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Petrography of the Siwalik sandstones, Amlekhganj-Suparitar area, central Nepal Himalaya

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ABSTRACT

Middle Miocene to early Pleistocene sedimentary sequence deposited in the foreland basin of the Himalaya is represented by the Siwalik Group. In the present study area the Siwalik Group extends in a NW-SE direction and well-exposed. Forty-four sandstone samples were studied for texture, fabric and composition in order to assess their petrographic properties and variation trends of these properties in stratigraphic levels. Sandstones were classified into sublitharenite, subarkose, lithic arenite, arkosic arenite and feldspathic graywacke and further thirteen sub-clans. Mean grain size (M_z) and Trask sorting coefficient (So) increase up-section. Recalculated quartz, matrix, modified maturity index (MMI), total cement (C_t), cement versus matrix index (CMI) and ratio of strong cement over total cement ($(C_{fc}+C_s)/C_t$) also increase, whilst packing proximity (PP), packing density (PD) and consolidation factor (Pcc) decrease up-section showing distinct trends, and therefore, these properties are promising in recognizing the older sandstones from the younger ones.

INTRODUCTION

More than 6 km thick, middle Miocene to early Pleistocene sedimentary succession distributed in the foreland basin of the Himalaya is known as the Siwalik Group, which is bounded between the Main Boundary Thrust (MBT) in the north and the Main Frontal Thrust (MFT) in the south (Fig. 1). The river systems brought detritus mainly from the low- to high-grade metamorphic, sedimentary and crystalline rocks from the Himalaya in the north (Chaudhri 1982; Tokuoka et al. 1986; Hisatomi 1992; Critelli and Ingersoll 1994; DeCelles et al. 1998). The detritus then underwent subsequent changes and lithification.

Mudstone, sandstone and conglomerate constitute the major rock types from the older to younger succession of the Siwalik Group. Sandstones are distributed extensively in the Siwalik Group and vary widely in types in stratigraphic levels. Changes in provenance (Chaudhri 1982; Critelli and Ingersoll 1994; DeCelles et al. 1998), fluvial system and climate (Nakayama and Ulak 1999), and post-depositional features (Chaudhri 1982; Tamrakar 1998) were studied earlier for the Siwalik sandstones. These factors probably have bearing on overall variation of sandstones in vertical sequence. Besides, post depositional changes in sediments can also modify original signatures in sediments (McBride 1985).

Although several studies on the Siwalik rocks of Nepal have been made, systematic description of sandstones and their petrographic properties have not been well treated yet. This study assesses quantitatively the texture, fabric and composition of sandstones and categorises sandstones into petrographic divisions for understanding how petrographic properties vary in time and space, and which of these properties shows better trend in distinguishing sandstones from different stratigraphic levels. Also, documentation of quantitative petrographic parameters may be useful in correlating such parameters with physical and mechanical properties of sandstones.

GEOLOGICAL SETTING

The Siwalik Group in the study area is bounded between the Samari Thrust (ST) and the MFT respectively in north and south (Fig. 1 and 2). Two major thrust sheets, extending roughly NW-SE and dipping regionally towards northeast, occupy the Siwalik Group. One of the sheets lies between the MFT and the Central Churia Thrust (CCT) and the other

