Radioactive element concentration			Dose rate (Gy/ka)	Palaeodose (Gy)	Age (ka)
	U (ppm)	Th (ppm)	K (%)			
SDP-1	1.35±0.01	11.1±0.07	0.21	1.25±0.1	2.1±0.1	1.7±0.2
SDP-2	1.06±0.01	8.15±0.06	0.22	1.02±0.1	8.6±0.1	8.4±0.8
SDP-3	1.12±0.01	7.81±0.05	0.31	1.07±0.1	8.4±0.1	7.9±0.7

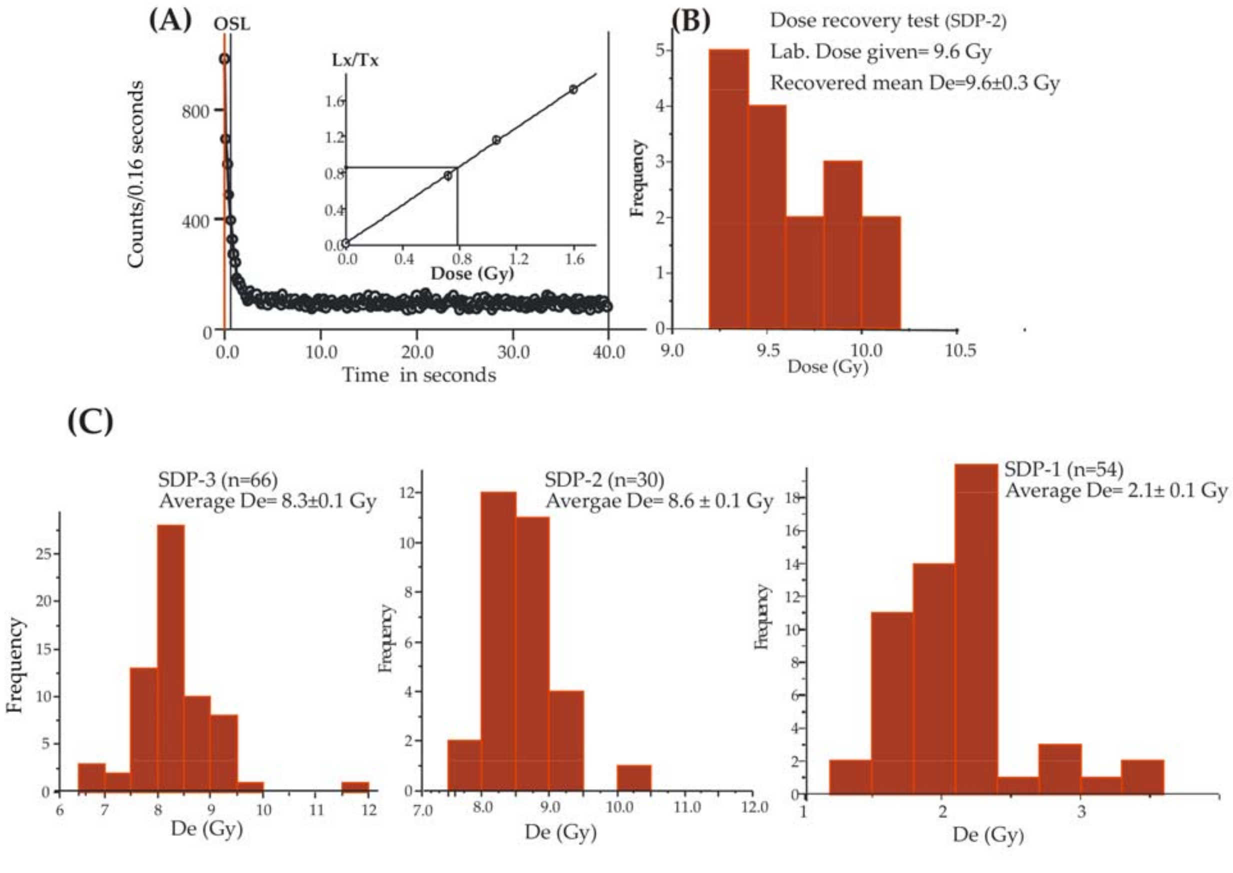

Fig. 4. *(A) The BLSL shine down curve from the quartz from SDP-2. The inset figure shows laboratory generated dose-growth curve of quartz. The growth curves were linear in the range of palaeodoses obtained from all the samples. (B) Dose recovery test result from the quartz. (C) Histograms showing dose distribution in all the samples.*

160°C cut heat was used for regeneration and test doses respectively. A set of 16 bleached aliquots (sample SDP-2) were given a laboratory dose of 9.6 Gy and then using SAR, these doses were recovered considering them as a natural dose. The ratio of average recovered dose (average dose=9.61±0.3 Gy; error is standard deviation from 16 aliquots in total) and given laboratory dose is 1.0, which is indicative of successful application of SAR protocol within accepted range of deviation from the accurate dose (**Fig. 4B**).

