Jour. Indian Association of Sedimentologists, Vol. 37, No. 1 (2020) pp 69 - 90
ISSN 2582-2020

FACIES EVALUATION, DEPOSITIONAL ENVIRONMENT AND PALAEOFLOW OF THE LOWER SIWALIK SUBGROUP, RAMNAGAR, JAMMU, INDIA

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ABSTRACT: This paper embodies the results of facies evaluation of Lower Siwalik Subgroup of Ramnagar area of Jammu region. These sedimentary rocks comprising of sandstone, mudstone and siltstone alternations were studied at two adjacent localities in Ramnagar area at Kalaunta and Ramnagar in the stratigraphic order for lateral and vertical facies variations and signatures of palaeoflow directions. We have established three lithofacies associations with lateral and vertical variability in the studied sections and interpret them as representing deposits of fine-grained meandering, flood flow dominated meandering and floodplain areas within the meandering river system. We also observed highly variable Spatio-temporal palaeoflow directions.

Keywords: Lower Siwalik, Ramnagar, Jammu, Facies association, Depositional environment.

INTRODUCTION

The continental collision of the Indian and Asian plates c. 50 Ma ago (Searle, 2013) resulted into the closure of the Tethyan Ocean and subsequent emergence of the Himalaya. India-Asia collision was initiated as early as 65Ma in the westernmost part of the orogen (Beck *et al.*, 1995). Ongoing convergence has led to flexural down warping of the overridden Indian plate, forming the Himalayan molasse basin, the world's largest terrestrial foreland basin (Burbank, 1996; Watts, 1992). There is well exposed, continuous record of detritus shed from the Himalaya into this basin called as Himalayan Foreland Basin (HFB). The sedimentary sequence in the HFB includes Murree (Dharamsala) Group of Oligocene - Miocene age and the overlying Siwalik Group of Middle Miocene to Pleistocene age. The tectonics of the Himalaya has largely controlled the evolution of the Siwalik basin and its sedimentation.

Lithofacies associations have been used for the interpretation of the various depositional environments in the Siwalik Group of rocks extending from Potwar Plateau (Pakistan) in the west through Nepal to Arunachal Pradesh (India) in the east (e.g., Willis 1993a,b; Willis and Behrensmeyer, 1994; Hisatomi and Tanaka 1994; Tokuoka *et al*., 1986, 1988, 1990; Harrison *et al*., 1993; Declles *et al*., 1998; Huyghe *et al*., 2005; Kumar *et al.,* 2004, 2007; Suresh *et al*., 2007; Sinha *et al.,* 2007). In Jammu region few studies have been carried out on facies analysis in the Middle and Upper Siwalik Subgroups (e.g., Bhat and Pandita, 1991; Pandita 1996; Pandita and Bhat 1996, 1999; Sharma *et al.*, 2002; Bhat *et al*., 2008; Pandita *et al.,* 2011, 2012, 2014). However, no detailed study has been carried out in the Lower Siwalik Subgroup to work out the depositional setting in the region except that of Sharma *et al.* (2001) and Pandita and Bhat (2011).

Ramnagar area in Udhampur District is famous for its rich vertebrate fossil record hosted in the Lower Siwalik Subgroup and different workers have collected and described the fauna in this area (e.g., Gupta and Shali, 1989, 1990; Nanda and Sehgal 1993; Sehgal 1994 & 1998; Gupta, 2000; Sehgal and Nanda, 2002; Parmar and Prasad., 2006; Parmar *et al*. 2017). The present study has been carried out in Lower Siwalik strata at Ramnagar (Fig. 1) and is aimed at documentation of the spatio-temporal lithofacies variations of these deposits and deciphers their depositional environment.

GEOLOGICAL SETTING

The Siwalik Group of rocks in the Jammu region is disposed in parallel folded zones constituting the outermost foot hill belt approximately 40 km wide (Wadia, 1975). Here the Siwalik Group is represented by four prominent structural units i.e. Udhampur thrust (Main Boundary thrust), Udhampur syncline, Mansar-Jhajjar (Suruin-Mastgarh) anticline including a number of tight folds, and Kishanpur thrust. The salient features of these structural units have been described by Dasarthi (1968). The Siwalik Group of rocks has been traditionally divided into Lower-, Middle-, and Upper Siwalik subgroups. These rocks generally dip in southwest-northeast directions at varying angles between 80^0 (Lower Siwalik) to 10^0 (Upper Siwalik). Lower Siwalik represents alternation of light grey to brown, thick bedded, fine to coarse-grained sandstones, mudstones and siltstones, whereas, the Middle Siwalik consists of light grey, medium to coarse and pebbly sandstones, which are soft and friable. The interbedded mudstones are thinner as compared to Lower Siwalik mudstones. The Upper Siwalik