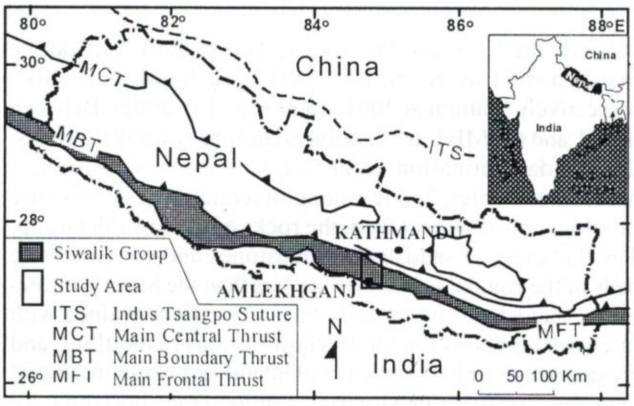

Fig. 1: Location map of the study area

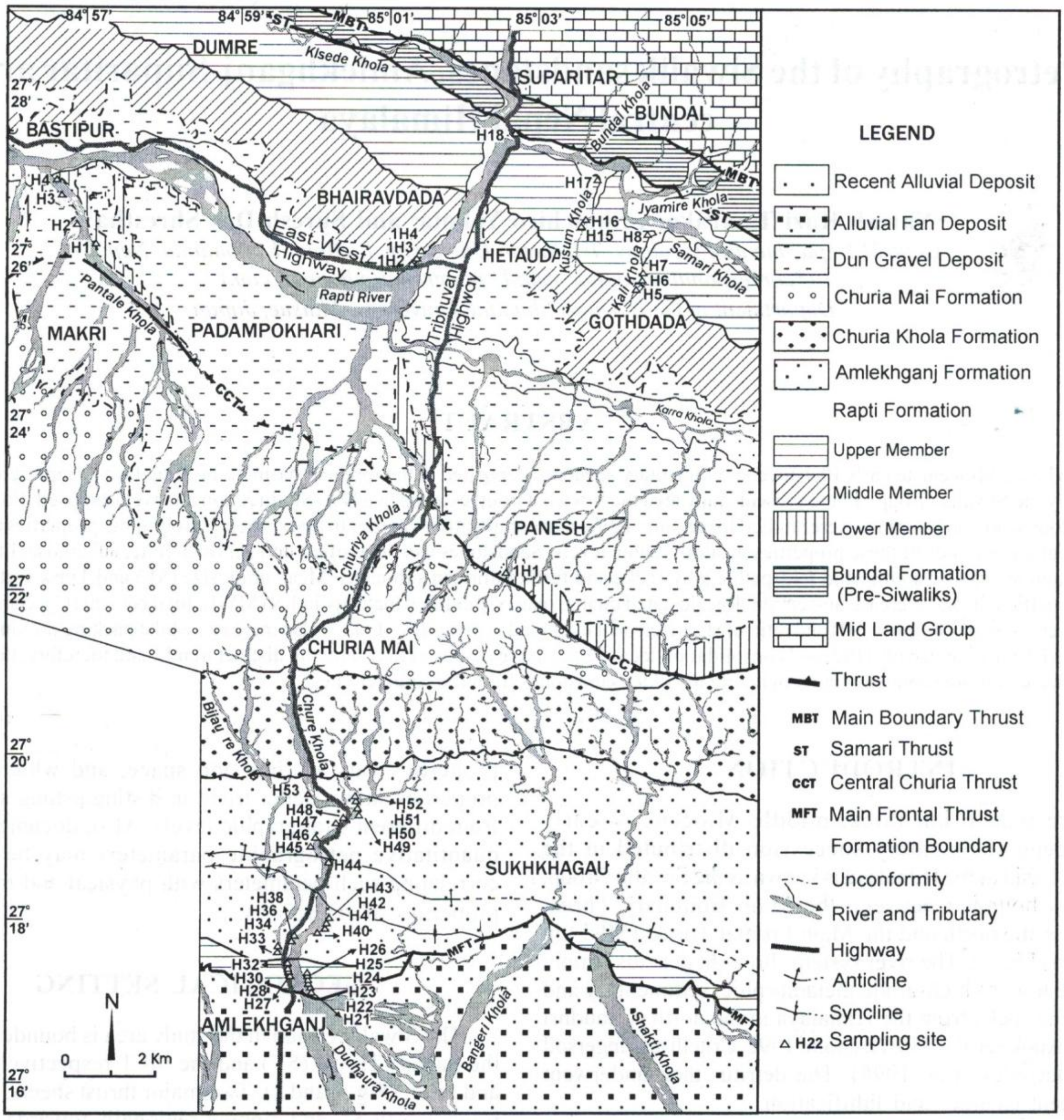

Fig. 2: Geology of the Siwalik Group in Amlekhganj-Suparitar area (compiled from Sah et al. 1994; Kimura 1995; Ulak and Nakayama 1998; Tamrakar and Khakurel 2000; Tamrakar and Khakurel 2001; and Tamrakar 2001) showing sampling sites of sandstones

