Late Quaternary fine silt deposits of Jammu, NW Himalaya: Genesis and climatic significance

RAJINDER K GANJOO* and VINOD KUMAR

Department of Geology, University of Jammu, Jammu 180 006, India.

**Corresponding author. e-mail: ganjoork@rediffmail.com*

The fine silt deposits of Jammu (J & K State, India) stretch all along the Siwalik foothills from Jammu to the Potwar Plateau in Pakistan. The post-Siwalik deposits, first discussed by de Terra and Paterson (1939), are attributed to wind action. The deposits termed as 'Potwar loessic silt' comprising sandy silt are essentially of late Quaternary age (75–18 ka) and are re-looked herein from the point of view of genesis and climatic significance. The sorting, skewness and kurtosis parameters of fine silts of Jammu suggest fluvial environment of the deposits wherein the water budget fluctuated. The weak pedogenesis of fine silts at certain intervals corroborate to periods of less or no sedimentation. The bivariate plot studies further suggest fluvial environment of deposition for the fine silt at Jammu, with regular fluctuations in the budget of river water that was perhaps in consonance with oscillations in the climate of the region.

1. Introduction

de Terra and Paterson (1939) were the first to identify silt deposits along the foothills of the Jammu Siwalik Range and equate them with the 'Potwar loessic silt' of the Potwar Plateau (Pakistan). The silts are uniformly fine in texture but the angularity of mineral grains suggests their origin by 'violent wind transport' (de Terra and Paterson 1939, p. 272–273). They also observed that light yellow and brown (or faintly pinkish) strata interchange with each other and the bedding planes at places show films of clay matter (p. 273). They identified that the fine silt deposits of the Potwar Plateau and adjoining areas are texturally similar to the loess of North China but the fine silts are stratified or coarsely laminated at places (such as Soan and Sil). Unconsolidated gravels and sand at the base of Potwar silt are yet another similarity to the loess of North China (particularly the Upper Pleistocene Malan Loess) (de Terra and Paterson 1939, p. 273). Rendell *et al* (1989), however, disagreed over any

comparison between the fine silt deposits of the Potwar Plateau and the loess of North China. Potwar silt is attributed to the gigantic windstorms with intermittent rains that led to the widespread deposition of silt all along the Siwalik foothills from Jammu (India) to the Potwar Plateau (Pakistan) (de Terra and Paterson 1939). The braided course of the Indus river and exposed surfaces of alluvial fans along the mountain foot are identified as the probable source for desert 'loess' of Pakistan (Rendell *et al* 1989). Ganjoo (1993) argued in favour of fluvio-aeolian genesis of the deposits.

The loessic silt deposits in Pakistan are dated by thermoluminescence (TL) method and the age ranges between 130 and 18 ka (Rendell *et al* 1989). The deposition of fine silt is more widespread and dominating between 75 and 18 ka, but between 75 and 130 kyr, loess is only preserved in isolated pockets. Loess deposits overlie the eroded surfaces of the Siwaliks and Lei Conglomerate. These deposits include both primary and reworked (by rain splash, surface flow and slumping) loess

Keywords. Fine silt; Potwar loessic silt; Jammu; NW Himalaya; late Quaternary.

(Rendell 1988). The fine silt deposits of Jammu are dated between the late Pleistocene and Holocene on the basis of geographical contiguity, granulometric and geochemical correlations with the Potwar loessic silt of Pakistan.

2. Sedimentary succession and age

The fine silt deposits, from Samba to Akhnoor ($32^{\circ}33'40''$ – $33^{\circ}00'N$ and $74^{\circ}30'$ – $75^{\circ}6'E$) (figure 1) support badland topography dissecting the sediments and giving rise to small mounds. The thickness of the deposit is variable, ranging from as little as 3 m (where the base of the deposits is not well exposed) to 10 m with poorly developed

stratification. The silt deposit is pale yellow in colour (figure 2a), whereas weathered (pedogenised and bioturbated) silt is dark brown in colour (figure 2b). The fine silt deposits show considerable variation in lithology from pebble to silt grade. By and large, the exposed litho-sections have fine silt at the base that is of uniform grain size (silt grade) and finely laminated. Overlying it is the unconsolidated matrix-supported sandy pebbly gravel unit with an erosional contact and a medium-grained sand matrix lacking any primary sedimentary structure (figure 2c). The pebbles show weak orientation and are uniform in size. Above this unit, once again, lies 1-m thick fine silt with a sharp contact. Gradually above it lies kankerised silt (0.5–1.5 m thick) containing specks

Figure 1. Geological map of the study area between Samba and Akhnoor (modified after Verma *et al* 1990).

Figure 2. Field photographs of (a) fine silt unit, (b) pedogenised fine silt unit, and (c) pebbly gravel unit (PGU).

of kankers and rootlets. The silt unit has an accumulation of calcium carbonate (kankars) along the pedal surfaces and rootlets cementing the silt material. The kankerisation and presence of rootlets suggest *in situ* soil formation, though incipient in nature. In sections exposed to the northwest (Akhnoor), fine silt deposits are strongly pedogenised and bioturbated with both horizontal as well as vertical burrows. Thin lenses (0.5 m thick) of semi-consolidated sand occur within this fine

silt. The sand grades from fine-to-medium grain and lack primary sedimentary structure. Above it, once again, lies a thick (1–2 m thick) deposit of fine silt. The litho-sections are invariably capped by matrix-supported pebbles.

Most of the litho-sections show a dominance of silt grain size (Vijaypur 58.62%, Najwal 49.01%, Samba 51.69%, Supwal 48.30%, Pambarwan-A 69.72%, Pambarwan-B 61.95%, Sanyal 73.36% and Daskal 58.12%). The percentage of sand grain size varies between 17.13% (Sanyal) and 42.22% (Supwal) (figures 3 and 4), whereas the percentage of clay is between 13.42% (Pambarwan-A) and 8.06% (Samba). Granulometrically, the fine silt deposits of Jammu comprise 31% sand, 59% silt, and 10% clay by average. The fine silt deposits of Jammu are dominated by illite, chlorite and kaolinite clay minerals. Geochemically, the fine silt deposits of Jammu have a dominance of SiO_2 (73%), Al_2O_3 (19%) and total Fe oxides (2.6%).

The percentiles of sand, silt and clay obtained from the analysis of fine silt of the area of investigation are shown in table 1 and plotted in ternary diagram (figure 5). The results suggest that 23% of total samples fall within the zone of silty sand, and 77% within the zone of sandy silt. Hence, the fine silt deposits of Jammu are predominantly sandy silt.

The fine silt deposits of Jammu are granulometrically and geochemically well correlatable to the Potwar loessic silt of Pakistan. Besides the textural and chemical similarities between the fine silt deposits of Jammu and the loessic silt of Pakistan, the geographical contiguity of deposits from Jammu to Potwar further substantiate to the regional deposition of fine/loess silt all along the foothills of Siwaliks from Jammu (India) to Potwar Plateau (Pakistan).