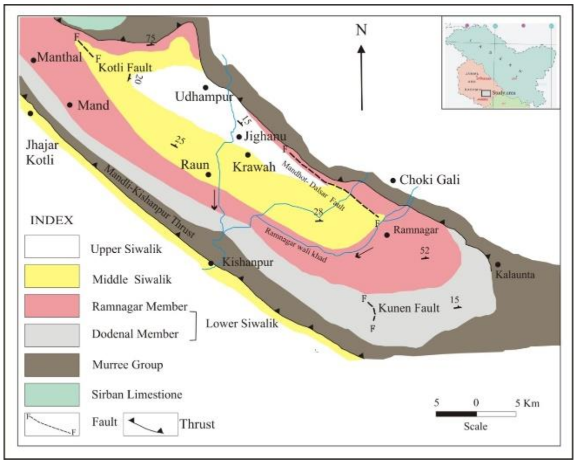

Fig. 1: Location and geological map of the part of the northern limb of the Suruin- Mastgarh anticline (modified after Gupta, 2000). The lithosections studied are around Kalaunta and Ramnagar localities.

mostly consists of medium to coarse, massive and friable sandstone in the lower part, grey and brown mudstones in the middle part and conglomerate in the upper part with a few sand and clay lenses.

In the northern limb of the Suruin-Mastgarh anticline the Lower Siwalik Subgroup of rocks is exposed in different tectonic dispositions in Tikri - Udhampur - Ramnagar sector in the Jammu region. These rocks occur sandwiched between the Murree Group and the Middle Siwalik Subgroup on both the limbs of the doubly plunging Udhampur Syncline (Fig. 1). In Ramnagar area this subgroup has been divided into Dodenal and Ramnagar members (Gupta, 2000). The Dodenal Member which is lower part of the Subgroup is well exposed at Kalaunta locality and consists of alternation of sandstones, mudstones and siltstones. The upper part of the subgroup, Ramnagar Member is exposed along the Ramnagar wali *Khad* (seasonal stream) and comprises of multistoried sandstone bodies with fine to coarse grained sandstones, mudstones and siltstones.

FACIES ANALYSIS

Since the Ramnagar area has thick vegetation cover and the rocks are exposed along the *nallas* and streams, two representative lithosections, Kalaunta (194m, Fig. 2) of the Dodenal Member and Ramnagar (310m, Fig. 3) of Ramnagar Member, are studied for facies evaluation and to work out the depositional process of the subgroup. Different lithofacies were identified on the basis of lithological characters, bedding types, nature of contacts, sedimentary structures and texture. The nomenclature adopted for facies description followed in the present study is after Miall (1977, 1978). The various lithofacies recorded are described in Table 1.

Kalaunta Section

This measured section (194m, Fig. 2) is the lower most part of the Lower Siwalik and is represented by alternation of sandstone, mudstone and siltstone rich strata. The strata measured here are mostly composed of brown, reddish brown, grey and buff sandstones with intervening light brown and reddish brown mudstones. The sandstone beds range in thickness from 0.70 to 7.60m with an average thickness of 2m. The sandstones are fine to medium grained, massive, parallel laminated and planar cross stratified. Intraformational mud balls up to 1cm in diameter are sparsely oriented along the planar cross stratified strata. However at certain places the frequency of these clasts in the cross bedded sets is very high. Internally a very few sandstone beds are composed of multistoried nature. These multistoried sandstone bodies range in thickness from 0.70 to 4.16m and show sharp contacts with the underlying mudstone bodies. The bedsets within the storeys are fining upward and exhibit changes in sedimentary structures from planar cross laminated to horizontal stratification. Mudstone lenses of about 50cm thick are observed in a few sandstone beds.

