Depositional environment and provenance of Middle Siwalik sediments in Tista valley, Darjiling District, Eastern Himalaya, India

ABHIK KUNDU^{1,*}, ABDUL MATIN² and MALAY MUKUL³

¹*Department of Geology, Asutosh College, 92, S.P. Mukherjee Road, Kolkata 700 026, India.*

²*Department of Geology, University of Calcutta, 35, Ballygunge Circular Road, Kolkata 700 029, India.*

³*Department of Earth Sciences, Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India.*

**Corresponding author. e-mail: kundu.abhik@gmail.com*

The frontal part of the active, wedge-shaped Indo-Eurasian collision boundary is defined by the Himalayan fold-and-thrust belt whose foreland basin accumulated sediments that eventually became part of the thrust belt and is presently exposed as the sedimentary rocks of the Siwalik Group. The rocks of the Siwalik Group have been extensively studied in the western and Nepal Himalaya and have been divided into the Lower, Middle and Upper Subgroups. In the Darjiling–Sikkim Himalaya, the Upper Siwalik sequence is not exposed and the Middle Siwalik Subgroup exposed in the Tista river valley of Darjiling Himalaya preserves a ~325 m thick sequence of sandstone, conglomerate and shale. The Middle Siwalik section has been repeated by a number of north dipping thrusts. The sedimentary facies and facies associations within the lithostratigraphic column of the Middle Siwalik rocks show temporal repetition of sedimentary facies associations suggesting oscillation between proximal-, mid- and distal fan setups within a palaeo-alluvial fan depositional environment similar to the depositional setup of the Siwalik sediments in other parts of the Himalaya. These oscillations are probably due to a combination of foreland-ward movement of Himalayan thrusts, climatic variations and mountain-ward shift of fan-apex due to erosion. The Middle Siwalik sediments were derived from Higher- and Lesser Himalayan rocks. Mineral characteristics and modal analysis suggest that sedimentation occurred in humid climatic conditions similar to the moist humid climate of the present day Eastern Himalaya.

1. Introduction

The collision of the Indian and Tibetan plates, initiated ~55 Ma ago, resulted in the formation of the Himalayan orogen. The Himalayan foreland basin has evolved since the Palaeogene time in the frontal part of the orogen as the thrust belt propagated towards its foreland and is currently located in the Indo–Gangetic plains. The sediments deposited in the Himalayan foreland basin are

preserved almost continuously since the Miocene (Brozovic and Burbank 2000 and references therein). The Early Miocene–Pliocene sedimentary rocks are known as the Siwalik Group in India and Pakistan and Churia Group in Nepal (Medlicott 1864; Nakayama and Ulak 1999). The Siwalik Group of rocks is seen exposed in primarily two kinds of frontal settings. In the western Himalaya, the Siwalik rocks are exposed in a ‘Dun-type’ frontal setting whose morphology is

Keywords. Eastern Himalaya; Middle Siwalik; foreland basin; facies; alluvial fan.

dominated by intermontane, longitudinal valleys termed as the Duns (e.g., Pinjore Dun, Dehra Dun (Nakata 1972)), the easternmost of which is the Trijuga Dun in Nepal (e.g., Kimura 1999). The Duns are typically bounded by an east-west trending mountain range associated with the Main Frontal Thrust (MFT). In contrast, the eastern Himalaya is dominated by 'imbricate-type' fronts defined by an imbricate or schuppen zone of thrust faults that may or may not involve a unique MFT similar to the Dun-type front. The mountain front in this setting is defined by faults other than the MFT (e.g., the Ramgarh Thrust, Matin and Mukul 2010) or an imbricate or schuppen zone of thrust faults that repeat the Siwalik section (e.g., Mukul 2000).

The Siwalik Group of rocks is exposed along the Tista river and road sections in Tista valley in the Darjiling Himalaya of West Bengal. Pilgrim (1906); Heim and Gansser (1939); Ganguly and Rao (1970); Acharyya (1976, 1994); Banerji and Banerji (1982) have studied the Siwalik rocks of this area. The Siwalik sequence of the Tista valley section (TVS) is subdivided into lower and upper units (Banerji and Banerji 1982). Siwalik sediments in this region have been interpreted as alluvial fan deposits (Acharyya 1976; Banerji and Banerji 1982).

Sedimentary facies is defined as sediments or sedimentary rocks that can be recognized and distinguished from others by their geometry, lithological composition, sedimentary structures, palaeoflow patterns and fossils (Selley 1985). According to Reading and Levell (1996), a sedimentary facies is a body of rock whose characters bear the signature of the processes involved in its formation. Mineralogical and textural characters of clastic sedimentary rocks and analysis of modal values of quartz (Q), feldspars (F), lithic fragments (L), monocrystalline quartz (Qm) and total lithic fragments (Lt) including polycrystalline quartz (Q_p) constituting the framework of sandstones help to decipher the sedimentation history and the tectonic setting of the rocks (Pettijohn *et al* 1972; Basu *et al* 1975; Suttner *et al* 1981; Dickinson *et al* 1983; Dickinson 1985; Arribas and Tortosa 2003; Datta 2005; Kundu and Matin 2007; Banerjee and Banerjee 2010). These established tools have also been successfully and widely applied to understand the palaeoclimate during sedimentation and the provenance of Siwalik (Critelli and Ingersoll 1994; DeCelles *et al* 1998; Najman and Garzanti 2000; White *et al* 2002) and other sedimentary rocks (Garzanti *et al* 1996; Najman 2006; Ullah *et al* 2006) from different parts of the Himalaya. However, such studies are not attempted from the Darjiling Himalaya, particularly from an imbricate-type frontal setting as seen in the frontal Darjiling

Himalaya. Although the depositional setup of the Middle Siwalik Subgroup of the Tista valley has been worked out (Banerji and Banerji 1982), a detailed account of the lithology, sedimentary facies and the stratigraphy of the Middle Siwalik Subgroup is not available. This study works out the detailed sandstone petrography of the Middle Siwalik sedimentary rocks exposed in the Tista valley for the first time. Modal analysis of framework minerals of sandstones for the first time and data generated from facies analysis (Kundu *et al* 2011) to unveil the provenance characteristics, depositional environment and palaeoclimate during Middle Siwalik sedimentation in the Darjiling Himalaya.

2. Geological setting

The major structural units of the Himalayan orogen from north to south are the South Tibet Detachment (STD), Main Central Thrust (MCT), the Ramgarh Thrust (RT), the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT) (figure 1a and b; Yin 2006; Mukul 2010). The MCT marks the boundary between Greater- and Lesser Himalayan sequences and MBT marks the boundaries between the Lesser- and Sub-Himalayan sequences (Gansser 1964). The MBT carries the Gondwana and Daling Group of rocks over the Tertiary Siwalik sedimentary sequence in its footwall (Heim and Gansser 1939; Yin 2006 and references therein). The southernmost and youngest MFT carries the Siwalik Group over the Quaternary deposits that include recent alluvium of Indo-Gangetic plains in its footwall (Hodges 2000; Yin 2006 and references therein). In the TVS of the Darjiling Himalaya, the MFT is not exposed. The Lower Siwalik rocks are exposed in the South Kalijhora Thrust (SKT) sheet (Basak and Mukul 2000). The Middle Siwalik rocks are exposed in the hanging wall of several imbricate thrusts south of the SKT and define the imbricate-type mountain front in the Darjiling-Sikkim Himalaya (Mukul 2000 and references therein).