By accepting the fact of regional contiguity, granulometric and geochemical similarity of the fine silt deposits at Jammu and Potwar, the time brackets suggested for the Potwar loessic silt (Pakistan) are extrapolated to the fine silt deposits of the Jammu area. The youngest loess of Pakistan yielded an age of 20–22 ka (TL dates) while the base yielded an age of 132 ka (Rendell and Dennell 1987). Still older deposits (170 ka) are reported from a few places in the Potwar that lie above the eroded Siwaliks (Rendell 1987–88). However, no such older deposits of loess/fine silt are reported from the Jammu Siwalik foothills between Samba and Akhnoor.

3. Material and methods

The parameters used to describe grain size distribution fall into four principal groups: those

Figure 3. Variation of sand, silt and clay in the litho-sections at (a) Vijaypur Railway Station, (b) Najwal, (c) Samba, and (d) Supwal.

measuring (a) the average size, (b) the spread (sorting) of the sizes around the average, (c) the symmetry or preferential spread (skewness) to one side of the average and (d) the degree of concentration of grains relative to the average (kurtosis). In the present investigation, textural parameters such as mean (M_z), standard deviation (σ_i), skewness (S_{ki}) and kurtosis (K_G) are calculated using the method of moments instead of conventional graphic approximations, because grouped moment measures yield more reliable results than the graphic approximations, particularly for skewness and kurtosis (Krumbein and Pettijohn 1938; Swan *et al* 1979; Friedman and Johnson 1982). Several sedimentologists (Inman 1949; Einstein 1950; Moss 1963; Doeglass 1964; Spencer 1963) have interpreted grain size distribution curves and concluded that a population is a mixture of two or

more log-normal sub-populations shown by their log probability cumulative curves and proposed close relationship between sedimentation dynamics and texture. Visher (1969) showed that most distribution includes one or more sub-populations, each of which display a log-normal distribution and are attributed to three modes of sediment transport, i.e., suspension, saltation and traction. Further, he differentiated environments such as aeolian dune, fluvial, deltaic, tidal, channels, waves and turbidity currents.

In the present investigation, textural statistical parameters (mean, standard deviation, skewness and kurtosis) are calculated using moment measurements on sample populations containing one-phi interval classes in all fractions (Friedman and Sanders 1978; Forrest and Clark 1989). A total of 87 samples are collected from eight different

Figure 4. Variation of sand, silt and clay in the litho-sections at (a) Pambarwan-A, (b) Pambarwan-B, (c) Sanyal, and (d) Daskal (for index see figure 3).

sections. All the samples were subjected to grain size analysis with the help of sieving (particles coarser than 0.0625 mm) and pipette analysis (particles finer than 0.0625 mm) wherein different fractions of particle grade size were separated based on the Wadels modification of Stoke's Law (table 1). The fractions so obtained were subjected to calculations of different textural parameters such as skewness, kurtosis, mean size and standard deviation using the mathematical 'methods of moments' by Friedman and Johnson (1982) (table 2).

3.1 Mean size

The mean size in the sediment depends upon the source, mode of transportation and depositional conditions. Mean size is an average size of sediment and represents an index of energy condition. The

formula used for calculating the mean size of fine silt of the study area is given in table 2. The maximum value of mean size in fine silts of the study area is 0.48 mm (1.08ϕ) and the minimum value of mean size is 0.05 mm (4.35ϕ) (table 3). The mean size values of fine silt of the study area reveal a low-energy condition of deposition.

3.2 Sorting/standard deviation

Standard deviation measures the sorting of sediments and indicates fluctuations in the kinetic energy or velocity conditions of the depositing agent (Sahu 1964). Also, sorting has an inverse relation with standard deviation. In the present study, the minimum and maximum values of the standard deviation are 0.08 mm (3.67ϕ) and 0.37 mm (1.41ϕ), respectively (table 3). These

Figure 5. Ternary diagram of post-Siwalik deposits of study area with three end-members of classes sand, silt and clay (after Folk 1954, 1980).

values when compared with various grades of sorting proposed by Folk and Ward (1957), Cadigan (1961) and Friedman (1961) show that these deposits are characterized by poorly sorted to very poorly sorted grains. The sorting characteristics of fine silt reveal that the depositional environment must have been fluvatile. The little variation in sorting of fine silt is attributed to difference in water turbulence and variability in the velocity of depositing currents (Casshyap and Khan 1982).

3.3 Skewness

Skewness measures asymmetry of frequency distribution and marks position of mean with respect

to median. In a material of sufficient quantity of different sizes, a coarsely skewed sample implies that the velocity of depositing agent operated at a higher value than the average velocity for a greater length of time (Sahu 1964). In the present study, the fine silt has minimum and maximum skewness values of 0.70 mm (0.51ϕ) and 5.64 mm (-2.2ϕ), respectively (table 3) implying that the fine silts of the study area are dominantly coarse skewed to very coarse skewed. A comparison of the skewness values of the study area with the classification of skewness proposed by Folk and Ward (1957) and Cadigan (1961) show that the skewness values of samples in which silt is dominating are negatively

Table 1. *Settling times according to the Wadell modification of Stoke's Law.*

ϕ	Diameter (mm)	Velocity cm/s	Depth (cm)	Time of settling		
				Hours	Minutes	Seconds
4	1/16	0.223	20	0	1	00
5	1/32	0.0558	10	0	2	59
6	1/64	0.0139	10	0	11	51
7	1/128	0.00349	10	0	47	—
8	1/256	0.00087	10	3	12	—
9	1/512	0.000217	7	8	58	—
10	1/1024	0.000054	5	25	43	—
11	1/2048	0.000013	5	106	50	—

Figure 6. Standard deviation *vs.* mean size.

Table 2. *Formulae used for the calculation of different moments.*

Equations	Moment	Standard notation	Notation used in grain-size calculation	Statistic
1	m_1	$\sum x/n$	$\sum (D \times W) / \sum W$	Mean
2	m_2	$\sum (x - x^-)^2 / (n - 1)$	$\sum W(D - M)^2 / \sum W$	Variance
3			$\sqrt{m_2}$	Standard deviation
4	m_3	$\sum (x - x^-)^3 / (n - 1)$	$\sum W(D - M)^3 / \sum W$	
5			$m_3 / m_2^{3/2}$	Skewness
6	m_4	$\sum (x - x^-)^4 / (n - 1)$	$\sum W(D - M)^4 / \sum W$	
7			m_4 / m_2^2	Kurtosis

Table 3. *Mean size, standard deviation, skewness and kurtosis values with the weight percentiles of sand, silt and clay in the fine silt samples of the study area.*