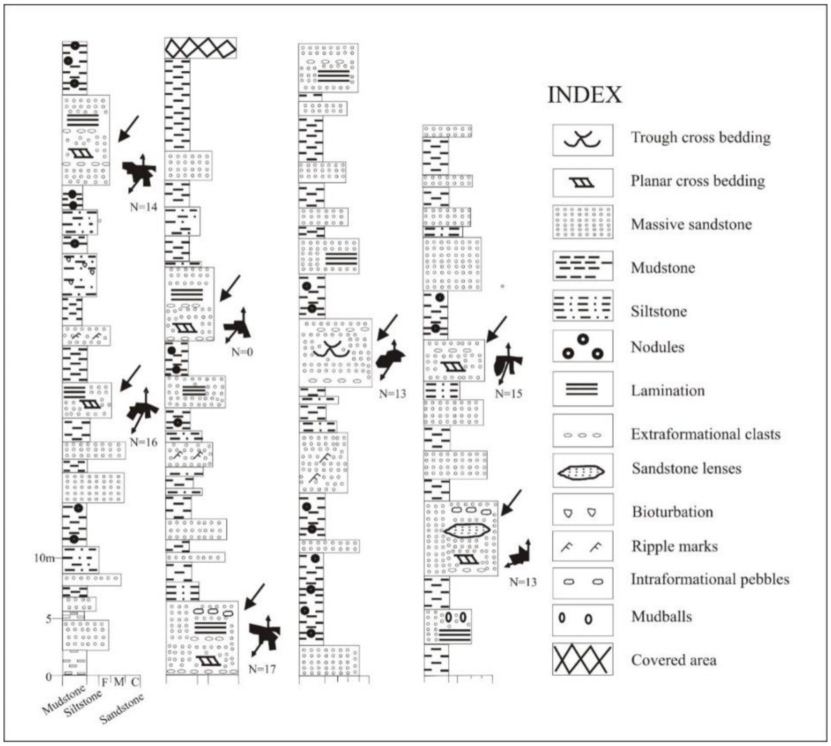

Fig. 2: Litholog of basal part of the Dodenal Member at Kalaunta locality

The mudstones are light brown, bright red, dark reddish brown and grey in colour and range in thickness from 0.80 to 8m with an average of 2m in the measured section. These mudstones are massive and nodular and show sharp contacts with the overlying sandstones. The siltstones observed in the section are hard thinly laminated, reddish brown to dark brown in colour and range in thickness from 0.34 to 4m with an average thickness of 1m. At certain places a few siltstone beds show burrows, the thickness of these units varies from 0.50 to 0.90m.

Ramnagar Section

A 311m thick succession was studied around Ramnagar town. This section is composed of sandstone-mudstone and siltstone alternations (Fig. 3). The sandstones are fine to coarse grained, purple, buff, brown, dull grey and greenish grey in colour and range in thickness from 0.50 to 10m with an average of 3.1m. Major sediment bodies are at places represented by multistoried sandstones. These multistoried sandstone bodies range in thickness from 2.50 to 10m and show sharp/ erosional contacts with the underlying mudstone bodies. Individual sandstone storeys are 0.60 to 2.50m thick separated by erosional surfaces. The erosional bases are marked by the presence of intraformational mud balls and extraformational clasts. The sandstone bodies display large scale planar cross stratification throughout the succession grading into laminated and massive fine sandstone. Trough cross beddings are also observed at some places. Some sandstones display intraformational mud clasts which are either evenly distributed or oriented along the cross beddings.

The mudstones are bright red, reddish brown at places blackish grey and light grey in colour. The mudstones range in thickness from 0.80 to 12m with an average of 3.1m in the measured section. These mudstones are nodular, massive and thinly laminated. At certain places sandstone lenses varying from few mm to 30cm thick are observed in mudstone beds. These bodies display vertical changes ranging from undisrupted basal sediments through fine lamination to isolated lenses or laminated siltstone. The siltstones observed in the section are hard thinly laminated, reddish brown to dark brown in colour and range in thickness from 0.30 to 2.20m with an average thickness of 1.1m.

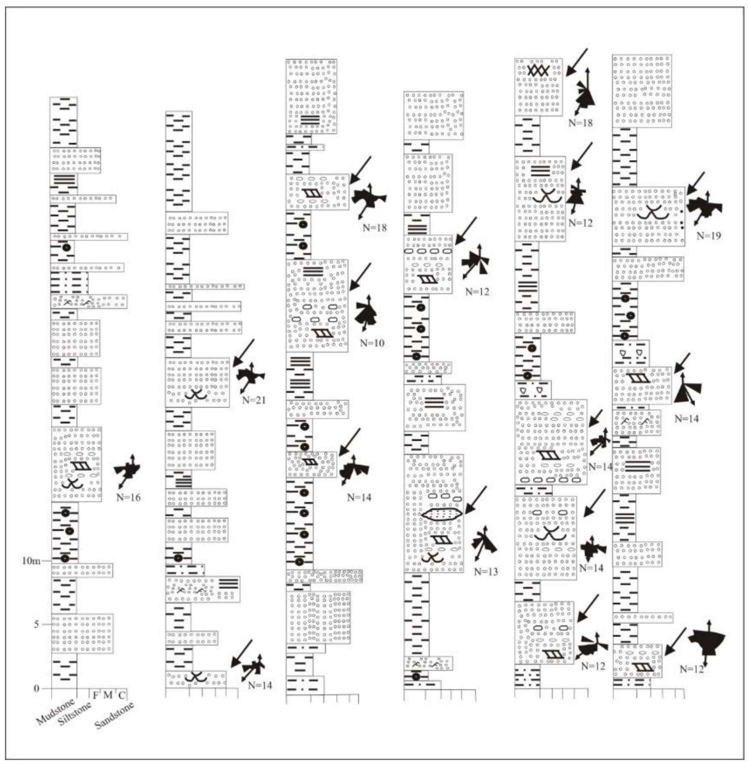

Fig. 3: Litholog of basal upper part of the Ramnagar Member at Ramnagar locality. (See Fig. 2 for index)

The lithofacies identified and described in this study (Table 1) are grouped into three facies associations.

