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Lithofacies and Granulometric Analysis of Middle Siwalik Sandstones of Jammu, NW Himalaya, India

S. K. Pandita, Sumit Johar*, Shifali Chib, Yudhbir Singh, G. M. Bhat and S.S. Kotwal
Department of Geology, University of Jammu, Jammu-180006 (India)
*Email: sumit.johar@jammuuniversity.ac.in

ABSTRACT

In the Northwest Himalaya, the Siwalik Group of rocks are exposed in the Suruin-Mastgarh anticlinal folded succession and has been classified into Lower, Middle and Upper subgroups. The Middle Siwalik Subgroup is exposed at various locations in the Jammu region and is primarily made up of multistoried sandstones embedded with thin beds of mudstone. In the present study, these rocks have been studied to understand the depositional history using the sediment size of sandstones and the lithofacies in addition to the paleocurrent analysis. The multistoried nature of the sandstone and the scour fills observed in these rocks imply that there were frequent and periodic strong stream encounters at the depositional site where saltation was the dominant process of transportation of sediments. The data obtained on grain size, lithofacies, cross beddings, and the type of contacts between different lithofacies suggest that the southerly flowing braided river system underwent multiple episodes of avulsion and abandonment of the channel system during the deposition of the Middle Siwalik subgroup in Jammu region.

KEYWORDS: Middle Siwalik, Lithofacies, Grainsize, Paleocurrent, Paleoenvironment.

INTRODUCTION

The Himalayan Foreland Basin is a component of the marginal fold and thrust belt that resulted from the collision of the Indian and Eurasian plates. This foreland basin encompasses Tertiary rocks including the Subathu, Murree and Siwalik groups. The Siwalik extends from the Potwar plateau in the northwest all along the Himalaya arc to the Brahmaputra valley in the east, forming a series of parallel-dissected ridges. The Siwalik Group of rocks (consolidated to semi-consolidated) comprise a 5-6 km thick pile of late Cenozoic freshwater molasse sedimentary succession that forms the youngest mountain belt in the form of Himalayan foothills. The Siwalik Group of sediments were deposited in two coarsening up megacycles consisting of sandstone-clay alternations in the lower portion passing gradually into coarse sandstones and/or conglomerates towards the top (Parkash et al., 1980; Pandita and Bhat, 1999). Prominent structural units i.e. Udhampur Syncline, Udhampur Thrust, the Suruin-Mastgrah anticline and Kishanpur Thrust (Dasarathi, 1968) distinguish the Jammu foothills. The Siwalik Group of rocks are exposed in the Suruin-Mastgarh anticlinal folded succession. Sandstone, mudstone, and conglomerate make up the majority of the Siwalik succession in Jammu region (Pandita et al., 2014).

The Siwalik Group has been classified into three subgroups: Lower, Middle, and Upper Siwalik**.** The Lower Siwalik subgroup consists of indurated sandstone, mudstone and siltstone and has been interpreted as deposited within the meandering river system (Pandita et al., 2014). The Middle Siwalik subgroup is composed of dominantly thick semiconsolidated and consolidated multistoried-sandstone (90%) embedded with thin mudstone (10%) beds. The Upper Siwalik subgroup comprises of semiconsolidated conglomerates, sandstones and mudstones. The Siwalik sediments have been studied for palaeontology (Gupta and Verma, 1988; Ranga Rao et al., 1988; Nanda and Sehgal, 1993; Kundal and Prasad, 2011), sedimentology (Pandita and Bhat, 1999; Sharma et al., 2001; Bhat et al., 2008; Pandita et al., 2011, Irfan et al., 2022), structural geology (Dasarathi, 1968; Karunakaran and Ranga Rao, 1979) and petrography (Krynine, 1937; Bhatia, 1970; Pandita and Bhat, 1995, Pandita et al., 2014). Besides, magnetostratigraphy (Ranga Rao, 1993) and fission track dating of the bentonite beds in the upper Siwalik (Ranga Rao et al., 1988 and Mehta et al., 1993) have been carried out. The current study aims to discuss the depositional environment of the Middle Siwalik subgroup in the Jammu region by examining the lithofacies and granulometric analysis of these sediments.

STUDY AREA

The area under investigation displays some of the spectacular exposures of Siwalik Group extending for tens of kilometres along the strike and for 5 to 6 km in thickness (in different hillocks) and offers opportunity to study these sediments in Jammu Region. To understand the depositional history of the Middle Siwalik subgroup in Jammu region, three stratigraphic sections exposed near Bantalao (Nandni-Nagrota section), Aitham (Bajalta-Aitham section) and Parmandal (Parmandal-Utterbehni section) (Fig. 1) were studied laying emphasis on recording lateral and vertical facies variations within the sediment bodies; the nature of stacking, grain size and sedimentary structures.