Sample no.	Mean	SD	Skewness	Kurtosis	Sand (%)	Silt (%)	Clay (%)
VR1	0.12	0.16	2.28	8.72	41.55	46.93	11.52
VR2	0.11	0.15	2.38	9.40	43.31	44.61	12.08
VR3	0.48	0.37	-1.10	1.33	56.25	36.80	6.95
VR4	0.05	0.09	4.30	26.40	17.79	72.75	9.46
VR5	0.25	0.21	2.57	7.99	17.22	73.03	9.75
VR6	0.06	0.12	3.96	20.41	18.17	71.57	10.25
VR7	0.34	0.15	3.07	12.39	23.61	70.74	5.65
VR8	0.05	0.10	5.64	37.16	11.18	78.51	10.31
VR9	0.10	0.14	3.67	16.63	16.29	70.15	13.55
VR10	0.41	0.20	2.34	7.48	28.31	66.79	4.90
VR11	0.28	0.16	2.87	10.94	21.56	75.79	2.65
VR12	0.06	0.13	4.32	22.12	14.20	76.38	9.42
VR13	0.24	0.22	2.01	5.86	31.47	62.07	6.47
VR14	0.21	0.19	1.28	4.36	70.26	27.19	2.55
VR15	0.15	0.19	1.05	3.94	68.10	23.02	8.87
VR16	0.06	0.11	4.16	22.53	15.30	72.44	12.26
VR17	0.12	0.14	3.37	15.27	22.84	67.65	9.51
VR18	0.05	0.11	4.72	27.28	13.17	78.46	8.37
VR19	0.12	0.18	2.73	9.85	23.35	66.71	9.94
VR20	0.12	0.15	2.30	9.04	69.17	23.16	7.67
VR21	0.16	0.18	1.86	6.26	55.15	35.90	8.95
VR22	0.06	0.13	4.06	20.75	16.97	72.83	10.20
VR23	0.25	0.22	2.05	5.83	30.11	59.41	10.48
VR24	0.05	0.08	5.42	40.01	17.26	69.63	13.11
VR25	0.10	0.16	1.74	6.44	66.20	21.76	12.04
VR26	0.22	0.20	1.23	3.99	66.49	30.29	3.22
VR27	0.13	0.17	2.97	11.39	22.42	65.74	11.84
VR28	0.26	0.19	2.56	8.45	21.56	71.08	7.36
VR29	0.07	0.13	3.27	15.01	24.07	68.52	7.40
NJ1	0.08	0.23	1.06	3.27	65.09	20.52	14.38
NJ2	0.08	0.24	0.96	2.92	58.47	30.12	11.40
NJ3	0.24	0.24	0.90	2.79	58.45	35.64	5.90
NJ4	0.42	0.25	1.72	4.36	32.26	62.67	5.07
NJ5	0.36	0.26	1.20	3.03	51.82	41.69	6.49
NJ6	0.28	0.18	0.97	3.94	80.68	16.02	3.29
NJ7	0.07	0.12	4.23	22.29	14.73	72.98	12.29
NJ8	0.07	0.13	3.12	14.47	28.68	59.15	12.16
NJ9	0.11	0.14	2.95	12.24	22.58	67.81	9.60

Table 3. (Continued).

Sample no.	Mean	SD	Skewness	Kurtosis	Sand (%)	Silt (%)	Clay (%)
NJ10	0.12	0.23	1.33	3.75	66.99	21.53	11.48
NJ11	0.47	0.37	-1.10	1.31	53.46	37.93	8.60
NJ12	0.03	0.15	3.58	14.89	26.11	63.75	10.14
NJ13	0.23	0.14	3.56	15.80	15.72	76.43	7.85
NJ14	0.08	0.16	3.12	12.44	23.19	66.34	10.47
NJ15	0.30	0.23	1.86	5.07	32.84	62.59	4.56
SM1	0.07	0.25	1.11	3.04	60.62	29.08	10.29
SM2	0.12	0.17	2.61	9.51	50.91	37.46	11.63
SM3	0.39	0.18	2.39	8.07	31.80	60.04	8.16
SM4	0.31	0.21	2.54	8.04	23.32	72.33	4.35
SM5	0.08	0.15	3.52	15.11	23.18	66.74	10.08
SM6	0.27	0.21	1.54	4.61	51.67	44.51	3.82
SP1	0.17	0.18	2.38	8.33	42.92	52.96	4.12
SP2	0.22	0.20	2.51	7.97	26.60	59.68	13.71
SP3	0.25	0.18	2.29	7.67	26.48	62.99	10.53
SP4	0.27	0.29	0.94	2.07	74.96	19.76	5.28
SP5	0.05	0.13	4.04	19.89	14.64	70.94	14.42
SP6	0.15	0.19	2.17	7.28	67.70	23.45	8.85
PBA1	0.07	0.12	4.25	22.57	16.12	72.27	11.60
PBA2	0.16	0.16	3.16	12.91	21.98	65.33	12.69
PBA3	0.08	0.16	3.26	13.32	17.14	65.76	17.10
PBA4	0.26	0.15	3.75	16.53	13.16	68.11	18.72
PBA5	0.07	0.13	4.03	20.27	18.67	70.86	10.46
PBA6	0.12	0.11	4.34	24.90	14.87	73.21	11.92
PBA7	0.08	0.12	3.79	19.25	21.71	67.42	10.87
PBA8	0.13	0.13	3.99	19.52	15.04	71.20	13.77
PBA9	0.26	0.15	3.86	17.56	13.08	73.29	13.63
PBB1	0.08	0.17	2.90	10.98	22.14	62.09	15.77
PBB2	0.07	0.13	3.73	17.70	17.80	70.46	11.74
PBB3	0.08	0.16	3.12	12.39	18.69	65.51	15.81
PBB4	0.26	0.25	0.70	2.31	72.58	20.80	6.62
PBB5	0.42	0.19	2.73	9.48	21.35	64.55	14.10
PBB6	0.25	0.18	2.97	10.87	19.06	71.81	9.13
PBB7	0.28	0.18	2.90	10.33	17.40	68.66	13.93
PBB8	0.10	0.19	2.88	10.05	18.08	71.74	10.19
SN1	0.12	0.15	3.61	15.45	11.44	78.07	10.49
SN2	0.20	0.15	3.62	16.10	14.36	72.88	12.76
SN3	0.07	0.13	4.71	25.17	9.72	80.97	9.31
SN4	0.12	0.14	3.48	15.70	20.07	71.26	8.67
SN5	0.10	0.12	4.26	22.69	19.34	75.37	5.29
SN6	0.09	0.16	3.09	12.30	27.87	61.61	10.53
DS1	0.21	0.21	2.36	7.29	25.53	61.59	12.88
DS2	0.08	0.16	3.10	12.60	36.66	54.79	8.55
DS3	0.07	0.14	3.38	14.75	18.45	75.10	6.45
DS4	0.09	0.19	2.44	8.17	45.43	46.37	8.20
DS5	0.26	0.30	1.05	2.25	44.09	47.39	8.52
DS6	0.35	0.20	2.18	6.87	27.61	61.99	10.40
DS7	0.25	0.21	2.17	6.62	29.93	58.39	11.67
DS8	0.28	0.22	1.91	5.46	31.74	59.37	8.89

to positively skewed, and samples in which sand is dominating are positive- to very positive-skewed. Accordingly, the negatively skewed sediments

indicate a beach environment whereas positively skewed sediments belong to a fluvial or aeolian environment. Thus, the sediments under study

show a fluvial environment with a mix of sediments by aeolian activity.

3.4 Kurtosis

Kurtosis is a quantitative measure used to describe the departure from normality of distribution. Many curves designated as 'normal' by the skewness measure turns out to be markedly non-normal when the kurtosis is computed. For abnormal distribution, the kurtosis value is unity. It is the ratio between the sorting in 'tails' of the curve to that of the central portion. If the central portion is better sorted than the tails, the curve is said to be excessively peaked or leptokurtic, but if the tails are better sorted than the central portion, the curve is flat peaked or platykurtic. According to Cadigan (1961), kurtosis is the measure of peakedness of the curves and mathematically, it is a function of the internal sorting or distribution. Kurtosis values of natural sediments vary from 0.50 to 8.0 (average around 1.0). In the fine silt of the study area, the maximum value of kurtosis is 40.01 mm (-5.31ϕ), and the minimum value is 1.31 mm (-0.39ϕ) (table 3), which indicates that the fine silt of the study area is very platykurtic in nature. Extremely low values of kurtosis suggest that part of the sediments is sorted out elsewhere in a high-energy environment (Folk and Ward 1957). The kurtosis is also an environment-sensitive parameter, and the absence of extreme values in the investigated units probably shows a lack of previous sorting of the modes.