Facies Code	Facies Description	Characters	Interpretation
St	Trough cross bedded sandstone	Fine to medium grained,brown to reddish brwon, poorly sorted, normal grading,	3-dimensional dunes migrating in channels under upper part of lower flow regime
Sp	Planar cross bedded sandstone	Fine to medium grained, brown–grey, buff intraformational mudballs oriented along cross bedded sets	Transverse bars, plane bedded bed forms
Sh	Massive and horizontally laminated bedded sandstone	Lenticular to sheet geometry, followed upward by St, Sp, Sr, Fst or Fm	Stream flow deposits with gradual decrease in energy
Sr	Rippled drift sandstone	Very fine to fine sand –silt, grey to buff, fining upward grain size, ripple marks	Ripples (lower flow regime)
Fst	Massive and laminated siltstone	Massive, thinly laminated, bioturbated	Lower flow regime
Fm	Massive and nodular mudstone	Massive, nodular, root casts, mudcracks	Over bank deposits
Fl	Laminated mudstone	Thinly laminated, reddish to dark brown, bioturbated	Levee deposits
Flt	Intercalations of sandstone/mudstone-siltstone	Very fine sand, silt and mud, burrows, root marks and calcareous concreations	Low energy deposits

Table 1: Summarized description and interpretation of lithofacies recorded in the study area

FACIES ASSOCIATION 1 (FA1)

The FA1 is characterized by mudstones, siltstones and fine to medium grained sandstones. The thickly bedded sandstones show various sets of planar cross stratification as multiple storeys which grade into laminated or massive fine sandstone. Occasional trough cross stratification are also observed which grade into the planar cross stratified sandstone. The basal contact of the sandstone bodies is marked by erosional surfaces and sandstone gradually passes upward into mudstone/siltstone. Ripple cross laminations are well preserved in thinner sandstone and siltstone beds. The fine grained sandstones have sheet- like geometry and are massive or rippled and locally grade into mudstone. Climbing ripple laminations are also observed in the sandstones. The fine to medium grained sandstones are frequently ribbon to lensoid- shaped with lateral accretionary architectures. Calcareous nodules are well developed on the upper surfaces of the fine grained sandstones, siltstones and mudstones, and in places the sandstone beds contain burrows towards the upper parts indicating the development of vegetation at the top of the fining upward sequence.

The siltstones observed in the section are hard thinly laminated, reddish brown to dark brown in colour and range in thickness from 0.30 to 4m with an average thickness of 1.1m. The primary bedding features are often obliterated, however, fine parallel laminations can be seen. Small scale cross laminations can be seen at few places in these siltstones. Intense bioturbation and colour mottling with faint parallel lamination and ripple lamination can be seen. The mudstones constitute about 48% of the measured strata. These mudstones continue along the strike for a few hundred metres and are mostly truncated upward by an overlying channel deposit. In certain cases these mudstones pinch out laterally and finally become indistinguishable from the surrounding deposits. These mudstones contain centimetre-thick layers internally finely and horizontally laminated. The overall thickness of mudstone and siltstone is more than the sandstones.

Interpretation

FA1 (Fig. 4a) is interpreted as the product of a fine grained meandering system with associated floodplain deposits. The predominance of fine grained facies (mudstone and siltstone), bioturbation and presence of calcareous nodules suggest extensive floodplain deposits which were exposed for a long time at the surface. The red colour of the fine sediments shows evidence of sub-aerial exposure and is related to oxidizing conditions and to periodic wetting (Walker, 1967) and reflects low water table (Reading, 1986). The rippled and sheet like geometry of sandstone beds interbedded within the mudstone imply crevasse splay deposits. Laterally accreted fine to medium grained cross-stratified sandstones within the mudstone beds represent the bed load of meandering channels. The combination of these features supports the interpretation of a fine sediment laden meandering system.

FACIES ASSOCIATION 2 (FA2)

This facies association is comprised of sandstones, mudstone and siltstone alternations. The sandstones are fine to coarse grained, massive to horizontally laminated with varying bedset thickness. Some of the sandstones are multistoried in nature with erosional basal contacts, whereas, the upper contact with Sh- and Fm- facies is sharp and erosional with coarse grained facies. The erosional surfaces are marked by the presence of intraformational and extraformational clasts which are followed upward by large scale planar cross stratification or trough cross stratified sandstones. Generally the bedsets within the storeys are fining upward and exhibit changes in sedimentary structures from trough cross stratification to planar cross stratification to horizontal bedding. The sandstone bodies show downstream and lateral accretionary architecture. Planar stratified sandstone beds are frequently observed in these units at the upper part of the storey. The sequence of sedimentary structures observed in some of the sandstone beds is internally laminated thinly bedded basal units, followed by rippled units which in turn are followed by thinly laminated sandstone top. Thinner fine to medium grained sandstone beds with sheet like geometry show centimetre-scale laminations and locally grade into mudstone beds, the top of which is truncated by an overlying fine grained sandstones.

The siltstone beds are brown, dark brown to light grey in colour ranging from 0.30 to 4m in thickness and show well developed bioturbation. The siltstones show sheet- like geometry and small scale rippled cross laminations and wavy laminations are commonly observed in these siltstones. The mudstones are characterized by thinly laminated, massive, nodular and variegated nature and show dark brown, reddish brown to light brown colour. These mudstones have gradational to sharp bases and are mostly truncated upward by an overlying channel deposit.