The Siwalik succession consists of conglomerate, sandstone, siltstone and shale layers, deposited in the Himalayan foreland basin since the Early-Middle Miocene (Acharyya 1976; Banerji and Banerji 1982; Kumar 1997; DeCelles *et al* 1998; Brozovic and Burbank 2000; Sharma *et al* 2002; Yin 2006; Ranjan and Banerjee 2009). On the basis of biostratigraphy, the Siwalik rocks are classified into three broad subgroups as Lower, Middle and Upper Siwalik subgroups (Medlicott 1864) and further subdivisions of these subgroups were done on the basis of mammalian fossil assemblage (Pilgrim 1913; Prasad 2001). The Siwalik sequence is now

Figure 1. Location maps and sections: (a) A generalized map of the Himalayan orogen (after Yin 2006). (b) A simplified cross-section across the Himalaya showing major thrusts and litho-tectonic units (after Mukul 2010). (c) Detailed map of the Tista River section with a part of the area of study shown (in broken rectangle). (d) Part of the Tista River section showing the imbricate thrust zone deforming the Middle Siwalik Subgroup. (e) Restored cross-section of Middle Siwalik Subgroup in the study area. The shaded area is the facies association Fa3 (the lowermost Fa3, which the third facies association from the base of the lithostratigraphic column), used as the marker horizon.

formally known as the Siwalik Group (Kumar *et al* 2003) and is subdivided into: (1) Lower Siwalik Subgroup comprising an upward-coarsening mudrock–sandstone succession; (2) Middle Siwalik Subgroup consisting mainly of sandstones, and (3) Upper Siwalik Subgroup consisting of conglomerates, sandstones and mudrocks (Kumar *et al* 2003). In the Darjiling Himalaya, the Lower, Middle and the Upper Siwalik successions are represented by Chunabati Formation, Geabdat Sandstone and Parbu Grit and Murti Boulder Beds, respectively (table 1) (Acharyya 1994; Kumar 1997; Matin and Mukul 2010). According to Banerji and Banerji (1982), the tripartite divisions of the Siwaliks is not applicable in the TVS in the Darjiling Himalaya (figure 1c) as the Upper Siwalik Subgroup is absent here. The folded sequence of the Lower Siwalik Chunabati Formation is transported over the Middle Siwalik Geabdat Sandstone by the SKT (Basak and Mukul 2000; Mukul 2000). The Geabdat Sandstone have been repeated by imbricate faults in the footwall of the SKT and are exposed all the way to the mountain front (Mukul 2000; figure 1d, e) and accommodate a minimum of 47% (3.5 km) shortening (table 2). The Siwalik Group of rocks are exposed in the Tista River section and adjacent road sections between the Kalijhora (26°55'30.44"N, 88°27'16.39"E) in the north and mountain front (26°52'52.30"N, 88°28'22.69"E) in the south (figure 1c).

3. Middle Siwalik Subgroup

The Middle Siwalik Subgroup occupies the major part (~70%) of the frontal TVS south of the MBT; the rest is occupied by the Lower Siwalik Subgroup. The Middle Siwalik lithologic units are repeated several times by imbricate thrust faults. There are totally eight in-sequence and one out-of-sequence imbricate thrusts (figure 1d and e). From hinterland to foreland, the in-sequence thrusts are named T1–T8, T1 being the oldest in the sequence of thrusting and T8 is the youngest. From structural and sedimentological data, a restored cross-section (figure 1d and e) of the deformed Middle Siwalik succession has been prepared (Kundu *et al* 2011). The most complete sequence (figure 2) is preserved in the T3 sheet in the TVS (figure 1d and e) on the basis of which we conclude that the minimum thickness of the Middle Siwalik section was ~325 m. About 69.5% (226 m) of the 325-m thick sequence is occupied by sandstone beds, ~19.5% (63 m) by siltstone–shale and ~11% (36 m) by conglomerate beds. The conglomerates

are of two types, viz., matrix-supported and clast-supported. They are common in the upper and lower parts of the sequence. The sandstone beds occur throughout the sequence. They are coarse- to medium-grained, medium-grained and fine-grained sandstone; fine-grained and medium-grained sandstone beds dominate over the coarse- to medium-grained sandstone beds. Siltstone and shale are present in the entire sequence except the lower part. Heterolithic units consisting of intercalated layers of fine-grained sandstone, siltstone and shale are present in the middle and upper parts of the sequence. Beds with sheet geometry without internal primary structure, planar tabular cross-strata, trough cross-strata and channel structures are common sedimentary structures in both conglomerate and sandstones. Finer rocks are planar-bedded and often internally laminated. Some of the heterolithic units preserve soft-sediments deformation structures that may be interpreted as seismites (Kundu *et al* 2011).

3.1 Petrography of Middle Siwalik sandstone and finer rocks

3.1.1 Coarse- to medium-grained sandstone

The framework clasts consist of quartz, potash feldspar, plagioclase and rock fragments and a small amount of muscovite and biotite (altogether constituting <5% of the total clasts). Size of clasts varies between 0.25 and 0.75 mm with a dominant size range from 0.25 to 0.6 mm. The clast-matrix ratio varies from 4:1 to 9:1. Quartz clasts constitute ~60–75% of the framework and dominantly comprise monocrystalline grains (~90% of the quartz grains) with subordinate amount of polycrystalline grains. These quartz clasts are angular to subrounded with rough to smooth grain boundaries. Polycrystalline grains contain three or more than three individual crystals with either straight or sutured inter-crystal margins. Feldspar clasts constitute ~30–10% of the framework. About 90% or more of the feldspar grains are potash feldspar. These are angular to subrounded and show a greater degree of roundness than the quartz grains. Feldspar grains show incipient to high degree of alteration to sericite (figure 3a). Rock fragments constitute ~10–15% of the framework and consist of fragments of gneiss, shale, phyllite and mica schist. Matrix constitutes ~20–10% of the volume of rock and is made up dominantly of silica. Tiny biotite grains are also present within the matrix. Silica cement is commonly present (figure 3a) while carbonate (calcite) cement is occasionally present. Secondary calcite are present along microfractures (figure 3a).