The clay content of the fine and pedogenized fine silt unit is as high as 14% and as low as 3% for sandy units. At Pambarwan-A, Sanyal and Daskal; the sand, silt and clay variation curves run almost parallel to each other, depicting their uniform distribution with the least variation in their content down the section. The striking feature of fine silt deposits of Jammu is an overall low percentage (8.5%) of clay, which is also true for loess of Central Europe (Bronger 1976; Pecsli 1982) and China (Liu *et al* 1982).

4. Bivariant scatter plots

Various attempts have been made to establish the mutual relationship of size-parameters (Folk and Ward 1957; Friedman 1961; Moliola and Weiser 1968) by plotting pairs of parameters as scatter plots to understand their geological significance. Depositional environments are claimed to have been identified from bivariant plots (Folk and Ward 1957; Passega 1957, 1964; Doeglas 1964). Folk and Ward (1957) constructed six bivariant

plots and evaluated their utility in sedimentological studies. Stewart (1958) plotted the median diameter against standard deviation and skewness to find out the process of deposition. Passega (1957, 1964) and Bull (1962) plotted the coarsest one-percentile grain size (C) and median grain-size (M) of sediment samples on double-log paper and obtained specific CM pattern characteristics of the agent of transportation such as tractive currents, quiet water, beaches and turbidity currents. However, other researchers (Schlee *et al* 1965; Sevón 1966; Duarah and Das 1997) also indicate that textural parameters are not environmental sensitive.

4.1 Mean size versus standard deviation

Generally this type of plot gives much information about an environment (Inman 1949; Folk and Ward 1957). If a wide range of grain size (gravel to clay) is present, scatter bands often form some segment of a broadened M-shaped trend. Often, only a V-shaped or inverted V-shaped trend develops, and if size range is very small, only one limb of the V may occur. Minima of best sorting coincide with prominent modes in the sediments, and maxima (poorest-sorting) correspond to mean sizes midway between modal diameters. The plot (following Folk and Ward 1957) of fine silt of the study area show almost a linear trend, indicating a decrease in grain size with an increase in standard deviation (figure 6). The same plot after Friedman (1967) (figure 7) and Moliola and Weiser (1968) lies in the river field (figure 8).

4.2 Mean size versus skewness

Skewness is a function of grain size and has a markedly sinusoidal trend when the grain size range is wide (Folk and Ward 1957), but commonly, finer the sediment, the more skewed it is

Figure 7. Standard deviation *vs.* mean size.

Figure 8. Standard deviation *vs.* mean size plot. Figure 11. Standard deviation *vs.* skewness (S_{ki}). Figure 9. Mean size (M_z) *vs.* skewness. Figure 12. Standard deviation *vs.* skewness (S_{ki}).

4.3 Mean size versus kurtosis

The bivariate plot of mean size versus kurtosis (figure 10) does not seem to bear any significant relationship in the fine silt samples of the study area. According to Friedman (1961), kurtosis is not sensitive to environment and there is no apparent correlation between mean size and kurtosis. Folk and Ward (1957) used normalized kurtosis value $\{K'_G = [K_G/(1 + K_G)]\}$ instead of kurtosis (K_G) against mean size and obtained a complex curve whose exact nature as well as significance is not understood.

4.4 Standard deviation versus skewness

Both standard deviation and skewness are functions of mean size, which implies that sorting and skewness bear a mathematical relation to each other. The plot, following Folk and Ward (1957), of the fine silt shows a segment of the circular ring (figure 11). Thus, standard deviation versus skewness plots of fine silt of the study area does not follow the shape. Standard deviation versus skewness is also used for identification of depositional environment following Moiola and Weiser (1968)

Figure 10. Mean size (M_z) *vs.* kurtosis (K_G).

(Hough 1942; Inman 1949). The plot of mean size versus skewness does not show a sinusoidal trend as obtained by Folk and Ward (1957). Instead, the sediments show a linear relationship indicating that with decrease in grain-size, skewness increases (Hough 1942; Inman 1949). The plots from fine silt (figure 9) show that almost all points lie above, i.e., positive side of the normal skewness curve.

Figure 13. Normalized kurtosis ($K_{G'}$) vs. standard deviation.

Figure 14. Normalized kurtosis ($K_{G'}$) vs. skewness (S_{ki}).

and Friedman (1961) (figure 12). In the present study, Friedman's (1967) curve is found to be a suitable boundary line between river and beach environments (figure 12).

4.5 Standard deviation versus normalized kurtosis

The standard deviation (σ_1) versus normalized kurtosis (K_G') plot of the sediments (figure 13) gives a broad V-shape. This indicates that the sediments having a kurtosis value of normal range possess moderate sorting ($\sigma_1 = 0.6$), and higher kurtosis values are obtained in sediments possessing poor as well as better sorting.

4.6 Skewness versus normalized kurtosis

In skewness versus normalized kurtosis (figure 14), plots of the fine silt occupy mostly the upper right quadrant of the diagram and few samples are plotted in the top left quadrant. This indicates that the sediments are better sorted in the central part and also have a dominant finer mode. Regarding the separation of environment of sediments, Moiola and Weiser (1968) concluded that bivariate plot of kurtosis and skewness is not effective in most cases. They found this type of plot suitable

Figure 15. Median diameter (Md) vs. skewness (S_{ki}) after Stewart (1958).

Figure 16. Median diameter (Md) vs. standard deviation.

only to separate inland dune and coastal dune by using quarter phi data.

Median diameter (50th percentile) versus skewness (S_{ki}) (figure 15) and median diameter versus standard deviation (σ_1) plots (figure 16) (Stewart 1958) of the fine silt deposits of Jammu show a mixed environment. Although the plot suggests an absence of river process, the fall of maximum number of samples within the zone of 'slow deposition from quiet water' (figure 16) points to depositional process in flood plains, where the velocity of water is diminished due to loss of flow competence and rapid deceleration (Nicholas and McLelland 1999) and there is a gradual decrease with distance in mean grain size of over-bank deposits (Marriott 1992).

5. CM plot

The depositional environments of the older deposits may be delineated partly by the CM pattern through the logarithmic plots of the coarsest one-percentile grain size (C) and the median grain size (M). The plot so obtained may make patterns characteristic of distinct sedimentary environments

Figure 17. CM plot for the silt deposit of the study area. (i) Tractive currents: NO – rolling, OP – rolling with some grains transported in suspension, PQ – graded suspension with some grains transported by rolling, QR – graded suspension, RS – uniform suspension. (ii) No tractive currents: T – pelagic suspension.