Interpretation

Facies association FA2 (Fig. 4b) is characterized by lateral accreted cross stratified sandstone deposits reflecting bed load of meandering channels. The climbing ripple laminations observed at a few places represent gradual velocity change of flood flow. Variegated mudstones beds were formed on floodplains. The frequency and thickness of mudstone/siltstone bodies suggest extensive flood plain deposits which were exposed for a long time at the surface. The combination of these features supports the interpretation of a flood flow dominated meandering system. Abundance of laterally accreted sandstones, which increase stratigraphically upward and sandstone ratio may suggest a change in the meandering system from a distal setting to a proximal setting.

FACIES ASSOCIATION 3 (FA3)

Facies association FA3 is characterized with fine to very fine sandstones, siltstones and mudstones and overly the sand-mud dominated association. These deposits are highly oxidized. The thin sandstone beds are sheet-like in nature, with gradational to erosional underlying contacts. The basal part of these beds show well preserved bedding structures like small scale ripple cross laminations and parallel laminations. Well developed mottling is seen towards the top of these units. The siltstones show non-erosional bases, parallel and ripple laminations and mottling. The mudstones are often lensoid in nature and show intense bioturbation and colour mottling. However, at places faint parallel and ripple laminations can also be seen. Thin calcareous layers and nodules are frequently seen in these units. Thin siltstone layers are interbedded within the mudstones at some places. The brown and light yellow mudstones and siltstones are persistent over a few hundred meters in both the measured sections. These mudstones display thin (1–2mm thick) wavy and parallel laminationand numerous dwelling burrows (2–5mm in diameter). In some places, thickly bedded, finely laminated siltstones and mudstones exhibit preserved rootlets and mottling. Interbedded with mudstones are many thin (5–15cm thick) beds of structure less, silt-bearing fine-grained sandstones. In some cases, mottling and secondary carbonate accumulations are observed. The dominant mottled mudstone facies, with the presence of rootlets and bioturbation, is associated with thin lensoidal sand bodies, moderately to well sorted, which are persistent over a few hundred meters without any marked change in grain size. These sandstone bodies do not merge laterally with any major channel sandstone body. The mudstone facies is characterized by calcareous nodules and bedded calcretes.

Interpretation

Bhat *et al*. (2008) have identified this type of facies association as typical of interfluvial depositional settings. Interfluvial areas in most of the fluvial basins are low-lying features showing development of floodplain, swamps and ponds (Singh *et al.*, 1999). These typically low-lying areas with respect to the river channels are characterized by the facies architecture that indicates crevasse splay and suspended fall-out of fine-grained sedimentation. These deposits are usually referred to as overbank or flood plain deposits. Smith and Perez-Arlucea (1994), Tye and Colman (1989a,b), Farrell (1987), Ray (1976), Singh (1972), Singh *et al.* (1999) and Sharma *et al.* (2001) have studied these deposits in modern environments and concluded that many of the thick mud-dominant fluvial deposits of the ancient fluvial record represent deposition in interfluvial areas. In some major alluvial plains (e.g. Ganga plain), the interfluve areas include large tracts of deposition of muddy sediments located above the major channels and have been referred to as upland interfluve areas (Singh *et al.,* 1999). Srivastava *et al.* (1994) and Kumar *et al.* (1996) have studied this type of muddy sediment in the Ganga plain, and Singh *et al.* (1999) have carried out a comparative study of these interfluvial deposits in Ganga plain and Lower Siwalik strata in Jammu. In the present study area, the interfluvial (upland area) facies consists of very fine-grained sandstones, laminated and structure less mudstones deposited in the inter-channel areas. The predominance of bioturbated, pigmented mudstone/siltstone and the presence of calcareous nodules suggest extensive floodplain deposits which were exposed for long time at the surface. The rippled and sheet-like geometry of the fine sandstone and siltstone beds interbedded within the mudstones indicate crevasse splay deposits. The fine grained sandstone with erosional base suggests the deposition in small channels developed on the floodplain areas. Intense mottling related to bioturbation suggests a slow rate of deposition. The mottled/laminated mudstone can be related to deposition in low-lying areas like ponds or lakes where fine sediments were preferentially deposited under still water conditions. This facies association (Fig. 4c) is interpreted to be deposited in the floodplain areas associated with the meandering river system.

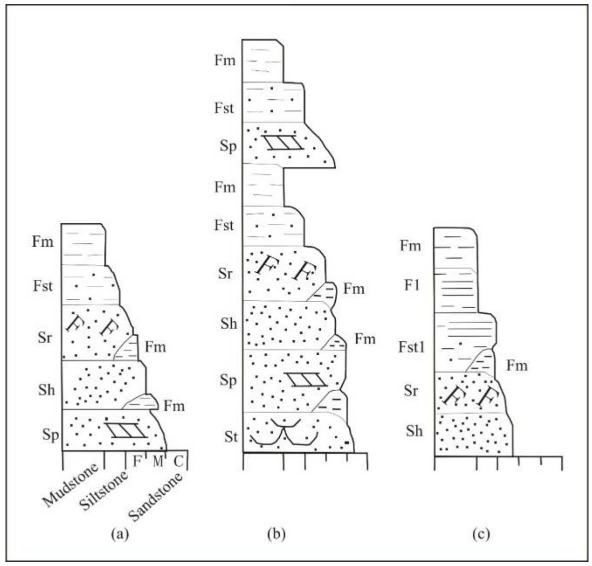

Fig. 4: Summary sequence of the facies association of the study area
a) Facies association-1 (FA1);
b) Facies association-2 (FA2);
c) Facies association-3 (FA3)