MATERIALS AND METHODS

Three well-exposed sections of Middle Siwalik at Bantalao in Nandni-Nagrota, at Aitham in Bajalta area and near Parmandal in Parmandal-Uttarbehni lithosections were studied in detail to understand the sedimentation pattern for interpreting the depositional environment. The lithosections were measured and different lithofacies were recorded in the field. The attitude of beddings and cross beddings was recorded for understanding the paleoflow direction in the area. A total of 30 (10 from each locality) semi-consolidated sandstone samples were collected for granulometric analysis. The sandstone samples were disintegrated and dry sieved in the sedimentology laboratory of the Department of Geology, University of Jammu. From each sample, 100 grams of the representative sediment sample was taken to perform sieve analysis by employing a series of standard sieves with 1Φ class interval using a mechanical sieve shaker. The weight of the sample size left in each sieve was recorded and the cumulative grain size distribution curves were prepared to calculate size statistical parameters as outlined by Lindholm (1987).

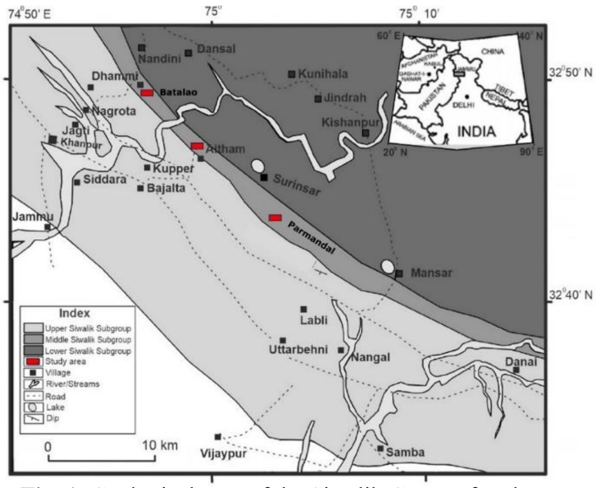

Fig. 1. Geological map of the Siwalik Group of rocks in the southern limb of the Suruin- Mastgarh anticline in Jammu region (after Pandita et al., 2014)

FIELD OBSERVATIONS

Nandni-Nagrota Lithosection

In this lithosection, Middle Siwalik is exposed along the Nandni-Nagrota Road near Bantalao area and a 97m thick stratigraphic succession comprising of sandstone-mudstone couplets (Fig. 2A) was measured. The sandstone beds are grey-coloured, medium to coarse-grained, friable, 1.0 to 11.2 m thick with an average thickness of 8 m. These sandstone beds mostly grouped as multi-storeyed sandstone bodies display large scale trough and planar cross bedding throughout the succession. Hard calcareous sand balls and sand lenses are distributed irregularly throughout the lithosection. Extra formational clasts are either unevenly distributed or oriented along bedding, cross-bedding and erosional bases of the sandstone bodies. The erosional surfaces are marked by the presence of intra formational mud balls, mud pellets and sand balls, and extra formational clasts. Deformation in the bedding and cross bedding due to liquefaction is observed at places. Channel cut and fill structures containing thin laminated sand beds are also observed. Sand nodules associated with coarse to medium sandstone are also observed.

The mudstones are yellow, brown, grey, variegated in colour, and range in thickness from 0.40 to 2.80 m with an average thickness of 1 m. These mudstones are thinly laminated, nodular, flaky and at places calcretised. The mudstones have mostly erosional contacts with overlying sandstone bodies but at places show sharp contacts also.

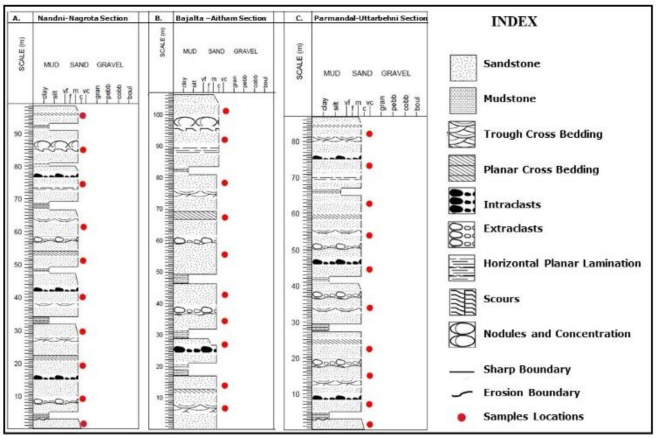

Fig. 2. Lithologs of the measured stratigraphic sections of Middle Siwalik in Jammu region: (A) Nandni-Nagrota section; (B) Bajalta-Aitham section; and (C) Parmandal-Uttarbehni section

Bajalta-Aitham Lithosection

A 106 m thick stratigraphic section of the Middle Siwalik subgroup was measured near Aitham, which embeds an alternation of sandstone and mudstone couplets (Fig. 2B). The sandstone beds are grey in colour, medium to coarse-grained. The basal contacts of the sandstone beds with mudstone/sandstone beds are erosional and sharp at places, whereas, the overlying contacts are mostly sharp but occasionally erosional. Various sandstone storeys are stacked one above the other and separated by erosional contacts. The erosional contacts are represented by the scour filling with intra formational mud balls, mud pellets and extra formational clasts of sandstone and quartzite composition. Various mud lenses are observed within the sandstone beds. At some places, sand balls are also observed within sandstone beds. The sandstone beds display planar and trough cross-stratification.