(Passega 1957). The two parameters such as coarsest one-percentile grain size (C) and the median grain size (M) are selected since the coarse fraction of the deposit is more representative of the depositional environment than the finer fraction and C is representative of the upper limit of competence of

the depositional agent that further depends on the fact that the full range of sizes is available (Passega 1957). The CM plot for the silt deposits of the study area (figure 17) is plotted on a logarithmic scale. The pattern of the plot is parallel to the RS segment that reveals the deposition from uniform suspension. The deposition of the silt rich cohesive sediments is not only by uniform suspension (Bravard and Piere 1999) but also scatter of points to the left of the line $C = M$ suggest poorer sorting in the size range of 50th and 99th percentiles.

6. Lithofacies of fine silt deposits

Sedimentary processes in alluvial channels are qualitatively well known, in contrast to relatively meager knowledge of overbank sedimentary processes (Allen 1978). However, natural floodplains have provided valuable information on deposition (and erosion) rates (for details, see Bridge and Leeder 1979) and on lithofacies of near-surface overbank deposits (Fisk 1947; Jahns 1947; Allen 1965; McKee *et al* 1967; Coleman 1969; Williams 1971; Singh 1972; Ray 1976).

6.1 Lithofacies gmm: Matrix-supported gravel

The lithofacies lie in the middle and top of the litho-section and comprises unconsolidated sandy pebbly gravel unit (about 1.5 m thick) (figure 18) having erosional contact with underlying fine silt lithofacies Fsm (figure 19a). The pebbles are matrix supported and of uniform size. Pebbles show weak palaeoflow orientation. The sandy matrix of facie is fine to medium-grained and lacks any primary sedimentary structures. The clasts in this lithofacies are essentially of pebble grade. The sand of the

Figure 18. Field relationship of Fl, Gmm, Ss and Sm facies.

Figure 19. Lithofacies of the field area. (a) Sandwiched Gmm facies between Fsm facies at the bottom and the top. (b) Lithofacies Fr with root cast (encircled with dotted line) and vertical burrows (arrows). (c) Lithofacies Mb. Note the pedal structure owing to the intense pedogenesis mud bioturbation. (d) A close-up of the lithofacies P (Carbonate) and root cast (dotted outline) in the section at Sanyal.

Figure 20. Depositional model of the post-Siwalik deposit of the study area. (a) Lithofacies correlation and disposition of the various lithofacies. (b) Lateral lithofacies diagram of the exposed post-Siwalik deposits of the study area. The architecture shows the interfingering of channel (Gmm, Sm, Ss, Fl) and overbank facies. In the SE side, the upper part of the section is capped by Gmm facies whereas it is patchily preserved in the NW side. The overbank deposit is pedogenically modified as shown by the presence of Fr facies and occasionally Mb facies.

Table 4. *Particle compositions in various lithofacies of the study area.*

Lithofacies	Cobbles (%)	Pebbles (%)	Sand (%)	Silt (%)	Clay (%)
Matrix-supported gravel (Gmm)	26	43	28	03	05–07
Scour-fill sand (Ss)	—	—	70	25	04
Laminated sand, silt and mud (Fl)	—	—	66	22	12
Massive silt–mud facies (Fsm)	—	—	20	70	10
Root bed facies (Fr)	—	—	28–11	78–66	13–04
Bioturbated mud (Mb)	—	—	11	77	12
Pedogenic carbonate (P)	—	—	13	78	09

VR = Vijaypur Railway Station, NJ = Najwal, SM = Samba, Sp = Supwal, PB = Pambarwan (A & B), SN = Sanyal, DS = Daskal.

facie ranges from 40%–80%, with silt 50%–10% and clay 5%–7%. The percentage of cobbles is 26% and of pebbles is 43% (table 4). The overall textural and morphological characteristics of the lithofacies reflect formation of this unit by the process of high strength debris flow.

6.2 *Lithofacies Sm: Massive sand*

The lithofacies in the study area is 30-cm thick (figure 18) and comprises coarse-grained sand. Facies Sm comprise massive bed of coarse-grained sand without any apparent organization. The facie comprises 70% sand, 25% silt and 4% clay (table 4). The sand content is as high as 98.5% in some cases. Such types of sand beds are a result of sediment gravity flows (Miall 1996). Massive texture may also be produced by post-depositional modification, for example by dewatering and bioturbation (Miall 1996).

6.3 *Lithofacies Fl: Facies formed by overbank flooding*

Inter-lamination of very fine sand, silt and clay is observed in overbank area that represents deposition from suspension and from weak traction currents (figure 18). Undulatory beds, selected bioturbation, rootlets and dispersed pedogenic nodules are present (Miall 1996). The lithofacies attain maximum thickness (0.8 m) at Vijaypur. The individual bed is millimeter thick. The lithofacies in the area represents fining upward succession. Lithofacies comprise 66% sand, 22% silt and 12% clay (table 4).

6.4 *Lithofacies Ss: Crevasse channel*

Above the fluvial erosion surface is few decimeter to a meter-thick poorly defined cross-bedded sand, coarse to very coarse-grained sand with abundant intraclasts. The beds cover irregular shape of the basal bounding surface. The thickness of lithofacies is 0.4 m at the Vijaypur Railway Station.

The characteristics of lithofacies Ss indicate rapid deposition of poorly sorted coarse bed load. Lithofacies comprises 70% sand, 25% silt and 4% clay (table 4). Sand is deposited in an overbank environment as crevasse-channel discharge from river to flood basin (Slingerland and Smith 1998). A number of small streams in river channel during high energy stage spills out the floodwater onto the floodplains and drain water back to river as floods subside (Alexander *et al* 1999), generating crevasse-splay deposits.

6.5 *Lithofacies Fsm: Floodplain fines or abandoned channel*

The lithofacies in the study area is represented by fine silt (figure 19a). The main feature of this lithofacies is absence of sand beds that distinguishes it from Fl. As far as bedding and presence of accessories are concerned, Fsm compares well with Fl. It, probably, represents a floodplain deposit that is more distal with respect to clastic source, such as nearby fluvial channel. The facie Fsm is in sharp contact with the overlying Gmm facie. The thickness of lithofacies is about 0.5 m and contains lenses of sand, which is described as separate lithofacies Fl. The lithofacies form about 60% of the total thickness of lithosections. The sand content in this lithofacies is 20%, silt content is as high as 70% and clay content ranges from 10% to 5.65% (table 4).

6.6 *Lithofacies Fr: Floodplain fines or abandoned channel*

Lithofacies Fr represent soil development in silts under humid climate. The 1-m thick lithofacies contain rootlets but carbonate nodules are typically absent (figure 19b). The host lithology is dominated by silt grain size. The facie has gradual contact with underlying silt. The presence of rootlets suggest *in situ* soil formation (though of incipient nature) of the silt horizon during the climate amelioration. The sand content in the

lithofacies range from 28%–11%, silt content ranges from 78%–66% and clay content ranges from 13%–4% (table 4).

6.7 Lithofacies Mb: Bioturbated mud

The lithofacies are seen at Pambarwan-A (figure 19c). Strong bioturbation characterize the facies. It comprises 11% sand, 77% silt and 12% clay (table 4). Lithofacies also contains vertical as well as horizontal burrows.