Table 1. *Stratigraphy of the Siwalik Group in the Darjiling–Sikkim sector of Himalayan Foreland Basin (after Matin and Mukul 2010).*

Geologic time	Group	Subgroup	Formation and lithology
Late Miocene to Pliocene	Siwalik Group	Upper Siwalik Subgroup	Murti Boulder Bed (Crude immature conglomerate) Parbu Grit (Pebbly sandstone and coarse-to-medium sandstone)
		Middle Siwalik Subgroup	Geabdat Sandstone (Medium-to coarse-grained sandstone and shale, pebble beds and marl)
		Lower Siwalik Subgroup	Chunabati Formation (Fine-to medium-grained sandstone, siltstone, mudstone, marl and conglomerate)
Early–Middle Miocene			
Upper Permian	Gondwana Group	Damuda Subgroup	Sandstone, carbonaceous shale and coal
Lower Permian		Rangit pebble-shale (Talchir?)	Diamictite, rythmite, quartzite marl
Precambrian	Daling Group		Buxa Formation Reyang Formation
			Daling Formation
	Paro Group		Parametamorphites with migmatitic and foliated granitic gneiss
		Darjiling Gneiss	Two-mica migmatitic gneiss

Table 2. *Length and percentage of shortening of base of Middle Siwalik Subgroup in the Tista River Section.*

Line	Shortening
Total length of the base of deformed section (l_d)	3.875 km
Total length of the base of restored section (l_r)	7.345 km
Total length shortening of the base of restored section ($l_r - l_d$)	3.47 km
Shortening in % $\{(l_r - l_d)/l_r\} \times 100$	47.24%

3.1.2 Medium-grained sandstone

The framework clasts of these sandstones consist of quartz, alkali and plagioclase feldspar, lithic fragments and little amount of biotite and muscovite. The size of clasts varies from 0.2 to 0.5 mm. The clast matrix ratio is $\sim 9:1$. Quartz clasts constitute $\sim 70\%$ of the framework. These are dominantly ($\geq 80\%$ of total quartz clasts) monocrystalline with subordinate amount of polycrystalline grains and are angular to subrounded with smooth or rough grain boundaries (figure 3b). Polycrystalline grains are with 3 or >3 individual crystals having sutured inter-crystal boundaries (figure 3b). Feldspar clasts constitute $\sim 15\%$ of the total framework. These are mainly ($\sim 70\%$) alkali feldspar with subordinate ($\sim 30\%$ of total feldspar) plagioclase feldspar grains. Feldspar grains are subrounded and commonly possess smooth grain boundaries.

Feldspar grains are partially altered though almost unaltered (figure 3c) grains are also present. Rock fragments constitute $\sim 15\%$ of the framework and consist of mica schist, chert and shale (figure 3b and c). The matrix occupies $<10\%$ of the volume, but locally the volume of matrix is $\sim 20\%$. It is mainly made up of silica with occasional presence of mica grains. Recrystallized silica cement is present along the intergranular spaces (figure 3b).

3.1.3 Fine-grained sandstone

The framework clasts consist of quartz, biotite and muscovite (figure 3d). The size of the clasts varies from ~ 0.125 to ~ 0.25 mm. Angular to rounded quartz clasts occupy $\sim 80\%$ of the framework. The quartz clasts are monocrystalline grains with either smooth or irregular grain boundaries. The matrix is made up of very fine sand to silt-sized quartz and opaque minerals. The cement is opaque and possibly iron-oxide.

3.1.4 Siltstone and shale

The siltstone and shale units consist of clasts of quartz, mica and opaque minerals. Quartz grains are angular to rounded. Some of the shale–siltstone samples show a foliation that is defined by a preferred orientation of the mica flakes and the long dimension of the inequant quartz grains (figure 3e).

Figure 2. Stratigraphic column of the Middle Siwalik Subgroup in the Tista River section showing the facies associations (Fa1, Fa2, Fa3 and Fa4 are facies associations).

3.1.5 Deformation signatures in mineral grains

The Middle Siwalik sequence is faulted. The rocks in the fault zones and in the fault-related damage zones show signatures of cataclasis (figure 3f) and deformation by frictional sliding. Rocks other than the fault rocks also preserve some grain-scale deformation features suggesting deformed nature of the source rocks. Many quartz and feldspar grains show undulose extinction (figure 3a and g), whose intensity varies from grain to grain. Intracrystalline deformation bands are present in quartz grains (figure 3g) (cf. Blenkinsop 2002). In many samples, more than 50% of the quartz grains show undulose extinction. Many rock fragments are recrystallized

quartz with either incipient or intense recrystallization (figure 3a). Kinks in twin lamellae of plagioclase feldspar grains (figure 3h) and in mica flakes is a common feature in almost all samples.

3.2 Modal analysis

Composition of the sand has a close relationship with the composition and tectonic setting of the source rock and the tectonic setting of the source rock and hence the type and tectonic setting of the source can be revealed from detrital modes of sand and sandstones (Suttner *et al* 1981; Dickinson *et al* 1983; Dickinson 1985). The modal counts of framework grains (quartz, feldspars and lithics) from 19 samples collected from different stratigraphic levels are plotted to understand the type and tectonic setting of the provenance (table 3). From the QFL plot (figure 4a), recycled orogenic provenance is envisaged whereas in the QmFLt diagram (figure 4b) all points except two suggest ‘quartzose recycled’ provenance. One of the sample plot lies on the boundary between quartzose recycled field and mixed provenance field while the other plots lie on the boundary between quartzose recycled and transitional field (cf., Dickinson *et al* 1983; Dickinson 1985). When plotted in quartz-feldspar-rock fragment (Q-F-RF) ternary diagram of Suttner *et al* (1981), the plots suggest plutonic–metamorphic source in humid palaeoclimate (figure 4c).

4. Sedimentary facies

4.1 Facies units

A detailed description of facies units is presented in Kundu *et al* (2011). Conglomerate units are divided into four different facies on the basis of the lithological and primary structural characters.

- (i) diamictite facies (figure 5a) (F1)
- (ii) thick bedded conglomerate facies (figure 5b) (F2)
- (iii) crude cross-stratified conglomerate facies (figure 5c) (F3)
- (iv) conglomerate facies with channel structure (figure 5d) (F4)

Sandstones are divided into four different facies

- (i) thick bedded sandstone facies (figure 5e) (F5)
- (ii) tabular cross-stratified and planar laminated sandstone facies (figure 5f) (F6)
- (iii) sandstone with channel structure (figure 5g) (F7)
- (iv) planar laminated fine-grained sandstone facies (F8)

Figure 3. (a) Photomicrograph of a coarse- to medium-grained sandstone. Q – quartz showing undulose extinction by dislocation glide, Qp – quartz showing subgrains with grain boundary migration indicating dislocation creep, Rq – rock fragment (recrystallized quartz), R – rock fragment (schist), F – feldspar partially altered to sericite, S – silica cement, C – secondary carbonate filling microfractures. (b) Photomicrograph of a medium-grained sandstone. Q – monocrystalline quartz, P – polycrystalline quartz, C – irregular and crenulated grain boundary of quartz, R – rock fragment (chert), S – silica cement. (c) Photomicrograph of a medium-grained sandstone. Q – quartz, F – fresh grain of plagioclase feldspar, Sh – shale (rock fragment) and C – chert (rock fragment), S – recrystallized silica cement. (d) Photomicrograph of a fine sandstone. Light-coloured grains are quartz, darker (brown) grains are mica. (e) Photomicrograph of a siltstone–shale sample. Note the alignment of inequant quartz grains following the preferred alignment of mica grains (marked by dotted line). (f) Photomicrograph of a cataclasite consisting T – transgranular, I – intragranular and C – circumgranular micro-fracture. Curved, unbranched and branched micro-fractures are also evident. (g) Photomicrograph of a sandstone consisting of quartz with undulose extinction (U) and intracrystalline deformation band in quartz (D). (h) A sandstone containing plagioclase grain (K) with kinked twin lamellae.

Table 3. Modal values of monocrystalline quartz (*Qm*), polycrystalline quartz (*Qp*), feldspars (*F*) and lithic fragments (*L*) in Middle Siwalik sandstones.