Parmandal-Uttarbehni Lithosection

In this lithosection, the Middle Siwalik subgroup is composed of an alternation of thick sandstone and thin mudstone beds. The total measured thickness of the Middle Siwalik rocks in this area is 86 m (Fig. 2C). The sandstone beds are grey and buff, medium to coarse-grained, friable and range in thickness from 2.8 to 20 m with an average thickness of 11.06 m. Some sandstone beds contain extra formational clasts disseminated either unevenly or form layers along the erosional base of the overlying cross-laminated beds. Few carbonaceous lenses are embedded in coarse-grained grey sandstone beds, which have a maximum thickness of 10 cm. Different sandstone beds are separated from the overlying and underlying sandstone beds, by erosional surfaces. These erosional surfaces are characterised by intraformational mud balls, mud pellets, mud layers, and extra formational clasts. Sand balls are also observed at places. The sandstone units display planar and trough cross-stratification. At places small mud pellets, mud balls and pebbles are oriented along the cross bedding. Occasionally, these cross-bed sets are deformed. Calcareous hard sandstone lenses are observed within sandstone beds. Thin mud lenses are present within the thick sandstone beds at different levels. In some places, the coarse-grained sandstone beds display channel cut filling. The mudstones are brown, grey, and blackish with various tints and variegated, and range in thickness from 0.40 to 1.18 m. These mudstones in some places are thinly laminated, nodular, hard and friable.

LITHOFACIES ANALYSIS

During the fieldwork, various lithofacies were identified and recorded and have been named as per the scheme adopted by Miall (1977, 1978). These lithofacies were encountered at different stratigraphic levels in the three lithosections (Fig. 3).

Pebbly Sandstone (Sp$_1$-facies)

In this facies, pebble size clasts constitute 5-70% of the rock. The maximum clast size ranges up to 10 cm. The thickness of individual bed sets varies from 0.10 to 1.70 m. This facies is characterised by pebble imbrication, horizontal- and cross-stratification, and intraformational mud balls and pellets. The underlying contact of the facies is generally erosional.

Trough Cross Bedded Sandstone (St-facies)

This facies is composed of fine to coarse-grained, poorly to well sorted, bright grey, grey and buff coloured, and trough cross bedded sandstones generally showing normal grading. At some places, mud clasts and pebbles are oriented along cross-bedding. Trough cross-bedding is occasionally distorted. In some cases, small mud lenses are aligned along the basal contacts of this facies. In normal grading, the lower pebbly cross-bedded set is followed by the trough cross-bedded set. Occasionally, the lower contact of this facies is characterised by a thin layer of small clasts. At some places, this facies shows sharp contacts with underlying Fm-, Sp- or Sh-facies, but mostly the underlying contacts are erosional. The St-facies is poorly cemented. However, hard calcareous coarse sandstone lenses occur along the bedding planes of this facies. These hard sandstone lenses sometimes display convolute structures. The thickness of individual bed sets varies from 0.15 to 2.0 m and that of the cosets varies from 0.60 to 3.0 m.

Planar Cross Bedded Sandstone (Sp-facies)

This facies is composed of fine to coarse-grained light grey, grey and buff, planar cross-bedded sandstones. Individual sets range in thickness from 0.10 to 1.50 m and different sets are superimposed over one another along either a sharp contact or scoured base. At places, the Sp-facies are underlain by either St- or Sh-facies. Sometimes this facies display reactivation surfaces, extra formational and intraformational clasts. Hard coarse calcareous sandstone lenses are occasionally seen in this facies.

Fig. 3. Field photographs displaying a) planar crossbedding, sand lenses and concretions; b) Planar and trough cross bedding, Erosional scour surfaces with mud balls and pebbles; c) Planar cross bedding; d) Mud balls in a scour surface.

Horizontally Bedded Sandstone (Sh-facies)

This facies is composed of fine to coarse grained, laminated, grey and buff coloured sandstones ranging in thickness from 0.05 to 5 m. This facies is generally followed either by Sp or St-facies. The upper and lower contacts of this facies are mostly sharp but occasionally erosional. In some cases, calcareous coarse sandstone lenses and distorted planar bedding in this facies are observed.

Erosional Scour Fill (Ss-facies)

Scour surfaces with a maximum relief of 0.5 to 1.0 m are observed at the upper contact of mudstone facies with sandstone facies and within the multistoried sandstone complexes. These scour fills consist of extraformational clasts of sandstone and quartzite and intraformational mudballs and mud pellets and at places thin mud lenses.