between the CCT and the Samari Thrust (ST), and can be distinguished as North belt (NB) and South belt (SB), respectively (Tamrakar 2001; Tamrakar et al. 2002). Between the ST and the MBT are distributed the pre-Siwalik (?) rocks; the Bundal Formation comprising sandstones, siltstones, mudstones, shales, and few conglomerates. These rocks are lithologically different from the rocks of the Siwalik Group. The thickness of sandstones, mudstones and conglomerate beds of the Bundal Formation are less than the Siwalik Group rocks. Sandstones are usually fine- to medium-grained with often ferruginous concretion showing purple mottling, and are quartzose with low mica content and are better indurated than the Siwalik sandstones. Conglomerate horizons are pebbly quartzite-clast dominant and are rather compact with siliceous cement and quartzose sand matrix. These conglomerates differ with those of the Middle Siwaliks, which are usually polymictic with quartzo-feldspathilithic matrix. The Bundal Formation is overlain by slates and carbonate rocks of the Midland Group.

Older to younger units of the Siwalik Group comprise mainly of mudstones, sandstones and conglomerates. The group attains more than 5.5 km thickness and ranges in age from >11 to <3 Ma (Fig. 3). The Siwalik Group is divided into the Rapti, Amlekhganj, Churia Khola and Churia Mai formations in ascending order (Sah et al. 1994). The Rapti Formation is subdivided into the Lower Member (Rl), Middle Member (Rm) and Upper Member (Ru). The Rapti Formation