Sample	Qm	Qp	F	L
17A	68.57	4.80	9.13	17.5
17FW	65.47	14.38	9.82	10.33
19	59.00	8.70	11.90	20.4
28	66.00	7.70	12.60	13.7
23	62.20	10.30	7.10	20.4
28A	49.20	15.90	12.60	22.3
4	55.00	11.00	16.40	17.6
4a(3)	58.30	9.00	11.70	21
HST-HW	59.20	7.90	15.60	17.3
13D/1	63.30	6.60	15.60	14.5
18	50.00	13.20	14.50	22.3
20-1	49.00	10.00	21.00	20
27A	50.60	15.60	14.80	19
6/1	59.30	6.90	15.60	18.2
14	57.60	11.10	15.70	15.6
13	61.60	7.60	13.30	17.5
13c	54.60	16.05	15.75	13.6
AJST-FW1	65.30	4.60	16.90	13.2
13D/1	65.30	11.30	10.20	13

Figure 4. (a) Ternary plot of Q–F–L modal values of Middle Siwalik sandstones in the recycled orogenic provenance field (after Dickinson 1985). (b) Ternary plot Qm–F–Lt modal values in the quartzose recycled provenance field (after Dickinson *et al* 1983). (c) Ternary plots of Q–F–RF modal values indicate to plutonic-metamorphic provenance within humid palaeoclimate (after Suttner *et al* 1981).

Finer-grained rocks are present either as heterolithic units or as siltstone and shale units. Heterolithic units consisting of shale–siltstone–fine–sandstone layers are addressed as hetero-

lithic facies (F9), while the siltstone–shale units are addressed as siltstone–shale facies (F10). Attributes of different facies are tabulated for ready reference (table 4).

Figure 5. (a) Exposure of diamictite. Pen (15 cm) for scale. (b) Thick-bedded, clast-supported conglomerate (Cgl) with normal grading. Note that the clasts are dominantly subrounded with moderate to high sphericity. Broken line marks erosional contact with underlying sandstone (Sst). Hammer (45 cm) for scale. (c) Conglomerate with low angle planar tabular cross-strata (marked by dotted lines). Traces of bedding planes are marked by broken lines. Pen (15 cm) for scale. (d) Sharp contact (marked by arrow) between matrix-supported conglomerate (C) and coarse- to medium-grained sandstone (S). The conglomerate shows interlaced trough cross-stratification (marked by broken line). Hammer (45 cm) for scale. (e) Sandstone with sheet geometry. Bedding planes are marked by broken lines. Height of the person standing is 155 cm. (f) Medium-grained sandstone with plane laminae (P) and cross-strata with asymptotic base (C). Bedding plane is marked by broken line. (g) Interlaced channels in sandstone. B – bedding planes, C – channel sand. Hammer (45 cm) for scale.

Table 4. *Characteristics of different facies units in the Middle Siwalik Subgroup (after Kundu et al 2011).*

Facies	Rock type	Attributes	Interpretation
F1	Diamictite	<ul style="list-style-type: none"> Thick beds (1–2.2 m) Angular to rounded pebbles and granules Grading commonly absent, locally both normal and reverse grading Plane stratification defined by arrangement of pebbles <p>High volume (>50%) of sandy–muddy matrix</p>	Deposition on a gentle slope from mudflow in proximal-fans or in proglacial outwash zones (Maizels 1993; Nemeć and Postma 1993; Zielinski and van Loon 1999a, 2000; Neves <i>et al</i> 2005)
F2	Thick-bedded conglomerate	<ul style="list-style-type: none"> Thick (~2 to 5 m) beds showing sheet geometry Framework consists of angular to subrounded pebbles Concentration of pebbles varies vertically and laterally <p>The conglomerates are matrix-supported</p>	Sedimentation from ice-melt water in low sinuosity streams (Rust 1975; Gordon and Bridge 1987; Miall 1996; Zielinski and van Loon 1999a)
F3	Conglomerate with of crude cross-strata	<ul style="list-style-type: none"> Comparatively thinner beds than others Angular to subrounded pebbles Planar tabular cross-strata, defined by arrangement of pebbles <p>These conglomerates are clast supported</p>	Deposited during migration of bars under high energy flow glacial melt water in straight or braided streams within mid- or distal-fan setup (Reineck and Singh 1980; cf. Nilsen 1982; Opluštil <i>et al</i> 2005)
F4	Conglomerate with trough cross-strata	<ul style="list-style-type: none"> Bed thickness 0.75 cm to ~3 m Subrounded to rounded clasts Normal grading/no grading <p>Trough cross-stratification</p>	Migration of dune (Opluštil <i>et al</i> 2005) and shifting of stream channels accompanied by channel filling (Miall 1977) or by vertical aggradations of braided streams (Casshyap and Tewari 1984) typical in the mid-fan part
F5	Thick-bedded sandstone	<ul style="list-style-type: none"> Bed thickness 60 cm to ~1 m Sheet geometry Medium- to coarse-grained, occasionally pebbly Pebbles are angular and are haphazardly arranged in sandy–muddy matrix Show normal grading <p>Internal primary structures are almost absent</p>	Deposition from sheet-flood after waning of energy (e.g., Heward 1978; Demicco and Gierlowski 1986; Zavala 2008). Presence or absence of channelized deposits indicates either mid-fan or distal-fan setup (Blair and McPherson 1994; MacCarthy 1990; Sadler and Kelly 1993)

Table 4. (*Continued*).

Facies	Rock type	Attributes	Interpretation
F6	Tabular cross stratified and horizontal laminated sandstone	<ul style="list-style-type: none"> • Bed thickness up to 1 m • Medium-grained sandstone • Normal grading • Bedding parallel lamina, tabular cross-strata often with asymptotic base 	Down the current bar and dune migration in low sinuosity stream channels in mid-fan setup (Miall 1992, 1996; Cadle and Cairncross 1993; Zielinski and van Loon 1999b and references therein) or deposition in bars adjacent to channel banks (cf. Mazumder 2002)
F7	Sandstone with channel structure	<ul style="list-style-type: none"> • Bed thickness up to ~1 m • Medium to coarse-grained sandstone • Interlaced channel structures and trough cross-strata • Channels are of various dimensions • Bases of channels are often pebbly 	Deposition in a laterally coalescing stream channel system in the mid-fan setup (Tewari 1995; Opluštil <i>et al</i> 2005). Channel floors filled with pebbles indicate high-energy conditions in the proximal-fan zone (Fraser 1982; Zakir Hossain <i>et al</i> 2002)
F8	Fine-grained sandstone with horizontal lamination	<ul style="list-style-type: none"> • 10 to 35 cm thick beds • Plane laminated • Associated with shale and coarser rocks 	Facies F5, F6 and F7 suggest deposition within a braided river system in mid-fan setup (cf. Friend <i>et al</i> 1976; Kumar <i>et al</i> 2004; Scherer and Lavina 2006; Veiga and Spalletti 2007)
F9	Fine-grained sandstone–siltstone–shale (heterolithic facies)	<ul style="list-style-type: none"> • Thickness up to 60 cm • Mainly associated with shale and fine-grained sandstone 	Facies F8, F9 and F10 were deposited under lower flow conditions (Rust 1972; Cant 1978) from suspension load in shallow braided channels in distal-fan (Hartley 1993; Dreyer 1993) or are overbank deposits (Kumar and Tandon 1985; cf. Nichols and Fisher 2007)
F10	Siltstone and shale	<ul style="list-style-type: none"> • Storehouse of various soft-sediment deformation structures • Thickness up to 30 cm • Associated with all types of rocks • Often as capping of channel structures in sandstones and conglomerates 	