Massive Mottled and Nodular Mudstone (Fm-facies)

This facies is composed of massive, variegated, brown, yellow, grey and blackish coloured mudstones. This facies show generally sharp contact with underlying sandstone facies but at places gradational contacts are observed. The upper contact with sandstone is mostly sharp but gradational/erosional contacts are also seen. This facies is characterised by nodular and mottled mudstone showing root casts and mud cracks.

PALAEOCURRENT ANALYSIS

The data on directional features were collected from the sandstone units possessing extensive and clear cross-beddings. The azimuths of planar and trough cross-beddings at different stratigraphic levels in the three studied lithosections were recorded. These data were corrected for tectonic tilt following the method outlined by Potter and Pettijohn (1963). The tilt corrected azimuthal data were grouped at the class interval of 20^0 and plotted as rose diagrams (Fig. 4). Vector means and vector magnitudes were determined both graphically and trigonometrically following the procedure outlined by Lindholm (1987).

For the Nandni-Nagrota section, the rose diagram shows a polymodal distribution with five prominent modes in the 80°-100°, 120°-160°, 200°-220°, 240°-260°, and 280°-300° class intervals (Fig. 4A). The trigonometric vector mean and vector magnitudes are 138° and 51% respectively whereas, the graphic vector mean and vector magnitude are 138° and 51% respectively. For the Bajalta-Aitham lithosection, the rose diagram shows a polymodal distribution with four prominent modes in the 100°-120°, 120°-160°, 200°-240° and 240°-260° class intervals (Fig. 4B). The trigonometric vector mean and vector magnitudes are 186° and 39% respectively whereas, the graphic vector mean and vector magnitude are 185° and 40% respectively. For the Parmandal-Uttarbehni lithosection, the rose diagram shows a polymodal distribution with three prominent modes in the 140°-160°, 160°-180° and 240°-280° class intervals (Fig. 4C). The trigonometric vector mean and vector magnitudes are 181° and 59% respectively whereas, the graphic vector mean and vector magnitudes are 181° and 59% respectively. For all three lithosections, the trigonometric and graphic vector means and vector magnitudes are in well agreement with one another indicating south-easterly palaeoflow for Nandni-Nagrota, south-south-westerly palaeoflow direction for Bajalta-Aitham lithosection and southerly palaeoflow for Parmandal-Uttarbehni area (Fig. 4).

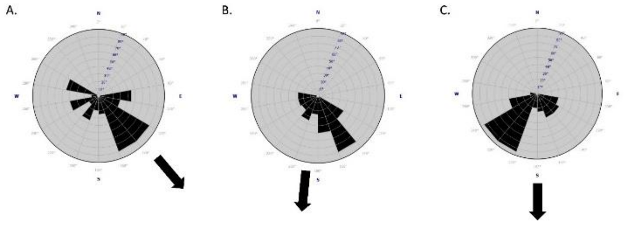

Fig. 4. Rose diagrams displaying the azimuthal data of the cross beddings recorded in Middle Siwalik of the three studied lithosections A) Nandni-Nagrota, B) Bajalta-Aitham, C) Parmandal-Uttarbehni.

GRANULOMETRIC ANALYSIS

The granulometric analysis is a well-known technique that provides additional information about the sedimentary depositional environment, energy conditions and sediment transport. Size statistical textural parameters with environmental significance including graphic mean, standard deviation (sorting), kurtosis and skewness are useful in comprehending synsedimentary hydrodynamic factors of transportation and deposition in a basin (Folk and Ward, 1957; Srivastava and Mankar, 2009; Vijaya Lakshmi et al., 2010; Weltje and Prins, 2007; Kanhaiya et al., 2017). The grain size data obtained from sieve analysis were used to calculate various statistical parameters (Table 1) and are discussed as under:

Textural Parameters

Textural parameters are quantitative measures used to describe the characteristics of sediment based on their grain size distribution. Different textural parameters are graphically derived using size analysis data plotted on cumulative frequency curves. Cumulative frequency curves are plotted on the arithmetic scale with the class interval (phi) at the X-axis and cumulative weight percentage at the Y-axis. These curves offer grain size information values of phi (Φ) which are employed in mathematical calculations of statistical parameters devised by Folk and Ward (1957). Cumulative curves approximately reflect an S-shape trend when plotted on an arithmetic scale. The slope of the central portion of the curve reflects the sorting of the sample; if there is a steep slope, it indicates good sorting and a very gentle slope means poor sorting. The cumulative frequency curves of the analysed sandstone samples in the present study are approximately S-type (Fig. 5) showing that the majority of the sediment was deposited by the saltation process with traction and suspension load contribution as well.

In this study, the size statistical parameters (textural parameters) namely graphic mean (Mz), graphic standard deviation (σ_I), graphic skewness (S_K), and graphic kurtosis (K_G) have been used. These parameters are useful for interpreting sedimentary processes that occur in depositional environments (Sengupta, 1977; Sun et al., 2002; Bartholdy et al., 2007; Le Roux and Rojas, 2007; Lakshmi et al., 2010).