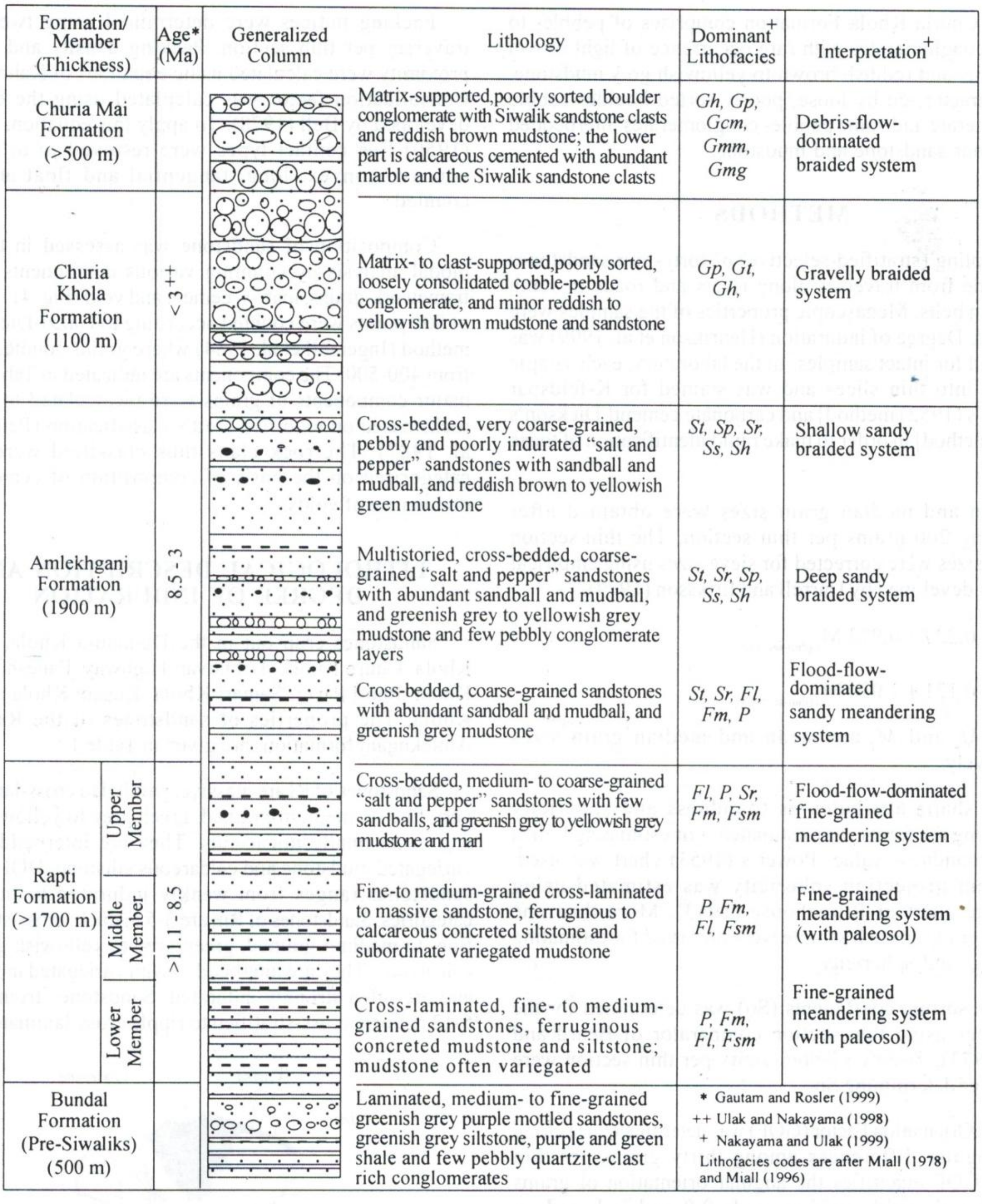

Fig. 3: Lithostratigraphic column and lithofacies assemblages of the Siwalik Group

is distributed mainly in NB and part of its Upper Member is distributed in SB. The Amlekhganj, Churia Khola and Churia Mai formations are distributed only in SB.

The Rapti Formation comprises of fine- to medium-grained sandstone interbedded with variegated mudstone, shale and siltstone. Sandstones gradually become coarser in the upper part and exhibit "salt-and-pepper" texture. Multi-storied, planar to trough cross-bedded, medium- to coarse-grained 'salt and pepper' sandstones characterise the Amlekhganj Formation. These sandstones are interbedded with green grey to light brown mudstone. Rl and Rm of the Rapti Formation can be interpreted as meandering river deposits (Fig. 3), whereas Ru and the Amlekhganj Formation can be interpreted respectively as sandy meandering river deposit and sandy to gravelly braided river deposits (Nakayama and Ulak 1999).

The Churia Khola Formation comprises of pebble- to cobble-conglomerates with rare occurrence of light brown sandstone, and reddish brown to yellowish grey mudstone. It is characterised by loose, poorly sorted boulder-cobble conglomerate and some pebble- conglomerates interbedded with minor sandstone and mudstone.

METHODS

Sampling (stratified-selective) of forty-four sandstones was made from traverses along rivers and roads in south and north belts. Megascopic properties of the samples were recorded. Degree of induration (Henrikson et al. 1999) was estimated for intact samples. In the laboratory, each sample was cut into thin slices and was stained for K-feldspar [Chayes's (1952) method] and carbonate cement[Dickson's (1966) method] in order to make rapid identification of those minerals.

Mean and median grain sizes were obtained after measuring 200 grains per thin section. The thin-section derived sizes were corrected for sieve sizes using empirical equation developed by Harrell and Eriksson (1979).

$$M_z = 0.227 + 0.973\ M_{z\,(thin\text{-}section)}$$

$$M_d = 0.121 + 1.030\ M_{d\,(thin\text{-}section)}$$

where, M_z and M_d are mean and median grain sizes respectively.

Two shape attributes as roundness and sphericity (expressing the form) were estimated. For estimating Folk's (1955) roundness value, Power's (1953) chart was used. Maximum projection sphericity was estimated using silhouette chart of Rittenhouse (1943). More than one hundred grains in each sample were observed for estimating roundness and sphericity.

Trask sorting coefficients (So) was determined for the sandstones using thin section comparator of Beard and Weyl (1973). Twenty random views per thin section were applied for determining So.

Grain Orientation Factor (GOF) was determined measuring acute angular differences among thirty grains per thin section. GOF quantifies the angular orientation of grains whose length/width ratio exceeds 2.0 and is based on calculation of angle factor proposed by Howarth and Rowland (1986). GOF is expressed as

$$GOF = \sum_{i=1}^{6} \{(AADi/(N(N-1)/2)).i\}i$$

where, AAD = Acute Angular Difference between each and every grains calculated for N grains, the expression N(N-1)/2 = unique angular difference and i = class weighting (herein six classes at the interval of 15 degrees between 0 and 90 degrees).