4.2 Sequence of facies associations

The present work includes a comprehensive account on associations of facies units and repetition of the facies associations in the Middle Siwalik sequence to understand the depositional environment and also aims to construct a broad stratigraphic sequence of the Middle Siwalik Subgroup exposed in the TVS of the Darjiling Himalaya. Within a particular broad depositional setup energy conditions may vary in different segments of the basin and also in different seasons. A facies association is a product of a series of sedimentary processes and interactions between them depicting a particular sedimentary environment (Neves *et al* 2005; Wysocka 2009). A facies sequence is the order of occurrence of facies or facies associations which have developed in response to a repetitive series of processes due to regular changes in conditions of sedimentation (Nichols 2009 and references therein). Hence, facies associations and sequences help to infer the sub-environments within a larger depositional setup. In the studied section of Middle Siwalik Subgroup, every facies appears a number of times and the sequence shows different facies associations from the bottom to the top. The associations and their repetitions are identified for the interpretation of the depositional setup.

In the TVS, the lowermost facies association is 30-m thick and is exposed in T3, T7 and T8a thrust sheets (figure 2). This association consists of conglomerate and sandstone units of facies F3, F4 and F6. In this part of the sequence, any facies of sub-sand grain-size is absent. This facies association is addressed as Fa1. The next, 44 m upward in the sequence from Fa1, the Fa2 sequence consists of an association of facies F5, F7, F8 and F9. In this association, coarse- to medium-grained sandstone, shale and siltstone appear for the first time, while the conglomerate is absent. Upward in the sequence, the next facies association, Fa3 is dominated by medium-grained sandstone and finer-grained rocks. This association is 30-m thick, begins with F6 and is dominated by this facies with one intercalated F4 conglomerate while the upper half consists of intercalation of F8, F9 and F10. This facies association can be identified in all thrust sheets in the Middle Siwalik and therefore it is used as the marker horizon for cross-section balancing (figure 1d and e), following the area balance method (Marshak and Mitra 1988). The next facies association, Fa4, comprises F1 and F2 conglomerate units and finer members namely F8, F9 and F10 and occupies ~25 m thickness above the underlying Fa3. This Fa4 is completely devoid of medium- or coarse- to medium-grained sandstone

units. The overlying association of 37 m thickness consists of F5, F7, F8, F9 and F10 and is devoid of any conglomerate unit. This association is similar to Fa2 and is thus named as Fa2. Upward, an association of 25 m thickness comprising F6, F8 and F9 with a single F4 conglomerate unit forms an association similar to that of Fa3. Overlying this is an 80-m thick pile of sandstone and finer sedimentary rocks. The member facies are F5, F7, F8, F9 and F10 with the coarser members dominating the lower portion of this association. The member facies are similar to Fa2 and the association is thus regarded as Fa2. The next upward association consists of F3, F4 and F6, without any siltstone–shale member. This association occupies a thickness of 30 m and the member facies are similar to Fa1. The top 20 m of the sequence consists of a facies association similar to Fa2. The Middle Siwalik sequence in the TVS thus indicates that each facies association appears more than once in the stratigraphic column. Hence, the 325 m thick lithostratigraphic column of the Geabdat Sandstone in the TVS is dominated by sandstone units. Conglomerate and siltstone–shale units are intercalated with the sandstone units. Conglomerates appear sporadically and is almost absent in the middle part of the sequence while the siltstone–mudstone units are distributed throughout the sequence excepting the lower part.

5. Interpretation

5.1 Depositional environment

A summary of interpretation of the facies units is presented in table 4. The cross-bedded conglomerate and sandstone in the associations Fa1 and Fa2 point to deposition from high-energy channelized flow. The laminated sand and finer sediments suggest deposition from overbank flows. Hence, these facies associations point to current and surface flood domination in high-energy regime and thus possibly indicate deposits of the mid-fan zone (c.f., Mishra *et al* 2004; Wysocka 2009 and references therein). Presence of interlaced channel structures in sandstones bodies are indicative of the braided nature of stream channels typical for the mid-fan setup, though possibility of proximal-fan environment cannot be fully ruled out as in-fills of coarser grain size indicate much higher energy condition of deposition characterizing a proximal fan environment. This is possible in tectonically active setup of foreland basins of a fold and thrust belt where repetitive thrust front propagation towards foreland may bring proximal fan environment over existing mid- or distal fan zones. Fa3, F8, F9 and

F10 facies indicate waning energy depositional conditions. Finer sand and shale of Fa3 are possibly deposited within shallow braided streams in distal fan setup (Mishra *et al* 2004 and references therein). Facies package in Fa4, is dominantly conglomeratic and appears to have been formed by high-energy gravity flow, typical to the proximal zone of an alluvial fan system (Mishra *et al* 2004; Neves *et al* 2005; Nichols and Fisher 2007 and references therein, Wysocka 2009 and references therein). Diamictites (F1) in Fa4 facies association might have deposited within a proglacial outwash zone (c.f., Maizels 1993, Zielinski and van Loon

1999a). This interpretation is supported by the fact that the Mio–Pliocene time was a period of intense glaciation on Himalayas (Gupta *et al* 2000 and references therein). From the sequence of facies associations (figure 2), it is evident that each association reappears with time reflecting spatial oscillation of proximal-, mid- and distal fan with time within an alluvial fan setup. This may be a result of a combination of foreland-ward migration of the mountain with propagation of Himalayan thrusts (Raiverman 2002) alternate with mountainward shift of the fan-apex due to erosion during tectonically quiet phases (figure 6).

Figure 6. Schematic diagram showing palaeogeographic and tectonic setup of the Middle Siwalik sedimentation in the TVS. (a) Formation of alluvial fan at the foreland basin at the initial phase (Fan1). (b) Migration of the fan (to the new phase Fan 2), basin ward shift of fan apex with foreland ward propagation of thrust and uplift of the hinterland. (c) Erosion at mountain front and adjacent hinterland in the tectonically quiet phase, migration of fan (Fan 3) with hinterland ward retreat of fan-apex. (d) Migration of the fan (to the new phase Fan 4), basin-ward shift of fan apex with foreland-ward propagation of thrust and uplift of the hinterland.

5.2 Provenance and palaeoclimate

Modal values of framework minerals suggest recycled orogenic source for the sediments constituting the Middle Siwalik Group rocks (figure 4a and b). Metamorphic or mixed metamorphic-acid plutonic rocks may be the sources of sediments containing monocrystalline quartz showing undulose extinction and polycrystalline quartz (Pettijohn *et al* 1972). Coexistence of quartz and feldspar grains with variable intensities of undulose extinction, quartz grains with intracrystalline deformation bands, plagioclase grains with deformed twin lamellae and warped and kinked mica flakes positively point to deformed source rocks. Character of the rock fragments in the framework points to metamorphic hinterland-like gneiss in the Greater Himalayan Crystalline terrain and quartzite, phyllite and muscovite-biotite schist in the Daling Group of Lesser Himalaya (Raina 1976; Yin 2006 and references therein; Bhattacharyya and Mitra 2009; Ranjan and Banerjee 2009).