PALAEOCURRENT ANALYSIS

In the present study the data on directional features was collected from the cross bedded sandstones. Azimuths of planar and trough cross bedding at different

Rose Pattern	**Average Azimuth (^{0})**	**Trigonometric**		**Graphic**	
		Vector Mean(^{0})	**Vector Magnitude (%)**	**Vector Mean(^{0})**	**Vector Magnitude (%)**
Polymodal(n=16)	201	203	78	205	81
Polymodal(n=14)	205	207	68	208	70
Bimodal (n=09)	217	218	83	218	84
Bimodal (n=13)	202	206	89	210	79
Unimodal(n=13)	234	234	90	236	92
Polymodal (n=17)	207	209	87	209	80
Polymodal (n=15)	192	196	73	196	75
Average	**208**	**210**	**81**	**212**	**80**

Table 2: Composite bedwise palaeocurrent parameters of cross-beddings of the Lower Siwalik Subgroup in Kalaunta section

stratigraphic levels were recorded. These data were corrected for tectonic tilt according to the procedure outlined by Potter and Pettijohn (1963). The tilt corrected azimuthal data were grouped at the class interval of 20^o and plotted in rose diagrams. The bed wise average tilt corrected azimuths were recorded from each rose diagram. Vector means and vector magnitudes of the palaeocurrent data were determined both graphically and trigonometrically following the procedure as outlined by Lindholm (1987).

To document the temporal variability of the palaeoflow, vector means of the cross bedding and the rose diagrams for the individual beds have been plotted against the respective lithologs (Figs. 2 & 3). The corresponding data on the vector means and vector magnitudes, and the patterns of rose diagrams are listed in Tables- 2 and 3.The section wise details of the palaeocurrent study are described as under:

Kalaunta Section

The palaeocurrent data of the cross beddings from the sandstone beds at various stratigraphic levels is shown as in Table-2 and the rose diagrams are displayed in Figure 2. The rose diagrams show unimodal to polymodal nature with average azimuth values ranging from 192 to 234^0 with an overall average of 208^0 (Table-2). The graphic vector mean ranges from 196 to 236^0 with an average of 212^0 and the vector magnitude ranges from 70 to 92% with an average of 80%. The trigonometric mean values ranges from 196 to 234^o with an average of 210^0 and the trigonometric magnitude ranges from 68 to 90% with an average of 81% indicating a low dispersion. The aggregate average azimuth in the Kalaunta section is 208^0 and the rose diagram shows a bimodal distribution with two prominent modes between 160^0-$180^0$and 200-260^0 (Fig. 5a and Table-2). The azimuth of the section indicates a south-westerly palaeoflow for the sediments with a low dispersion.

Ramnagar Section

The bed wise average azimuth, vector mean and vector magnitude of the Ramnagar section is displayed as Table-3 and the rose diagrams are shown as Figure 3. The rose diagrams are bimodal and polymodal in nature with average azimuth ranging from 151 to 227^0 with an overall average of 197^0. The graphic vector mean ranges from 186 to 238^0 with an average of 204^0 and vector magnitude ranges from 55 to 85% with an average of 70%. The trigonometric vector mean ranges from 151 to 237^o with an average of 199^0 and the vector magnitude range from 69 to 93% with an average of 82% indicating low dispersion. The consolidated rose diagram for this section shows a polymodal distribution with three prominent modes between 100-120^0, 200-220^0 and 240-

Rose Pattern	Average Azimuth (^{0})	Trigonometric		Graphic	
		Vector Mean(^{0})	Vector Magnitude (%)	Vector Mean(^{0})	Vector Magnitude(%)
Polymodal (n=16)	227	237	93	238	74
Polymodal (n=14)	185	185	85	186	54
Polymodal (n=16)	184	187	75	188	73
Polymodal (n=14)	223	225	78	225	83
Bimodal (n=21)	206	209	71	208	71
Polymodal (n=13)	198	196	69	197	71
Polymodal (n=14)	202	208	71	209	74
Polymodal (n=10)	193	191	90	190	85
Polymodal (n=19)	210	205	84	205	55
Polymodal (n=12)	218	220	83	218	60
Polymodal (n=18)	194	196	87	191	58
Bimodal (n=14)	151	151	87	242	82
Polymodal (n=12)	189	186	90	186	54
Bimodal (n=12)	190	190	71	191	72
Bimodal (n=15)	193	192	92	193	78
Average	**197**	**199**	**82**	**204**	**70**

Table 3: Composite bedwise palaeocurrent parameters of cross-beddings of the Lower Siwalik Subgroup in Ramnagar section

260^0 with an average azimuth of 197^0 (Fig. 5b and Table-3) indicating a south-westerly palaeocurrent direction.