6.8 Lithofacies P: Carbonate

Lithofacies P is developed in the section at Sanyal (figure 19d). The carbonates develop when flood plain is exposed to the surface weathering processes for extended periods (Miall 1996). The carbonates are formed by the infiltration of rainwater, which leaches dissolvable ions downward. Besides, capillary ground water flow and evaporation during arid periods concentrate the same ions near the surface leading to the development of carbonate cements that coalesces into nodules.

The host lithology in the present case is fine silt, which is highly indurated, due to the development of carbonate cement. The sand content in this facie is 13%, silt 78% and clay 9% (table 4). A generalized interrelationship of the lithofacies of the field area is shown in figure 19. The top of the lithofacies Sm is capped by Gmm facie, which reveals a high-energy debris flow close to the channel. The Sm facies is underlain by Ss facies, which depicts the deposition of Ss lithofacies as a rapid deposition of coarse and poorly sorted bed load. The details of the environmental interpretation of lithofacies depend on its facies association particularly the basal bounding surface on which it rests. The deposition of Ss here indicates a basal fill of element CH (Channel). The lithounit here also shows the Gmm facie with a sharp contact with the underlying Fl facie.

7. Depositional model

A schematic two-dimensional model of the fine silt deposits is given in figure 20, which is prepared from the measured lithosections and the disposition of the different lithofacies identified in the field. The model clearly depicts interfingering and lateral pinching out and thickening of the various lithofacies. It shows the dominance of floodplain fines (FF) (Lithofacies Fsm, Fr), which constitutes almost 80% of the whole deposit. Other lithofacies, e.g., Gmm, Ss, Sm, Mb, Fl, etc., together constitutes 20% of the deposit, which clearly indicates

that fine silt of the study area is dominantly a floodplain fine deposit. In the southeastern side of the study area, the deposit is capped by lithofacies Gmm that pinches out laterally towards NW and disappears at around Pambarwan-A. Gmm again appears at the extreme NW of the area at around Daskal with relatively very low thickness. Lithofacies Fsm and Fr are dominantly present in the fine silt of the study area. Lithofacies Mb is only present in the NW side of the study area at around Pambarwan-A and Pambarwan-B. Lithofacies P are also present in the section at Sanyal and pinches out laterally.

8. Discussion

The mean size of fine silt deposits at Jammu varies mostly between medium sand and coarse silt. The sorting or standard deviation of sediments indicates that the sediments are mostly poorly to very poorly sorted. This probably indicates that the fine silt sediments were transported in graded suspension (Passegga and Byramjee 1969). The fine silts of the study area are dominantly coarse skewed to very coarse skewed. The skewness values of samples, in which silt dominates, are negative-to positive-skewed and samples, in which sand dominates, are positive- to very positive-skewed. The positive and nearly symmetrical skewness values indicate fluctuation in energy conditions of the river/fluvial system. The higher percentage of coarse skewed (negative skewed) indicates relatively less fluctuation in the energy conditions. Kurtosis value of fine silt of the study area shows that these are very platykurtic in nature and better sorted in tails than the middle portion. The cumulative curves of fine silt of the study area are of elongate S-shape, with lower part of S (i.e., the coarsest tail) missing in most cases. Such cumulative curves are essentially in fluvial sediments (Visher 1969) and are of bimodal nature.

Standard deviation is found to increase with the decrease in grain size. Standard deviation versus mean size plot shows that the fine silt mainly represents river sediments (Friedman 1961, 1967; Moiola and Weiser 1968). Mean size versus skewness plots of fine silt sediments show an almost a linear relationship instead of sinusoidal (Folk and Ward 1957) that is attributed to the narrow grain-size range of the sediments. Standard deviation versus skewness plot indicates an incomplete circle due to narrow range of grain-size. Normalized kurtosis (K'_G) versus standard deviation (Folk and Ward 1957) plot gives either 'V'-shaped or inverted 'V'-shaped relationship. The highest kurtosis value indicates dominant single mode with a minor subordinate mode. The lowest value indicates mixing

of different modes. The present study shows that these two parameters possess a complex relationship. Skewness versus kurtosis plots indicate that the sediments possess a dominant finer mode with better sorting in the middle part.

Taking into consideration the sedimentary environmental parameters such as sorting, kurtosis, skewness, etc., a fluvial sedimentary environment is interpreted for the fine silt deposits of Jammu with incorporation of material by aeolian process. The over-bank flood plain provides a suitable depositional environment for the incorporation of blow in fine silt material during the dry winters.

9. Conclusions

The presence of silt and coarse (pebbly and sandy) units in the fine silt deposits exposed in the SE (Ravi basin) of the Jammu area do suggest fluctuations in water budget that could be attributed to seasonality in the hydrological regimes of the area. The dominance of silt deposits in Jammu foothills, both in SE (Ravi basin) and NW (Chenab basin), suggest the deposition of silt, transported by saltation process (Wiggs 1997), in the channel/bank of rivers under reduced flow conditions. The fluctuation in the water budget due to seasonality acts as a factor in sporadic high sediment load in rivers. It has been observed that large rivers store sediments in their channels and extensive riverbanks under the reduced flow and budget of river (Chakrapani 2005).

The climate conditions, yet another factor, change the quality and quantity of sediment load in river. Dry periods result in low sediment influx, whereas the sediment flux is almost five times greater during the wet periods (Inman and Jenkins 1999). Further, sediment flux in rivers in sub-zero temperatures is low compared to those tropical rivers that flow under temperature conditions of $>30^{\circ}\text{C}$ (Syvitski *et al* 2003). The frequent occurrence of coarser (pebbly and sandy) units, particularly in SE (Ravi basin) of the study area, undoubtedly corroborate to the fluvial aggradations in this part of the Jammu region. The absence of the coarser units in NW (Chenab basin) of the study area could be either due to the absence of a strong hydrological system in this part of the region, or the deposits are not deeply incised enough to expose the entire thickness of sediments.

The high relief and easily weatherable rocks of young continental crust play an important role in inducing high erosion of the land area (Montgomery and Brandon 2002; Ludwig and Probst 1998; Pinet and Sourian 1988). This holds true for the fine silt deposits of the Jammu area,

as tectonic uplift of Siwalik Group of rocks during Pleistocene provided both high relief and exposure of weatherable rocks. Enhanced hill-slope erosion and valley impoundment due to an intensified monsoon phase in late Pleistocene and Holocene is recorded from the Sutlej valley (Bookhagen *et al* 2005).

The production of smectite–illite–kaolinite–gibbsite, in increasing order, is linked to an increase in precipitation (Kudraas *et al* 2001). The enhanced illite from the clay of fine silt deposits of Jammu is related to the events of deglaciation and particularly the fluvial water influx that caused higher chemical weathering in the Himalayas under intensified precipitation regime (Chauhan *et al* 2004).

The fine silt deposits of Jammu suggest intensified monsoon phases during the late Pleistocene and Holocene as already recorded from elsewhere (Fleitmann *et al* 2003; Bray and Stokes 2004; Prins and Postma 2000; Thamban *et al* 2002; Fang 1991; Gasse *et al* 1991; Kotlia *et al* 2000). Besides, evidence from marine records also document enhanced terrigenous input and monsoon related increased upwelling off the west coast of India (Prins and Postma 2000; Thamban *et al* 2002), increased sedimentation rates during the Holocene due to an intensified monsoon phase from the Bay of Bengal (Goodbred *et al* 2003). Increased moisture transport during the late Pleistocene and Holocene is also reported from the southern tip of Arabian Peninsula (Fleitmann *et al* 2003; Bray and Stokes 2004).