Plots in the Q-F-RF diagram (figure 4c) of Suttner *et al* (1981) suggest that plutonic and metamorphic source rock and sediments were derived under humid climate. Intensely altered feldspars indicate long distance transport before deposition and/or humid palaeoclimate (Chaudhuri 1977). Presence of fresh as well as partly altered feldspars, together, suggests that the source was not far from the basin and the sediment underwent rapid deposition and negligible reworking (Basu 1976). Feldspars may be altered in both arid and humid climates (Basu 1976) though feldspars have a lesser chance of survival in humid climate. So, the presence of less altered to unaltered angular feldspars in these rocks point to quick burial, even under humid climatic condition (Basu *et al* 1975; Pettijohn 1975). Uplift of the source area and subsidence of basin might result in quick burial of sediment (Sengupta 1994). Coexistence of rounded and intensely or partly altered and angular unaltered feldspar grains points to mixing of grains of different sources at different distances from the depositional sites (Chaudhuri 1977).

6. Conclusions

The Middle Siwalik Subgroup in TVS is dominantly sandstone with subordinate conglomerate, siltstone and shale units. The character of the clasts in sandstones in the TVS suggests their derivation from spatially separated sources at different distance from the basin. Plutonic and metamorphic rocks from Lesser and Higher Himalayan thrust sheets undergoing uplift due to orogenic activity of the Himalayan mountain were the

sources of the sediments. Mineral character of the clasts and plots of modal values suggest that sediment transport and deposition took place in humid palaeoclimate. Analysis of sedimentary facies and sequence of facies associations reveal recurrence of proximal-, mid- and distal fan depositional conditions within an alluvial fan setup.

Acknowledgements

Abhik Kundu acknowledges University Grants Commission, India for the research grant PSW-22/06-07 (ERO). He also acknowledges supports from Dr D K Kar, Principal, Asutosh College. Abdul Matin acknowledges funding from DST, Govt. of India (Grant No. DST No. SR/S4/ES:276/2007 dated 04.06.2010). Malay Mukul acknowledges funding from IIT-B (Grant No. 09IRCC017). The authors thank Prof. Talat Ahmad and the anonymous reviewers for their constructive comments and suggestions that helped to improve the paper.

References

- Acharyya S K 1976 On the nature of the Main Boundary Fault in the Darjiling sub-Himalaya; *Geol. Surv. India Misc. Publ.* **24** 395–408.
- Acharyya S K 1994 The Cenozoic Foreland Basin and tectonics of the eastern sub-Himalaya: Problems and prospects; In: *Siwalik Foreland Basin of Himalaya* (eds) Kumar R, Ghosh S K and Phadtare N R, *Him. Geol.* **15** 3–21.
- Arribas J and Tortosa A 2003 Detrital modes in sedimentoclastic sands from first-order streams of the Iberian Range, Spain: The potential for sand generation of different sedimentary rocks; *Sedim. Geol.* **15** 275–303.
- Banerjee A and Banerjee D M 2010 Modal analysis and geochemistry of two sandstones of the Bhandar Group (Late Neoproterozoic) in parts of the Central Indian Vindhyan basin and their bearing on the provenance and tectonics; *J. Earth Syst. Sci.* **119**(6) 825–839.
- Banerji I and Banerji S 1982 A coalescing alluvial fan model of the Siwalik sedimentation – a case study in the eastern Himalaya; *Geol. Surv. India Misc. Publ.* **41** 1–12.
- Basak K and Mukul M 2000 Deformation mechanisms in the South Kalijhora Thrust and thrust sheet in the Darjiling Himalayan fold-and-thrust belt, West Bengal, India; *Indian J. Geol.* **72**(2) 143–152.
- Basu A 1976 Petrology of the Holocene fluvial sand derived from plutonic source rocks: Implications to palaeoclimatic interpretations; *J. Sedim. Petrol.* **46** 694–709.
- Basu A, Young S W, Suttner L J, James W C and Mark G H 1975 Re-evaluation of the use of undulatory extinction and polycrystallinity in detrital quartz for provenance interpretation; *J. Sedim. Petrol.* **45** 873–882.
- Bhattacharyya K and Mitra G 2009 A new kinematic evolutionary model for the growth of a duplex – an example from the Rangit duplex, Sikkim Himalaya, India; *Gondwana Res.* **16** 697–715.
- Blair T C and McPherson J G 1994 Alluvial fans – processes and forms; In: *Geomorphology of desert environments* (eds) Abrahams A D and Parsons A J (London: Chapman & Hall), pp. 354–402.