Interpretation

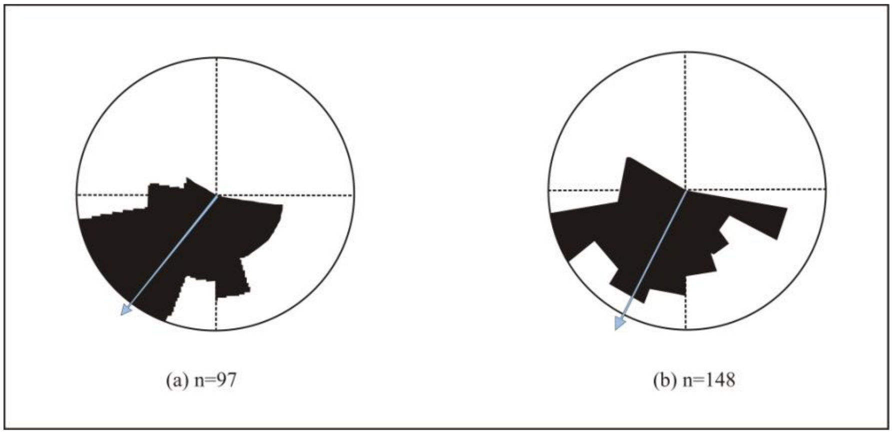

Fig. 5: Composite rose diagrams of the cross beddings showing the distribution and the azimuth of the palaeocurrent flow in Kaluanta (a) and Ramnagar (b) areas.

The present study shows wide variations in the temporal palaeoflow patterns in both the sections**.** In Ramnagar section these variations range from 102^0 to 280^0 and in the Kalaunta section the temporal palaeoflow variations range between 161-284^0. The average azimuth of the palaeocurrents in both the sections shows a south-westerly direction. The temporal palaeoflow variations are short ranging and oscillate between East and West directions with SE, SSE, S, SSW, and SW azimuth. Majority of the palaeoflow directions show a polymodal distribution. The temporal palaeoflow variations and the polymodal distribution can be related to sinuous character of meandering stream channels (Lindholm, 1987). The average azimuths in both the sections are consistently within the azimuth range between 197 and 210^0 with low to moderate dispersion. These data demonstrate that the rivers that deposited the Lower Siwalik in Ramnagar area flowed consistently southward, essentially identical to modern fluvial drainage pattern in Indus basin.

DISCUSSION

The Lower Siwalik Subgroup of the Ramnagar area under study represent alternating sandstone- mudstone and siltstone strata and document large and small scale sedimentary variations through time and space. The sandstone bodies are separated by thicker mudstone dominated intervals with minor sandstones and red mudstones and siltstones. The increase in the upsection mean grain size in the area supports the existence of large channel system of increasing depositional slope and the absence of pebble units within the sequence suggests the deposition in low gradient basin environment. The large lateral extent of the sediment bodies is suggestive of a network of channel system on a broad alluvial plain. As such the thick, well developed accretionary units associated with sandstone bodies are interpreted as a feature of meandering streams (Visser and Johnson, 1978). The cyclic sandstone-siltstone/mudstone couplets of the Siwalik Group have been attributed to an aggrading fluvial system resembling the modern Indogangetic plains (Gansser, 1964; Halstead and Nanda, 1973; LeFort, 1975).

The facies associations and the depositional processes that produced the Lower Siwalik Subgroup of rocks in the study area are directly related to the evolution of fluvial style. Based on the stratigraphic accumulation of facies associations, evolution of fluvial style has two stages in the study area. The stage first started with the deposition of fine grained mudstone-siltstone facies association FA1 characteristic of meandering system. This facies association shows predominance of fine grained facies (mudstone and siltstone) and bioturbation, and presence of calcareous nodules suggest extensive floodplain deposits which were exposed for a long time at the surface. The red colour of the fine sediments shows evidence of sub-aerial exposure. The rippled and sheet like geometry of sandstone beds interbedded within the mudstone imply crevasse splay deposits. Laterally accreted fine to medium grained cross-stratified sandstones within the mudstone beds represent the bed load of meandering channels. The stage two started with dominance of flood flow and crevasse splay sediments. This stage is characterized by laterally accreted cross stratified sandstone deposits of facies association FA2, reflecting bed load of meandering channels. The climbing ripple laminations observed at a few