Packing indices were determined using twenty-five traverses per thin section. Packing density and packing proximity were calculated using equations of Kahn (1956). Consolidation factor was calculated using the equation developed by Bell (1978). To apply this equation, Taylor's (1950) five contact types were resolved in to sutured, concavo-convex, long, tangential and float and were counted.

Composition of sandstone was assessed in terms of modal analysis by counting various components such as framework-grains, matrix, cement and void (Fig. 4). The total of 800 points were counted according to Gazzi-Dickinson's method (Ingersoll et al. 1984) where grains counted ranged from 400-500. The components are indicated in Table 3. The major components of grains were recalculated to classify rocks based on modified Dott's classification (Pettijohn et al. 1987). The rock clans thus classified were futher categorised on the basis of composition of cement, and dominance of voids.

LITHOLOGICAL DESCRIPTION AND DEGREE OF INDURATION

Sandstones crop out in the Dudhaura Khola, Bijaure Khola, Chure Khola, Tribhuvan Highway, Panesh, Pantale Khola, Rapti River, Samari Khola, Kusum Khola and Kali Khola. The properties of sandstones of the Rapti and Amlekhganj formations are given in Table 1.

Sandstones of Rl are massive, parallel to cross-laminated, very fine- to medium-grained, green grey to yellowish grey and occasionally micaceous. They are interbedded with variegated mudstone and calcareous siltstone. DOI of these sandstones ranges from weakly indurated to indurated categories. Sandstones of Rm are 3-5 m thick, cross-stratified, fine- to medium-grained, green grey to yellowish grey and calcareous. They are interbedded with variegated mudstones and are often strongly indurated. Sandstones from Ru are 5-12 m thick, cross-stratified to ripple cross-laminated, fine-

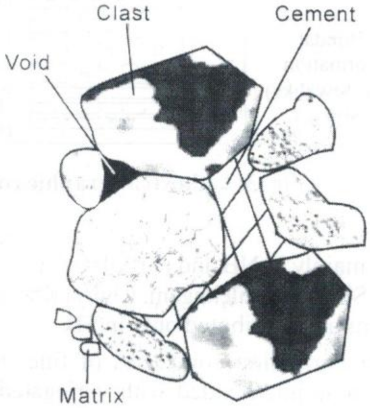

Fig. 4: Components of sandstone illustrating clasts, matrix, cement and void

to coarse-grained "salt-and-pepper" textured and geen grey to yellowish grey, which are intercalated with dark grey to yellow mudstones and shale. Samples from Ru (Kali and Kusum kholas) are weakly indurated to indurated, whereas those from the Dudhaura Khola are weakly to strongly indurated.

Sandstones of the Amlekhganj Formation crop out in the Bijaure and Chure Kholas. Samples from the Amlekhganj Formation are weakly indurated to strongly indurated. Sandstones from the lower part of the formation are trough to planar cross-stratified, ripple cross-laminated and medium- to coarse-grained. In the middle part of the formation, other sandstones become multistoried. Grain size in sandstones increases and becomes coarse-grained and sometimes pebbly "salt-and-pepper" textured. They are interbedded with reddish brown to yellowish green mudstones. Magnitudes of sandstone bed thickness and grain size increase upsection.

DOI does not show distinct trend of variation in stratigraphic level (Fig. 5) and does not correlate well with age of the sandstones, but tends to correlate with types and amount of cement content.

TEXTURE AND FABRIC

The results of grain size, grain shape, Trask sorting coefficient, GOF, and packing indices are indicated in Table 1.