- Blenkinsop T 2002 *Deformation microstructures and mechanisms in minerals and rocks* (Dordrecht: Kluwer Academic Publishers), p. 150.
- Brozovic N and Burbank D W 2000 Dynamic fluvial systems and gravel progradation in the Himalayan foreland; *Geol. Soc. Am. Bull.* **112**(3) 394–412.
- Cadle A B and Cairncross B 1993 A sandy, bed-load dominated fluvial system deposited by lateral-accretion: Permian Karoo Sequence, South Africa; *Sedim. Geol.* **85**(1–4) 435–455.
- Cant D J 1978 Bedforms and bar types in the South Saskatchewan River; *Geol. Soc. Am. Bull.* **94** 117–133.
- Casshyap S M and Tewari 1984 Fluvial models of the Lower Permian coal measures of Son–Mahanadi and Koel–Damodar Valley basins, India; *Int. Assoc. Sedimentologists Spec. Publ.* **7** 121–147.
- Chaudhuri A 1977 Influence of eolian processes on Precambrian sandstones of the Godavari valley, South India; *Precamb. Res.* **4** 339–360.
- Critelli S and Ingersoll R V 1994 Sandstone petrology and provenance of the Siwauk Group (northwestern Pakistan and western–southeastern Nepal); *J. Sedim. Res. A* **64**(4) 815–823.
- Datta B 2005 Provenance, tectonics and palaeoclimate of Proterozoic Chandarpur sandstones, Chattisgarh basin: A petrographic view; *J. Earth Syst. Sci.* **114**(3) 212–226.
- DeCelles P G, Gehrels G E, Quade J, Ojha T P, Kapp P A and Upreti B N 1998 Neogene foreland basin deposits, erosional unroofing, and the kinematic history of the Himalayan fold and thrust belt, western Nepal; *Geol. Soc. Am. Bull.* **110** 2–21.
- Demico R V and Gierlowski Kordes E 1986 Facies sequences of a semi-arid closed basin: The lower Jurassic East Berlin Formation of the Hartford Basin, New England, USA; *Sedimentology* **33** 107–118.
- Dickinson W R 1985 Interpreting provenance relations from detrital modes of sandstones; In: *Provenance of Arenites* (ed.) Zuffa G G, NATO-ASI. V.C.-148 (Dordrecht: D. Reidel Publ. Co.), pp. 333–361.
- Dickinson W R, Beard S L, Brakenridge R G, Erjavec J L, Ferguson R C, Inman K F, Knepp R A, Lindberg F A and Ryherg P T 1983 Provenance of North American Phanerozoic Sandstones in relation to tectonic setting; *Geol. Soc. Am. Bull.* **94** 222–235.
- Dreyer T 1993 Quantified fluvial architecture in ephemeral stream deposits of the Esplugafreda Fm. (Paleocene), Tremp–Graus Basin, N Spain; *Int. Assoc. Sedimentologists Spec. Publ.* **17** 337–362.
- Fraser J Z 1982 Derivation of a summary facies sequence based on Markov chain analysis of the Caledon outwash: A Pleistocene raided glacial fluvial deposit; In: *Research in glacial, glacio-fluvial and glacio-lacustrine systems* (ed.) Davidson–Arnott R, Proceedings of VI Guelph Symposium on Geomorphology (1980), (Norwich: Geo Books), pp. 175–202.
- Friend P F, Alexander–Marrack P D, Nicholson J and Yeats A K 1976 Devonian sediments of the east Greenland II: Sedimentary structures and fossils; *Medd. Gr.* **206**(2) 1–91.
- Ganguly S and Rao D P 1970 Stratigraphy and structure of Tertiary foothills of the Eastern Himalaya, Darjiling Dist. West Bengal; *Quart. J. Geol. Min. Metall. Soc. India* **42** 185–195.
- Gansser A 1964 *Geology of the Himalayas* (New York: Wiley), p. 289.
- Garzanti E, Critelli S and Ingersoll R V 1996 Paleogeographic and paleotectonic evolution of the Himalayan range as reflected by detrital modes of Tertiary sandstones and modern sands (Indus transect, India and Pakistan); *Geol. Soc. Am. Bull.* **86** 273–286.
- Gordon E A and Bridge J S 1987 Evolution of Catskill (Upper Devonian) river systems: Intra- and extrabasinal controls; *J. Sedim. Petrol.* **57** 234–249.
- Gupta A K, Ahmad S M, Dayal A M and Gopalan K 2000 Is strontium isotope record a strict proxy for chemical weathering rates during the late Miocene (Ocean Drilling Program Site 758A); *Curr. Sci.* **79**(6) 899–902.
- Hartley A J 1993 Sedimentological response of an alluvial system to source area tectonism: The Seilao Member of the Late Cretaceous to Eocene Purilactis Fm. of N Chile; *Int. Assoc. Sedimentologist Spec. Publ.* **17** 489–500.
- Heim A and Gansser A 1939 Central Himalayas – Geological observations of Swiss expeditions, 1936; *Mem. Soc. Helv. Sci. Natur.* **73** 1–246.
- Heward A P 1978 Alluvial fan and lacustrine sediments from the Stephanian A and B (La Magdalena, Ciñera–Matallana and Sabero) coalfields, N Spain; *Sedimentology* **25** 451–488.
- Hodges K V 2000 Tectonics of the Himalaya and southern Tibet from two perspectives; *Geol. Soc. Am. Bull.* **112** 324–350.
- Kimura K 1999 Diachronous evolution of sub-Himalayan piggyback basins, Nepal; *Isl. Arc* **8**(1) 99–113.
- Kumar G 1997 *Geology of Arunachal Pradesh* (Bangalore: Geological Society of India), p. 217.
- Kumar R and Tandon S K 1985 Sedimentology of Pliocene late orogenic deposits associated with intra-plate subduction – The Upper Siwalik Sub group of a part of Punjab sub-Himalaya, India; *Sedim. Geol.* **42** 105–158.
- Kumar R, Ghosh S K and Sangode S J 2003 Mio-Pliocene sedimentation history in the northwestern part of the Himalayan foreland basin, India; *Curr. Sci.* **84**(8) 1006–1113.
- Kumar R, Sangode S J and Ghosh S K 2004 A multistorey sandstone complex in the Himalayan foreland basin, NW Himalaya, India; *J. Asian Earth Sci.* **23** 407–426.
- Kundu A and Matin A 2007 Sedimentary and tectonic environment of deposition of the Archaeian Birtola Formation; *Indian J. Geol.* **79**(1–4) 22–34.
- Kundu A, Matin A, Mukul M and Eriksson P G 2011 Sedimentary facies and soft-sediment deformation structures in the Late Miocene–Pliocene Middle Siwalik Subgroup, Eastern Himalaya, Darjiling District, India; *J. Geol. Soc. India* **78**(4) 321–336.
- MacCarthy I A J 1990 Alluvial sedimentation patterns in the Munster Basin, Ireland; *Sedimentology* **37** 685–712.
- Maizels J 1993 Lithofacies variations within sandur deposits: The role of runoff regime, flow dynamics and sediment supply characteristics; *Sedim. Geol.* **85** 299–325.
- Marshak S and Mitra G 1988 *Basic Methods of Structural Geology*; Englewood Cliffs (New Jersey: Prentice-Hall), p. 449.
- Matin A and Mukul M 2010 Phases of deformation from cross-cutting structural relationships in external thrust sheets: Insights from small-scale structures in the Ramgarh thrust sheet, Darjiling Himalaya, West Bengal; *Curr. Sci.* **99** 1369–1377.
- Mazumder R 2002 *Sedimentation history of the Dhanjori and Chaibasa formations, eastern India and its implications*; Unpublished Ph.D. thesis (Kolkata, India: Jadavpur University), p. 119.
- Medlicott H B 1864 On the geological structure and relations of the southern portion of the Himalayan ranges between the rivers Ganges and the Ravee; *Geol. Surv. India Memoir* **3**(2) 1–212.
- Miall A D 1977 A review of the braided-river depositional environment; *Earth-Sci. Rev.* **13** 1–62.