The fine silt deposits of Jammu suggest that high sediment influx is coupled with higher precipitation that corresponds to increase in the averaged basin-erosion rates during the late Pleistocene and Holocene. The late Pleistocene–Holocene phase of high precipitation is intermittently punctuated by short but succinct events of low or no sedimentation causing pedogenesis of the deposits. The short and succinct phases of low/no sedimentation are equitable to semi-arid conditions in the region. The subsequent phase of increased precipitation has been responsible in the sediment evacuation from the poorly vegetated hill-slopes leading to massive sediment flux.

It is, therefore, concluded that:

- the fine silt deposits of Jammu are the result of fluvial action, particularly saltation processes, that fluctuated between strong and weak cycles of hydrological regime;
- the fine silt deposits preserve evidence of high to nil sediment flux that is linked to strong/intensified and weak monsoon phases;
- the Ravi basin (SE) sedimentary depositional environment shows variance from that of Chenab

basin (NW) that could be due to the presence of hydrological regimes of different magnitudes in regions; and

- variance in the flux of sedimentation from high to nil suggests oscillation in climate between wet and dry conditions during the interval of 50 ka (~75 ka to 18 ka).

Acknowledgements

The authors would like to thank the Head, Department of Geology, University of Jammu, Jammu for all the laboratory facilities. The fellowship to VK by the University of Jammu for undertaking the present study is acknowledged. Valuable suggestions and comments by reviewers are duly acknowledged.

References

- Alexander J, Fielding C R, Pocock G D 1999 Flood behaviour of the Burdekin river, tropical north Queensland, Australia. In: Floodplain: Interdisciplinary Approaches (eds) Marriott S B and Alexander J, *The Geological Society of London Special Publication* **163** 27–40.
- Allen J R L 1965 A review of the origin and characteristic of recent alluvial sediments; *Sedimentology* **5** 89–191.
- Allen J R L 1978 Achievements and prospects in fluvial sedimentology; *Canadian Soc. Petrol. Geol. Mem.* **5** 129–147.
- Bookhagen B, Thiede R C and Strecker M R 2005 Late Quaternary intensified monsoon phases control landscape evolution in the northwest Himalaya; *Geology* **33**(2) 149–152.
- Bray H E and Stokes S 2004 Temporal patterns of arid–humid transitions in the south-eastern Arabian Peninsula based on optical dating; *Geomorphology* **59** 271–280.
- Bravard J P and Peire J L 1999 *Floodplains: Interdisciplinary approaches* (eds) Marriott S B and Alexander J, *Geol. Soc. London* **163** 259–268, 1-86239-050-9/99.
- Bridge J S and Leeder M R 1979 A simulation model of alluvial stratigraphy; *Sedimentology* **26** 617–644.
- Bronger A 1976 Zur Quärtären Klima- und Landschaft-Entwicklung des karpatischen Beckens auf (Palao) Pedologischer und boden geographischer Grundlage; *Kieler Geographisches Schiften Band* **45** 266.
- Bull W B 1962 Relation of textural (CM) patterns to depositional environment of alluvial fan deposits; *J. Sedim. Petrol.* **32** 211–217.
- Cadigan R A 1961 Geological interpretation of grain size distribution measurements of Colorado plateau sedimentary rocks; *J. Geol.* **69**(2) 121–144.
- Casshyap A P and Khan Z A 1982 Paleohydrology of Permian Gondwana streams in Bokaro basin, Bihar; *J. Geol. Soc. India* **23** 419–430.
- Chakrapani G J 2005 Factors controlling variations in river sediment loads; *Curr. Sci.* **88**(4) 569–575.
- Chauhan O S, Patil S K and Suneethi J 2004 Fluvial influx and weathering history of the Himalayas since Last Glacial Maxima – isotopic, sedimentological and magnetic records from the Bay of Bengal; *Curr. Sci.* **87** 509–515.
- Coleman J M 1969 Brahmaputra River channel processes and sedimentation; *Sedim. Geol.* **3** 129–239.
- de Terra H and Paterson T T 1939 *Studies on the Ice Age in India and associated human cultures*, Washington: Carnegie Publications, 493p (reprinted in 1993, Aryan Books International, New Delhi).
- Doeglass D J 1964 Interpretation of the results of mechanical analyses; *J. Sedim. Petrol.* **16** 19–40.
- Duarah B P and Das B P 1997 Depositional condition of Tura sandstones as reflected by textural parameters around Dobagiri, East Garo Hills, Meghalaya; *J. Geosci.* **2** 51–66.
- Einstein H A 1950 The-bed load function for sediment transportation in open channel flows; *U.S. Department of Agricultural Techniques Bulletin* **1026** 70.
- Einstein H A and Chien N 1953 Transport of sediment mixtures with large ranges of grain size; University of California Institute of Engineering Research, M.R.D., Sedimentary Series No. 2: 49.
- Fang J Q 1991 Lake evolution during the past 30,000 years in China and its implications for environmental change; *Quat. Res.* **36** 37–60.
- Fisk H N 1947 *Fine-grained alluvial deposits and their effect on Mississippi River activity*; Mississippi River Commission, Vicksburg, Mississippi.
- Fleitmann D, Burns S J, Mudelsee M, Neff U, Kramers J, Mangini A and Matter A 2003 Holocene forcing of the Indian monsoon recorded in a stalagmite from southern Oman; *Science* **300** 1737–1739.
- Folk R L and Ward W C 1957 Brazos River Bar: A study in the significance of grain size parameters; *J. Sedim. Petrol.* **27** 3–26.
- Folk R L 1980 *Petrology of Sedimentary Rocks* (Austin, Texas: Hemphill).
- Folk R L 1954 The distinction between grain size and mineral composition in sedimentary rock nomenclature; *J. Geol.* **62** 344–359.
- Forrest J and Clark N J 1989 Characterizing grain-size distributions: Evaluation of a new approach using a multivariate extension of entropy analysis; *Sedimentology* **36** 711–722.
- Friedman G M and Sanders J E 1978 *Principles of Sedimentology* (New York: Wiley).
- Friedman G M and Johnson K G 1982 *Exercises in Sedimentology* (New York: Wiley).
- Friedman G M 1967 Dynamic processes and statistical parameters compared for size frequency distribution of beach and river sands; *J. Sedim. Petrol.* **37** 327–354.
- Friedman G M 1961 Distinction between dune, beach and river sands from their textural characteristics; *J. Sedim. Petrol.* **31** 514–529.
- Ganjoo R K 1993 Late Quaternary climato-tectonic history and re-assessment of the chronology of prehistoric culture of Jammu, sub-Himalaya, India; In: *Current Advances in Indian Archaeology* (eds) Ganjoo R K and Ota S B, Vol. I, 111–127 (Nagpur: Dattsons).
- Gasse F, Arnold M, Fontes J C, Fort M, Gilbert E, Huc A, Li B Y, Li Y E, Lju Q, Melieres F, VanVampo E, Wang F B and Zhang Q S 1991 A 13,000 year climate record from western Tibet; *Nature* **353** 742–745.
- Goodbred Jr S L, Kuehl S A, Steckler M S and Sarker M H 2003 Controls on facies distribution and stratigraphic preservation in the Ganges–Brahmaputra delta sequence; *Sedim. Geol.* **155** 301–316.
- Hough J L 1942 Sediments of Cape Cod Bay, Massachusetts; *J. Sedim. Petrol.* **12** 10–30.
- Inman D L 1949 Sorting of sediments in the light of fluid mechanics; *J. Sedim. Petrol.* **19** 51–70.
- Inman D L and Jenkins S A 1999 Climate change and the episodicity of sediment flux of small Californian rivers; *J. Geol.* **107** 251–270.