Graphic Mean (M_z)

The graphic mean (M_z) represents the average particle size of the sediment and is calculated by the formula Φ16+ Φ50+Φ84)/3 (Folk, 1957). This parameter measures the average kinetic energy of the depositing energy as well as the average grain size of the particle population in terms of energy.

Graphic Standard Deviation (σ_I)

Graphic standard deviation(σ_I) is a mathematical expression which measures the degree of the sorting and is calculated by the formula (Φ84 - Φ16)/4 + (Φ95- Φ5)/6.6 (Folk and Ward, 1957). The sorting is a measure of the magnitude of grain size distribution around the mean size. The standard deviation indicates the fluctuations in the kinetic energy conditions prevailing during transport.

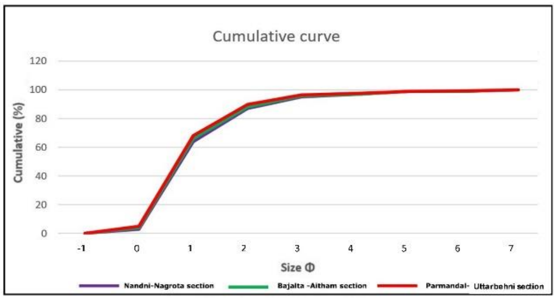

Fig. 5. Average cumulative curve of size analysis studied of lithosections.

Graphic Skewness (S_k)

The graphic skewness (S_k) measures the asymmetry in the frequency curves in terms of the domination of coarse or fine grained fractions (usually represented as negative or positive skewness). It is calculated by formula [(Φ84+ Φ16 - 2Φ50) / 2(Φ84- Φ16)] + [(Φ5+ Φ95-2 Φ50) / 2(Φ95- Φ5)] (Folk and Ward, 1957). This is the most accurate way to measure skewness because it accounts for both the tails and the central portion of the frequency curve in size analysis. The curve's tails essentially display the significant variations between samples.

Graphic Kurtosis (K_G)

Kurtosis (K_G) represents the distribution of grain size population between tails and central portion of the frequency curve. It is calculated by the formula K_G = (Φ95 - Φ5) / [2.44 (Φ75 - Φ25)]. Leptokurtic nature is due to better sorting in the central portion as compared to the tails in a frequency curve. Strongly platykurtic curves often represent a bimodal nature with subequal amounts of the two modes (Folk, 1980).

Interpretation of textural parameters:

Nandni-Nagrota section

For the Nandni-Nagrota section, the size statistical parameters of the Middle Siwalik subgroup show mean grain size varying from 0.31 to 1.30Φ (average = 0.85Φ) reflecting a coarse to medium grained nature for these sediments. The standard deviation ranges between 1.00 to 1.82 Φ (average=1.33 Φ) reflecting moderately to poorly sorted sands. The skewness ranges between -0.09 and 0.48 (average = 0.17Φ and reflects the coarse to finely skewed nature of these sands. The Kurtosis values range from 0.73 to 1.25Φ (average = 0.95Φ) and reflect platykurtic to leptokurtic nature for these sands (Table 1).

Bajalta-Aitham section

The sandstones of the Bajalta-Aitham section have mean grain size ranging from 0.67 to 1.87Φ (average=1.03Φ) and reflect coarse to medium grained nature. The standard deviation varies from 0.89 to 1.46Φ and reflects a moderately to poorly sorted nature with an average of 1.11Φ (poorly to moderately sorted). These sediments appear to be nearly symmetrical to very finely skewed (skewness -0.04 to 0.46Φ) averaging at 0.25Φ (finely skewed) and platykurtic to leptokurtic in nature (K=0.84 to1.29Φ) with an average kurtosis equal to 1.02 Φ (Table 1).

Parmandal-Uttarbehni section

In the Parmandal-Uttarbehni section**,** the mean size ranges from 0.43 to 1.30Φ (average = 0.78Φ) indicating medium to coarse-grained nature. The sediments are moderately to poorly sorted with a standard deviation of 0.96 to 1.16Φ averaging at 1.08Φ (poorly sorted). The skewness varies from 0.05 to 0.39Φ (average 0.27Φ and reflects a finely to near symmetrical skewed nature. The kurtosis ranges from 0.79 to 1.25Φ indicating platykurtic to leptokurtic (average 0.90Φ=platykurtic) nature (Table 1).