- Miall A D 1992 Alluvial deposits; In: *Facies models: Response to sea level change* (eds) Walker R G and James N P, Geological Association of Canada, pp. 119–142.
- Miall AD 1996 *The geology of fluvial deposits: Sedimentary facies, basin analysis, and petroleum geology* (Berlin: Springer-Verlag), p. 582.
- Mishra B, Pandya K L and Maejima W 2004 Alluvial Fan-lacustrine sedimentation and its tectonic implications in the Cretaceous Athgarh Gondwana Basin, Orissa, India; *Gondwana Res.* **7**(2) 375–385.
- Mukul M 2000 The geometry and kinematics of the Main Boundary Thrust and related neotectonics in the Darjiling Himalayan fold-and-thrust belt, West Bengal, India; *J. Struct. Geol.* **22** 1261–1283.
- Mukul M 2010 First-order kinematics of wedge-scale active Himalayan deformation: Insights from Darjiling–Sikkim–Tibet (DaSiT) wedge; *J. Asian Earth Sci.* **39** 645–657.
- Najman Y 2006 The detrital record of orogenesis: A review of approaches and techniques used in the Himalayan sedimentary basins; *Earth-Sci. Rev.* **74** 1–72.
- Najman Y and Garzanti E 2000 Reconstructing early Himalayan tectonic evolution and paleogeography from Tertiary foreland basin sedimentary rocks, northern India; *Geol. Soc. Am. Bull.* **112** 435–449.
- Nakata T 1972 *Geomorphic history and crustal movements of the Himalaya* (Aendai: Institute of Geography, Tohoku University), p. 77.
- Nakayama K and Ulak P D 1999 Evolution of fluvial style in the Siwalik Group in the foothills of the Nepal Himalaya; *Sedim. Geol.* **125** 205–224.
- Nemec W and Postma G 1993 Quaternary alluvial fans in southern Crete: Sedimentation process and geomorphic evolution; In: *Alluvial sedimentation* (eds) Marzo M and Puigdefabregas C, *Int. Assoc. Sedimentologists Spec. Publ.* **17** 235–276.
- Neves M A, Morales N and Saad A R 2005 Facies analysis of tertiary alluvial fan deposits in the Jundiá region, São Paulo, southeastern Brazil; *J. S. Am. Earth. Sci.* **19** 513–524.
- Nichols G 2009 *Sedimentology and stratigraphy*, 2nd edn (West Sussex: Wiley-Blackwell), p. 419.
- Nichols G J and Fisher J A 2007 Processes, facies and architecture of fluvial distributary system deposits; *Sedim. Geol.* **195** 75–90.
- Nilsen H 1982 Alluvial fan deposits; In: *Sandstone depositional environments* (eds) Scholle P A and Spearing D, *Mem. Am. Assoc. Petrol. Geol.* **31** 49–86.
- Opluštil S, Martínek K and Tasáryová Z 2005 Facies and architectural analysis of fluvial deposits of the Nýřany Member and the Týnec Formation (Westphalian D – Barruelian) in the Kladno–Rakovník and Pilsen basins; *Bull. Geosci.* **80**(1) 45–66.
- Pettijohn F J 1975 *Sedimentary Rocks*, 3rd edn (New York: Harper and Row), p. 718.
- Pettijohn F J, Potter P E and Siever R 1972 *Sand and sandstone* (New York: Springer), p. 618.
- Pilgrim G E 1906 Notes on the geology of a portion of Bhutan; *Rec. Geol. Surv. India* **34** 22–30.
- Pilgrim G E 1913 Correlation of the Siwalik with mammal horizon of Europe; *Rec. Geol. Surv. India* **43**(4) 264–326.
- Prasad K N 2001 *An introduction to the mammalian fauna of the Siwalik System* (Chennai: Prasad Publications), p. 295.
- Raina V K 1976 The Rangit Tectonic Window – stratigraphy, structure & tectonic interpretation and its bearing on the regional stratigraphy; *Geol. Surv. India Misc. Publ.* **41** 36–42.
- Raiverman V 2002 Foreland sedimentation, In: *Himalayan tectonic regime: A look at the orogenic process* (Dehradun, India: Bishen Singh Mahendra Pal Singh), p. 378.
- Ranjan N and Banerjee D M 2009 Central Himalayan crystallines as the primary source for the sandstone – shale suites of the Siwalik Group: New geochemical evidence; *Gondwana Res.* **16** 687–696.
- Reading H G and Levell B K 1996 Controls on the sedimentary record; In: *Sedimentary environments: Processes, facies and stratigraphy* (ed.) Reading H G (Oxford: Blackwell Science), pp. 5–36.
- Reineck H E and Singh I B 1980 *Depositional sedimentary environments* (Berlin: Springer), p. 549.
- Rust B R 1972 Structure and process in a braided river; *Sedimentology* **18** 221–246.
- Rust B R 1975 Fabric and structure of glaciofluvial gravels; In: *Glaciofluvial and glaciolacustrine sedimentation* (eds) Jopling A V and McDonald B C, *Soc. Eco. Paleontol. Mineral. Spec. Publ.* **23** 238–248.
- Sadler S P and Kelly S B 1993 Fluvial processes and cyclicity in terminal fan deposits: An example from the Late Devonian of southwest Ireland; *Sedim. Geol.* **85** 375–386.
- Scherer C M S and Lavina E L C 2006 Stratigraphic evolution of a fluvial–eolian succession: The example of the Upper Jurassic–Lower Cretaceous Guar and Botucatu formations, Paran Basin, Southernmost Brazil; *Gondwana Res.* **9** 475–484.
- Selley R C 1985 *Ancient Sedimentary Environments*, 2nd edn (London: Chapman and Hall), p. 317.
- Sengupta S 1994 *Introduction to sedimentology* (Calcutta, India: Oxford & IBH), p. 314.
- Sharma M, Sharma S, Shukla U K and Singh I B 2002 Sandstone body architecture and stratigraphic trends in the Middle Siwalik succession of the Jammu area, India; *J. Asian Earth Sci.* **20** 817–828.
- Suttner L J, Basu A and Mack G H 1981 Climate and the origin of quartz arenites; *J. Sedim. Petrol.* **51** 1235–1246.
- Tewari R C 1995 Braided fluvial depositional model of Late Triassic Gondwana (Mahadeva) rocks of Son valley, Central India, Tectonic and paleogeographic implications; *J. Geol. Soc. India* **45** 65–74.
- Ullah K, Arif M and Shah M T 2006 Petrography of sandstones from the Kamlial and Chinji Formations, southwestern Kohat Plateau, NW Pakistan: Implications for source lithology and palaeoclimate; *J. Him. Earth Sci.* **39** 1–13.
- Veiga G D and Spalletti L A 2007 The Upper Jurassic (Kimmeridgian) fluvial–aeolian systems of the southern Neuqun Basin, Argentina; *Gondwana Res.* **11** 286–302.
- White N M, Pringle M, Garzanti E, Bickle M, Najman, Y, Chapman H and Friend P 2002 Constraints on the exhumation and erosion of the High Himalayan Slab, NW India, from foreland basin deposits; *Earth Planet. Sci. Lett.* **195** 29–44.
- Wysocka A 2009 Sedimentary environments of the Neogene basins associated with the Cao Bang–Tien Yen Fault, NE Vietnam; *Acta Geol. Pol.* **59**(1) 45–69.
- Yin A 2006 Cenozoic tectonic evolution of the Himalayan orogen as constrained by along-strike variation of structural geometry, exhumation history, and foreland sedimentation; *Earth-Sci. Rev.* **76** 1–131.
- Zakir Hossain H M, Sultan-Ul-Islam M, Ahmed S S and Hossain I 2002 Analysis of sedimentary facies and depositional environments of the Permian Gondwana sequence in borehole GDH-45, Khalaspir Basin, Bangladesh; *Geosci. J.* **6**(3) 227–236.
- Zavala C 2008 Towards a genetic facies tract for the analysis of hyperpycnal deposits; American Association of Petroleum Geologists, Hedberg Conference, March 3–7, Ushuaia–Patagonia, Argentina, Abstracts, pp. 50–51.

- Zielinski T and van Loon A J T 1999a Subaerial terminoglacial fans I: A semi-quantitative sedimentological analysis of the proximal environment; *Geol. Mijnbouw-N. J. G.* **77** 1–15.
- Zielinski T and van Loon A J T 1999b Subaerial terminoglacial fans II: A semi-quantitative sedimentological analysis of the middle and distal environments; *Geol. Mijnbouw-N. J. G.* **78** 73–85.
- Zielinski T and van Loon A J T 2000 Subaerial terminoglacial fans III: Overview of sedimentary characteristics and depositional model; *Geol. Mijnbouw-N. J. G.* **79** 93–107.

MS received 15 October 2010; revised 26 September 2011; accepted 1 October 2011