Palaeodoses were measured from all the samples SDP-1, 2 and 3 using SAR protocol. The quartz from the studied area is very well suited for optical dating in terms of luminescence characteristics. All the aliquots have shown recycling ratio within 10% of unity and the recuperation was found to be less than 3% of D_e for all the aliquots. The error on all the D_e's were found to be less than 10%. Hence these are well through from the criteria of aliquot selection suggested by Murray and Olley (2002) and Thomas *et al*. (2005). All the palaeodose measurement, radioactive elemental concentration and dose rate data has been summarized in **Table 1**. **Fig. 4C** shows the histogram plot of palaeodoses obtained through SAR. The dose distribution of palaeodoses from Siddapur is indicative of well bleached grains and slightly positively skewed distribution (**Fig. 4C**). The average ages from these samples are 1.7±0.2, 8.4±0.8 and 7.8±0.7 ka for SDP-1, 2 and 3 respectively. The OSL ages of SDP-2 and SDP-3 are indistinguishable statistically. However, within error limits, these two can be considered same and suggest synchronous deposition, which cannot be resolved to a scale of few hundred years in the present case using OSL dating. The OSL ages suggest that the six discrete flash flood events occurred sometimes between ~8 and 2 ka.

6. FLOOD MAGNITUDE

The area under study has no well-documented records of historical floods or gauge data. Available reports indicate that the two most extraordinary floods on the upper Kaveri were recorded in July 1924 and July 1961. The latter being the highest on record. In the absence of gauge records, the following power-law relationship between catchment area (A) and the 100-yr flood (Q_{100}) developed for the upper Kaveri Basin by Huq (1986) was used

$$Q_{100}=5.88\ A^{0.757}\ (r^2=0.92) \qquad (6.1)$$

The above equation yields a discharge of ~700 m^3/s for the study site. The 1961 high flood level (HFL) and the channel cross-section at Siddapur site are shown in **Fig. 5**. It is reasonable to assume that the 1961 HFL represents the discharge of ~700 m^3/s.

The highest palaeoflood couplet-6 is nearly 3.0 m below the HFL, implying that the 1961 and perhaps the 1924 flood stages were higher than the mid-Holocene palaeofloods. Needless to say this inference is valid only if the channel geometry of the reach has not changed significantly or the channel has deepened in the last few millennia. Considering the present channel morphology of the reach the latter explanation appears to be plausible.

7. DISCUSSION AND CONCLUSIONS

The Western Ghat is the source area of the Kaveri and other large DPRs, such as Godavari, Krishna, Bhima, etc. The Ghat zone is an area of highest monsoon precipitation (~2500-6000 mm) in the Deccan Peninsula. The nature of Indian summer monsoon rainfall (ISMR) along the western margin of India since and prior to Last Glacial Maximum (LGM) is largely inferred from the Arabian Sea marine records, because a large proportion of the monsoon rainfall drains into the Arabian Sea, via

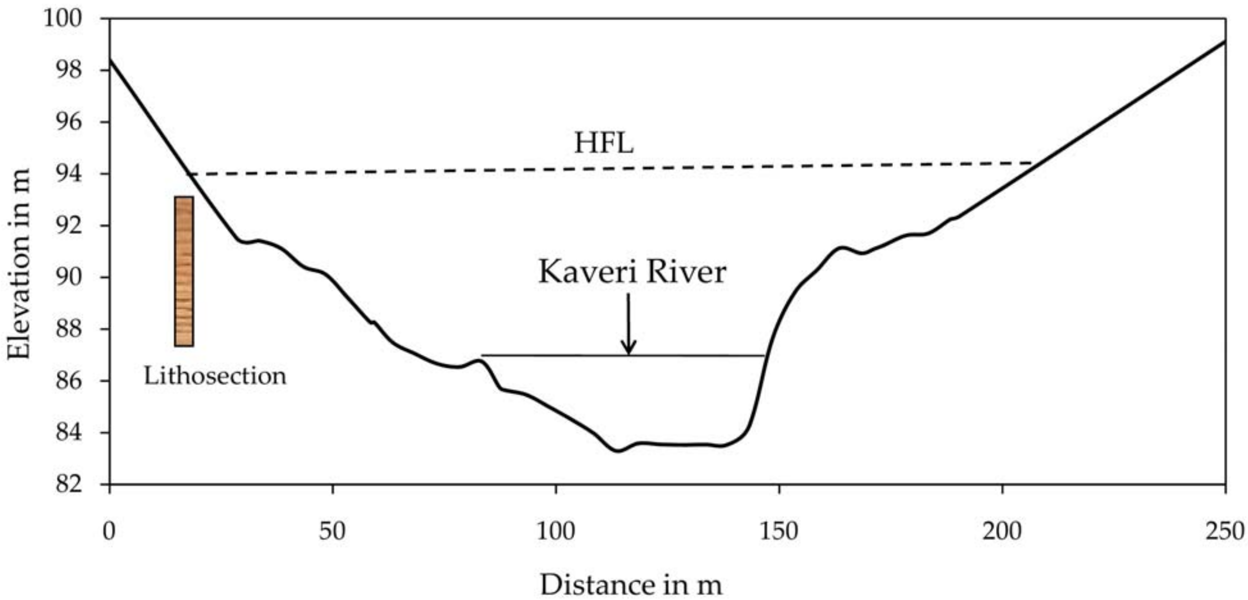

Fig. 5. *The Kaveri River channel cross-section at Siddapur. The lithosection is not located exactly on the profile but a few meters downstream. HFL= 1961 High Flood Level.*