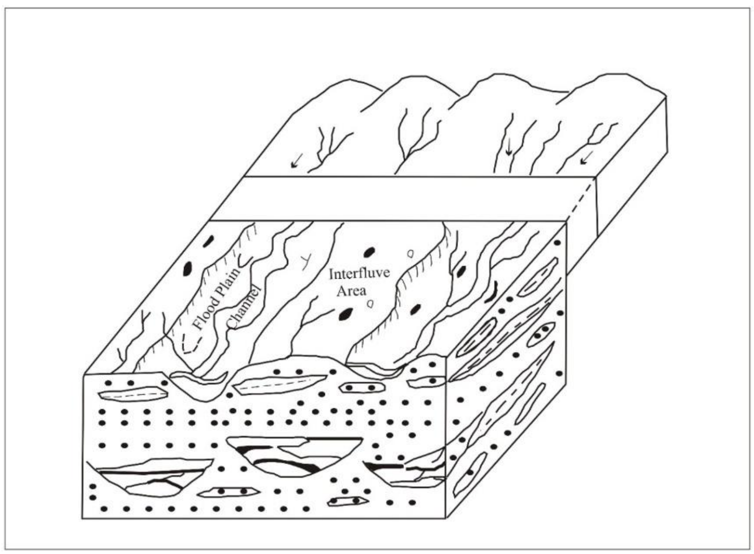

Fig. 6: Schematic block diagram showing the relationship of channel, flood plain and interfluv areas. Arrows indicate the direction of sediment movement. Thick lensoid bodies represent major rivers with multistoried build up along with over bank deposits (black). The bulk of stratigraphy is made up of fine-grained sediments comprising of mudstones and siltstones with thin sandy lensoid bodies representing minor rivers of interfluve areas. (Modified after Sharma *et al.*, 2001)

places represent gradual velocity change of flood flow. Variegated mudstone beds were formed on floodplains.

Facies association FA3 has been deposited between these two stages of sedimentation in the Lower Siwalik Subgroup of the study area. This facies association comprises of sequences of fine to very fine sandstones, siltstones and mudstones overlying the sand-mud dominated association. The fine grained sandstone with erosional base suggests the deposition in small channels developed on the floodplain areas. The predominance of bioturbated, pigmented mudstone/siltstone and the presence of calcareous nodules suggest extensive floodplain deposits which were exposed for long time under sub-aerial conditions. Intense mottling related to bioturbation suggests a slow rate of deposition. During a low energy regime the relatively slower sedimentation rate and longer exposure to weathering agents of finer sediments promote oxidation and red colouration (Raiverman, 2007). The mottled/laminated mudstone can be related to deposition in low-lying areas like ponds or lakes within the floodplain areas, where fine sediments were preferentially deposited under still water conditions. The dominant mottled mudstone facies, with the presence of rootlets and bioturbation, is associated with thin lensoidal sand bodies, moderately to well sorted, which are persistent over a few hundred meters without any marked change in grain size. These sandstone bodies do not merge laterally with any major channel sandstone bodies. The mudstone facies is characterized by calcareous nodules and bedded calcretes. Consistency of grain size in lateral accretion units and the absence of pebble units within the sequence under study suggest the deposition in low gradient basin environment. The schematic cross-section diagram showing the pattern of the depositional system is displayed as Fig. 6.

Hisatomi and Tanaka (1994) and Nakayama and Ulak (1999) performed facies analysis on the middle to lower part of the Siwalik Group in Nepal, and described the evolution of fluvial system. They noted that sediment accumulation began in meandering rivers, changed to meandering rivers of a dominant sheet type at 10Ma, and became braided at 7.5Ma. Pandita and Bhat (1996, 1999) and Pandita *et al.* (2005) have observed shift in the drainage system from meandering to braided and meandering for the Lower, Middle and lower part of the

Upper Siwalik Subgroups respectively in the southern limb of Suruin–Mastgarh anticline.

The palaeocurrent data in the present study demonstrate that the rivers that deposited the Lower Siwalik in Ramnagar area flowed consistently southward, similar to the modern fluvial drainage pattern in Indus basin. The palaeocurrent trends in this study range from SE to SW with temporal variations reflecting co-existence of small rivers draining the area and flowing in different directions with an overall trend due SW which coincides with the trend of the modern Chenab and Tawi rivers in the area. These observations are consistent with the views of Pandita (1996) and Pandita and Bhat (1996) who concluded that the Middle and Upper Siwalik subgroups of Jammu region were deposited by the southward flowing river system. Our observations suggest variations in palaeoflow were controlled by the local slopes on the individual sediment bodies. The distinct palaeocurrent direction changes reflect local changes in basin morphology and depositional slope.

CONCLUSIONS

1) The rocks in the Lower Siwalik Subgroup in Ramnagar area of Jammu region comprising of sandstone, mudstone and siltstone alternations were studied for lateral and vertical facies variations and signatures of palaeoflow directions.
2) Three lithofacies associations (FA1, FA2 & FA3) recorded in the study area and the depositional processes that produced these rocks are directly related to the evolution of fluvial style. The FA1 represents stage one of fine grained meandering river system whereas, in stage two FA2 facies association represent flood flow dominated meandering river system. Facies association FA3 has been deposited during these two stages of sedimentation in interfluvial depositional settings on the floodplain areas exposed for long time under sub-aerial conditions in low gradient basin environment.
3) The palaeocurrent trends in this study range from SE to SW with temporal variations reflecting co-existence of small rivers draining the area and flowing in different directions with an overall trend due SW which coincides with the trend of the modern river system in the area.

ACKNOWLEDGEMENTS

The authors are thankful to the Prof. G. M. Bhat for his valuable suggestions during the course of work. The facilities developed by the Geology Department, University of Jammu under DST-FIST and UGC-SAP programmes were used during this work.

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