Interrelationship among Textural Parameters

The relationship between the textural parameters is important for understanding the transport and depositional environment of sediments and is an excellent tool for identifying different

Table 1. Grain size textural parameters for the studied Middle Siwalik sandstones (NN: Nandni-Nagrota Section; BA: Bajalta-Aitham Section; PU: Parmandal-Uttarbehni Section)

Sample ID	Mean (M_Z)	Interpretation	Standard deviation (σ_I)	Interpretation	Skewness (S_K)	Interpretation	Kurtosis (K_G)	Interpretation
NN-1	0.31	Coarse sand	1.51	Poorly sorted	0.10	Fine-skewed	0.73	Platykurtic
NN-2	0.42	Coarse sand	1.69	Poorly sorted	0.18	Fine-skewed	1.25	Leptokurtic
NN-3	0.88	Coarse sand	1.73	Poorly sorted	0.36	Very fine-skewed	0.78	Platykurtic
NN-4	0.90	Coarse sand	1.82	Poorly sorted	0.48	Very fine-skewed	1.23	Leptokurtic
NN-5	0.97	Coarse sand	1.13	Poorly sorted	0.13	Fine-skewed	0.81	Platykurtic
NN-6	0.77	Coarse sand	1.00	Moderately sorted	0.20	Fine-skewed	0.87	Platykurtic
NN-7	0.87	Coarse sand	1.14	Poorly sorted	0.11	Very fine-skewed	0.99	Mesokurtic
NN-8	1.08	Medium sand	1.14	Poorly sorted	0.19	Fine-skewed	0.75	Platykurtic
NN-9	0.98	Coarse sand	1.09	Poorly sorted	-0.09	Near-symmetrical	1.23	Leptokurtic
NN-10	1.30	Medium sand	1.16	Poorly sorted	0.05	Near-symmetrical	0.85	Platykurtic
BA-1	1.13	Medium sand	1.07	Poorly sorted	0.27	Fine-skewed	1.29	Leptokurtic
BA-2	0.67	Coarse sand	1.08	Poorly sorted	0.29	Fine-skewed	0.84	Platykurtic
BA-3	1.87	Medium sand	1.16	Poorly sorted	0.41	Very fine-skewed	0.92	Mesokurtic
BA-4	0.75	Coarse sand	1.15	Poorly sorted	0.28	Fine-skewed	0.96	Mesokurtic
BA-5	0.85	Coarse sand	0.98	Moderately sorted	0.46	Very fine-skewed	0.98	Mesokurtic
BA-6	1.02	Medium sand	0.89	Moderately sorted	-0.04	Near-symmetrical	0.88	Platykurtic
BA-7	0.83	Coarse sand	1.25	Poorly sorted	0.39	Very fine-skewed	0.95	Mesokurtic
BA-8	1.40	Medium sand	1.07	Poorly sorted	-0.07	Near-symmetrical	0.94	Mesokurtic
BA-9	0.98	Coarse sand	1.07	Poorly sorted	0.22	Fine-skewed	1.18	Mesokurtic
BA-10	0.88	Coarse sand	1.46	Poorly sorted	0.25	Fine-skewed	1.08	Mesokurtic
BA-1	1.13	Medium sand	1.07	Poorly sorted	0.27	Fine-skewed	1.29	Leptokurtic
BA-2	0.67	Coarse sand	1.08	Poorly sorted	0.29	Fine-skewed	0.84	Platykurtic
BA-3	1.87	Medium sand	1.16	Poorly sorted	0.41	Very fine-skewed	0.92	Mesokurtic
BA-4	0.75	Coarse sand	1.15	Poorly sorted	0.28	Fine-skewed	0.96	Mesokurtic
PU-1	0.57	Coarse sand	1.12	Poorly sorted	0.39	Very fine-skewed	0.81	Platykurtic
PU-2	0.53	Coarse sand	0.96	Moderately sorted	0.11	Fine-skewed	1.25	Leptokurtic
PU-3	0.65	Coarse sand	1.08	Poorly sorted	0.24	Fine-skewed	0.83	Platykurtic
PU-4	1.00	Coarse sand	1.04	Poorly sorted	0.09	Near-symmetrical	0.96	Mesokurtic
PU-5	1.30	Medium sand	1.16	Poorly sorted	0.05	Near-symmetrical	0.81	Platykurtic
PU-6	0.77	Coarse sand	1.15	Poorly sorted	0.24	Fine-skewed	0.79	Platykurtic
PU-7	0.43	Coarse sand	0.95	Moderately sorted	0.16	Fine-skewed	0.91	Mesokurtic
PU-8	0.72	Coarse sand	1.13	Poorly sorted	0.24	Fine-skewed	0.96	Mesokurtic
PU-9	0.83	Coarse sand	1.16	Poorly sorted	0.11	Fine-skewed	0.91	Mesokurtic
PU-10	1.05	Medium sand	1.14	Poorly sorted	0.07	Near-symmetrical	0.87	Platykurtic

sedimentation processes. Bivariate plots are prepared using different pairs of size statistical parameters. For the current study the plots based on mean versus skewness and standard deviation show that most of the sediments are plotted in the river channel zone (Fig. 6). The bivariate plot between mean grain size and standard deviation (sorting) (Fig. 7) shows that the sediments are poorly to moderately sorted and composed primarily of coarse to medium-grained sand particles. The mean size versus skewness plot (Fig. 8) shows mostly finely skewed nature of the sediments. The scatter plot between mean grain size and kurtosis shows platykurtic to mesokurtic in nature (Fig. 9).