short, steep coastal rivers. The only study from the montane region of the Western Ghat is based on the $\delta^{13}C$ measurements in peat from Nilgiri Hills (Sukumar *et al*., 1993). All the ISMR proxies reveal: (a) a significant spatial variability in the monsoon rainfall within Holocene, (b) significant changes in the ISMR throughout the Holocene, (c) an abrupt increase in the ISMR ~9.5 ka, and (d) a long-term gradual decline in the monsoon strength since the middle Holocene (~8 ka) associated with the southerly shift in the position of Inter-Tropical Convergence Zone (ITCZ) (Sarkar *et al*., 2000; Fleitmann *et al*. 2007 and references therein). The beginning of the retreat of ITCZ almost coincides with the '8.2 ka cold event' seen in the records of North Atlantic as well as monsoonal tropics (Rohling and Pälike, 2005). Marine proxy records off Oman (Gupta *et al*., 2003) and from the Bay of Bengal (Kudrass *et al*., 2001), and stalagmite records from Oman (Fleitmann *et al*., 2003) all reveal a distinct change in monsoon strength in the mid-Holocene around 8 ka (Staubwasser, 2006). Because there is a close relationship between climatic variables and the flood response it is very likely that this and other modest changes in ISMR had a significant effect on the river discharges and flood magnitudes (Kale *et al*., 2003a). Curiously there is no sedimentary evidence of flood-dominated regime in the Western Ghat zone to directly relate the hydrological response to climatic events.

The Siddapur site discussed in this paper has provided the first clear evidence of half-a-dozen discrete floods on the upper Kaveri River that occurred sometimes between ~8 and ~2 ka. Such evidence is not present or reported from any other river in the Indian Peninsula. The Siddapur record lacks evidence of discrete floods during the intense phase of monsoon in early Holocene. This could be ascribed to intense erosion rather than sediment accumulation associated with high monsoon discharges. We further argue that the beginning of the retreat of ITCZ around 7.8 ka and gradual decrease in monsoon precipitation in response to decreasing insolation (Fleitmann *et al*., 2007), probably initiated the phase of flash floods in the upper Kaveri Basin and possibly in other parts of the Western Ghat. The OSL dates at the base of Unit-1 and 2 (7.8±0.7 ka and 8.4±0.8 ka) support this inference. Since only successively large floods could overtop and leave a sedimentary record at the site, it is logical to deduce that the successive increase in flash flood magnitude corresponded with the long-term gradual decline in the monsoon strength and increase in monsoon rainfall variability since middle Holocene (~8 ka) (Kale *et al*., 2003a; Staubwasser, 2006). Increased monsoon variability implies increased frequency of extreme rainfall (excess and deficient) years. We believe that the flash flood record preserved at Siddapur reflects this increased variability in the wettest part of the Deccan Peninsula, namely, the Western Ghat.

In the absence of absolute ages of all the individual couplets (floods) it is not possible to state when the mid-Holocene flash flood regime terminated or what the average recurrence interval of the flash floods was. The sharp (erosional) break between the top of flood couplet-6 and the overlying structureless unit (U-1) could indicate either a significant time gap or no time gap or even truncated nature of the record. Needless to say this issue could only be resolved by dating all the six couplets. For practical reasons this was not feasible.

The comparison of the elevation of the highest couplet with the 1961 HFL demonstrates that the mid-Holocene palaeofloods were lower than the modern floods. Here it is pertinent to mention that the sedimentary record of several other floods that might have occurred between ~8 and 2 ka has not be preserved at Siddapur because they did not exceed the stage (elevation) defined by the six large-magnitude floods. In simple words they were lower in magnitude.

The OSL date (1.7±0.2 ka) from the base of overlying structureless Unit-1 implies that there is no evidence of major flash floods roughly since the beginning of the Common (Christian) Era. In western India also there is no sedimentary record of a major flood after 1.7±0.5 ka on the Mahi River (Sridhar, 2007). A change in the fluvial regime around this time (~2200 ^{14}C yrs BP) is also indicated by a marked change in vegetation and hence the monsoon rainfall in the southern segment of the Western Ghat (Caratini *et al*., 1994).

To sum up, the sedimentary records at Siddapur have provided robust evidence of at least six short-term, high discharge events on the upper Kaveri River during the period of deterioration of monsoon climate that started with the retreat of ITCZ in middle Holocene (~8 ka). It remains however unknown whether these flash floods were localized or regionally widespread. Needless to say, generation of similar type of palaeoflood data from other large Indian Peninsula rivers would be helpful in answering this simple yet profound question.

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