- Jahns R H 1947 Geological features of the Connecticut Valley, Massachusetts, as related to recent floods; *U.S. Geological Survey Water Supply Irrigation Paper* 996.
- Kotlia B S, Sharma C, Bhalla M S, Rajagopalan C, Subrahmanyam K, Bhattacharyya A and Valdiya K S 2000 Palaeoclimatic conditions in the late Pleistocene Wadda lake, eastern Kumaon Himalaya (India); *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **162** 105–118.
- Krumbein W C and Pettijohn F J 1938 *Manual of Sedimentary Petrography* (Plenum: New York).
- Kudraas H R, Hofman A, Dooze H, Emeis H and Erlenkueser H 2001 Modulation and amplification of climate changes in Northern Hemisphere by Indian summer monsoon during the past 80 Kyr; *Geology* **29** 63–66.
- Liu T-S, An Z and Yuan B 1982 Aeolian processes and dust mantles in China; In: *Quaternary Dust Mantles of China, New Zealand and Australia* (ed.) Wasson R J, pp. 1–19 (Canberra: Australian National University).
- Ludwig W and Probst J 1998 River sediment discharge to the oceans: Present-day controls and global budgets; *Am. J. Sci.* **298** 265–295.
- Marriott S 1992 Textural analysis and modeling of a flood deposit: River Severn, UK; *Earth Surf. Proc. Land.* **17** 687–697.
- Miall A D 1996 *The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis, and Petroleum Geology* (New York: Springer-Verlag) 582p.
- McKee E D, Crosby E J and Berryhill H L 1967 Flood deposits, Bijou Creek, Colorado, June 1965; *J. Sedim. Petrol.* **37** 829–851.
- Moiola R J and Weiser D 1968 Textural parameters and evaluation; *J. Sedim. Petrol.* **38**(1) 45–53.
- Montgomery D R and Brandon M T 2002 Topographic controls on erosion rates in tectonically active mountain ranges; *Earth Planet. Sci. Lett.* **201** 481–489.
- Moss A J 1963 The physical nature of common sandy and pebbly deposits, Pt. 2; *Am. J. Sci.* **261** 297–343.
- Nicholas A P and McLelland S J 1999 Hydrodynamics of a floodplain recirculation zone investigated by field monitoring and numerical simulation; In: *Floodplains: Interdisciplinary Approaches* (eds) Marriott S B and Alexander J, *Geol. Soc. Spec. Publ.* London **163** 1526.
- Passega R 1957 Texture as characteristic of clastic deposition; *Bull. Amer. Assoc. Petrol. Geol.* **41** 1952–1984.
- Passega R 1964 Grain size representation by C–M Patterns as a geological tool; *J. Sedim. Petrol.* **34** 840–847.
- Passega R and Byramjee R 1969 Grain size image of clastic deposits; *Sedimentology* **13**(3) 180–190.
- Pecsi M 1982 The most typical loess profiles in Hungary; In: *Quaternary Studies in Hungary* (eds) Pesci M, Budapest, pp. 145–169.
- Pinet P and Souriau M 1988 Continental erosion and large scale relief; *Tectonics* **7** 563–582.
- Prins M A and Postma G 2000 Effects of climate, sea level and tectonics unraveled for last deglaciation turbidite records of the Arabian Sea; *Geology* **28** 375–378.
- Ray P K 1976 Structure and sedimentological history of the overbank deposits of a Mississippi river point bar; *J. Sedim. Petrol.* **46** 788–801.
- Rendell H M 1988 TL dating of a 10 meter loess profile in Pakistan; *Quarter. Sci. Rev.* **7** 251–255.
- Rendell H M and Dennell R W 1987 Thermoluminescence dating of an upper Pleistocene site, northern Pakistan; *Geoarchaeology* **2**(1) 63–67.
- Rendell H M 1987–88 Environmental changes during the Pleistocene in the Potwar Plateau and Peshawar basin calibrated by thermoluminescence dating of loess; *Pakistan Archaeol.* **23** 43–57.
- Rendell H M, Dennell R W and Halim M A 1989 Pleistocene and Palaeolithic investigations in the Soan Valley, northern Pakistan, BAR International Series 544, England, p. 346.
- Sahu B K 1964 Depositional mechanisms from the size analysis of the clastic sediments; *J. Sedim. Petrol.* **34** 73–84.
- Schlee J, Uchupi E and Trumbull J V A 1965 Statistical parameters of Cape Cod beach and aeolian sands; *US Geol. Surv. Prof. Paper* **501-D** 118–122.
- Sevon W D 1966 Distinction of New Zealand beach, dune and river sands by their grain-size distribution characteristics; *J. Geol. Geophys.* **19** 212–223.
- Singh I B 1972 On the bedding in the natural-levee and the point-bar deposits of the Gomti River, Uttar Pradesh, India; *Sedim. Geol.* **7** 309–317.
- Slingerland L and Smith N D 1998 Necessary conditions for a meandering-river avulsion; *Geology* **26** 435–438.
- Spencer D W 1963 The interpretation of grain size distribution curves of clastic sediments; *J. Sedim. Petrol.* **33** 180–190.
- Stewart H B 1958 Sedimentary reflections of a depositional environment in San Miguel Lagoon. Baja, California, Mexico; *Bull. Amer. Assoc. Petrol. Geol.* **42** 2567–2618.
- Swan D, Clayne J J and Luternauer J L 1979 Grain-size statistics II: Evaluation of grouped moments measures; *J. Sedim. Petrol.* **48** 863–878.
- Syvitski J P M, Peckham S D, Hilberman R and Mulder T 2003 Predicting the terrestrial flux of sediment to the global ocean: A planetary perspective; *Sedim. Geol.* **162** 5–24.
- Thamban M, Rao V P and Schneider R R 2002 Reconstruction of late Quaternary monsoon oscillations based on clay mineral proxies using sediment cores from the western margin of India; *Marine Geol.* **186** 527–539.
- Verma S N, Dhiman L C, Shali A K and Singh J 1990 Report on Quaternary geological and geomorphological mapping in parts of Chenab basin covering area falling in Jammu and R.S. Pura Tehsils, Jammu District, J & K, Unpublished Report of Geological Survey of India.
- Visher G S 1969 Grain size distributions and depositional processes; *J. Sedim. Petrol.* **39** 1074–1106.
- Wiggs G F S 1997 Sediment mobilization by the wind, In: *Arid Zone Geomorphology* (eds) Thomas S and David G (New York: Wiley), pp. 351–371.
- Williams G E 1971 Flood deposits of the sand-bed ephemeral streams of Central Australia; *Sedimentology* **17** 1–40.