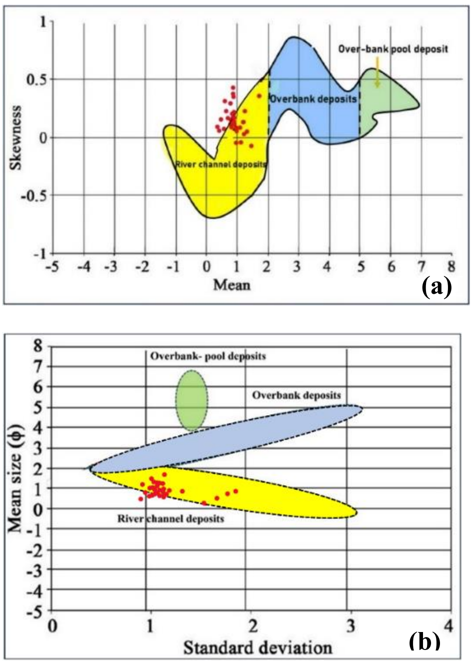

Fig. 6. Bivariate plots a) Mean and skewness b) Standard deviation and mean (after Mycielska-Dowgiallo, 2007; Ludwikowska-kedzia, 2000).

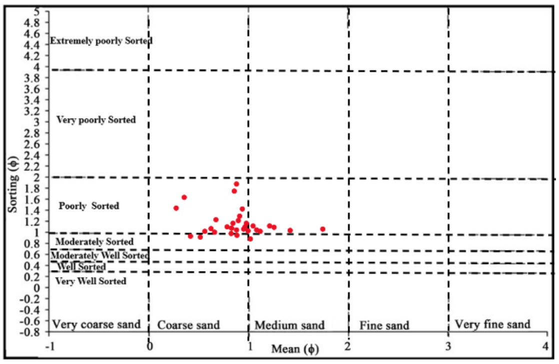

Fig. 7. Bivariate plot of mean grain size and sorting (after Blott and Kenneth, 2001).

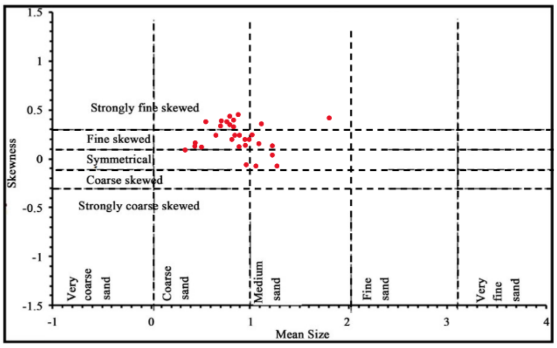

Fig. 8. Bivariate plot of mean grain size and skewness (after Blott and Kenneth, 2001).

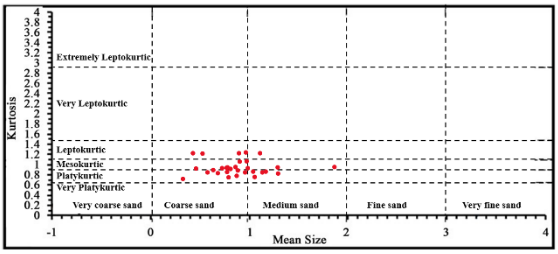

Fig. 9. Bivariate plot of mean grain size and kurtosis (after Blott and Kenneth, 2001).

RESULTS AND DISCUSSION

Grain size analysis of the sediments reveals that the sediments are medium to coarse grained in nature. The predominance of medium to coarse-grained sediment indicates moderate to high energy depositional conditions, where the current velocity was strong enough to transport sand in saltation and suspension mode. The occurrence of pebble clasts lower within the channel deposits and an overall increase in up section mean grain size observed in the Middle Siwalik subgroup in this study supports the existence of a large channel system of modestly increased depositional slope with coarse sediment load. The large lateral extent of the sand bodies suggests relatively low sinuosity streams (Keller, 1977) flowing on a broad alluvial plain like the modern Indo-Gangetic plain. The sediments of Middle Siwalik are moderately to poorly sorted, symmetrical to finely skewed and platykurtic to mesokurtic indicating deposition under fluctuating energy conditions in different geomorphic domains within fluvial settings. Strongly platykurtic curves often represent bimodal nature with subequal amounts of the two modes (Folk, 1980). The symmetrical nature of the sediments suggest that the hydrodynamic conditions may have caused the removal of fine particles due to the periodic encounters of strong stream currents at depositional sites (Pandita and Bhat, 1995).

The dominance of channel sandstone bodies and vertical and lateral stacking patterns of storeys within these sandstone bodies reflect the increased number and size of the active channels. The alternation of buff and grey sandstone strata demonstrates paleocurrent fluctuations over time and most likely reflects different river systems draining areas with diverse source material. The planar cross-bedding in sandstone facies indicates the linguoid depositional bars. Large scale trough cross-stratification lower in storeys suggests that the deeper channel bars were sinuously crested in nature. Vertical variation in grain size (fining-upward) and sedimentary structures (large scale trough cross stratification to planar strata or cross lamination) reflect variation in fluid flow during the single depositional event. Minor erosion surfaces may be related to local scouring and modification of bed form geometry during flash floods. Bioturbation and mottling of fine tops of bed sets suggest either the emergence of bed forms during low flow regime or abandonment of channels (Bridge et al., 1986) within a large braided river system (Pandita and Bhat, 1995). According to Singh (1977), channel bars migrate laterally during floods by depositing material in the form of extensive foreset laminae on the lee face. Additionally, during a flood, fluctuations in velocity causes scouring of the sedimentary surface and concurrent rapid deposition of sediments. Under turbulent flow conditions, the migration and development of the lee face of the bar are punctuated by strong scouring and filling action of the flow. Such large-scale bedforms that can produce planar sets comparable to those present here have been recorded in the large present-day river Brahmaputra (Coleman, 1969). The migration of three-dimensional dunes or scour origins lead to the development of trough cross-bedding (Miall, 1977; Reineck and Singh, 1980). The scale of the bedform that can produce the observed cross-beds is quite large and is only stable in deeper waters (Tyler and Ethridge, 1983; Singh and Kumar, 1974). The major channels of rivers like the Yamuna (Singh and Kumar, 1974) and Brahmaputra (Coleman, 1969) have reported similar-sized undulatory megaripple bedforms. Erosional surfaces separate various sandstone storeys (channel deposits), indicating the removal of fine-grained facies (over bank deposits). In confined rivers, episodic floods increase the probability of substrate erosion/scouring (Singh et al., 2006). The presence of scour-fill facies indicates that floods occurred during the Middle Siwalik sedimentation and there were periodic and frequent encounters at the depositional site. This indicates that the upper part of the sequence was eroded before the deposition of a complete cycle due to channel abandonment caused by avulsion (Miall, 1977).

Mudstone units associated with braided rivers are typically found on bar tops and in abandoned channels (Williams and Rust, 1969). Mudstone intraclasts related to braided river sandstone units have been described as fragmented, desiccated and eroded from bar tops and flood plains (Karcz, 1969). However, in most instances, broad lags of massive mudstone intraclasts are formed as a result of the collapse of muddy river banks, which is aided by desiccation fissures.

The palaeoflow trends in different sections of the area at the same stratigraphic levels are consistent with a small river system on a vast transverse sediment fan. The majority of the present fans in the Himalayan basins have low-relief braided channel patterns and sediment sources in the northwest (Willis, 1993). The variation reported in this study reflects only mountain proximal drainage system-induced local variation, as suggested for Pakistan's Siwalik belt (Willis, 1993). The distinct palaeocurrent direction shifts reflect local variations in basin physiography and depositional slope. The general palaeoflow pattern is due SE in the Nandni-Nagrota section, SSW in the Bajalta-Aitham lithosection and due south in the Parmandal-Uttarbehni lithosection suggesting an overall southerly drainage pattern during deposition of these sediments.

Sediment texture analysis reveals frequent strong stream encounters and saltation-dominated sediment transport, reflected in the multistoried sandstone bodies with trough and planar cross-bedding. The presence of erosional surfaces and channel cut-fill structures suggests multiple avulsion events and channel abandonments in a generally southerly drainage pattern in a braided river system.

The geometry of the Siwalik basin is thought to be substantially identical to those of the modern-day Himalayan frontal basin as rates of continental convergence have remained relatively consistent since the Miocene Period. Therefore, the contemporary Himalayan drainage system may have an identical resemblance to the Miocene and later river systems that left their imprints in the Siwalik strata. The presence of pebble clasts lower in the channel deposits, as well as an overall rise in up-section mean grain size seen in the Middle Siwalik subgroup, support the existence of a wide channel system with a significantly enhanced depositional slope and coarse sediment load. The wide lateral extent of the sand deposits suggests relatively low sinuosity streams moving across a broad alluvial plain similar to the contemporary Indo-Gangetic plane (Keller, 1977). The laterally interfingering sand and mudstone facies indicate simultaneous active and interchannel areas of the braided river system. The comparatively significant variations in facies and palaeocurrent direction are evident in meter-scale facies sequences indicating periodic channel belt avulsion. The braided pattern of these channels is replicated by cross-cutting erosional surfaces that surround lensoid facies sequences.

CONCLUSION

The Middle Siwalik sandstones were investigated in three stratigraphic sections in Jammu region to understand the depositional history of these rocks. These multistoried sandstone bodies with erosional basal contacts embedded with minor mudstone beds were deposited in a southerly flowing braided river system.

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CONFLICT OF INTEREST:

The authors declare no conflict of interest.

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