Grain size

M_z and M_d ranges from 3.12ϕ to 0.77ϕ and from 3.16ϕ to 0.51ϕ respectively. Mean and median grain sizes increase

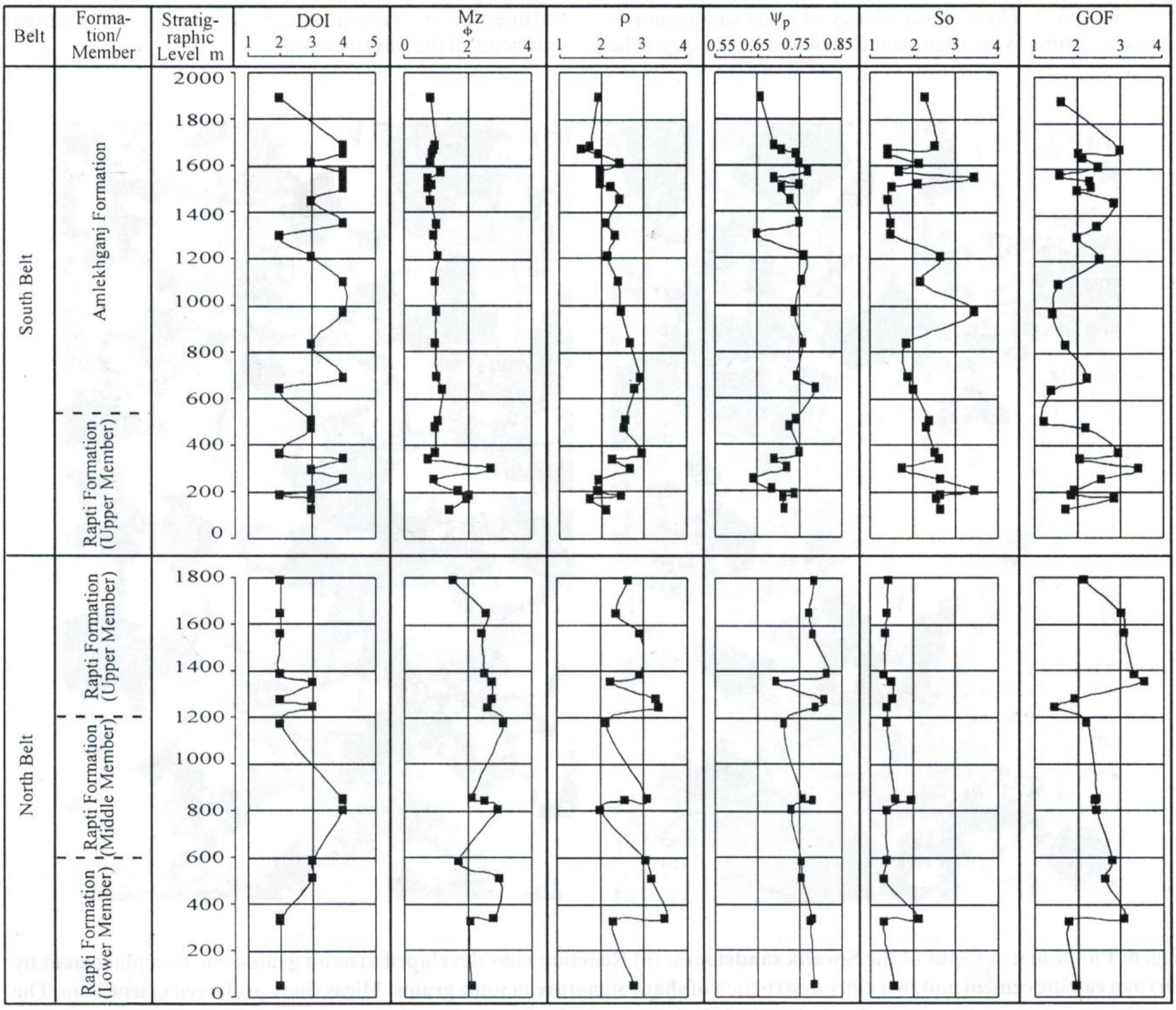

Fig. 5: Stratigraphic variation trends of degree of induration and textural parameters

gradually from the older to younger horizons (decrease in ϕ-value indicates increase in grain size up-section) (Fig. 5). Gradual increase in grain size up-section in the stratigraphic level indicates change in river systems from meandering to briaded (Ulak and Nakayama 1998), increase in relief and nearing of source rocks.

Grain shape

Barrett (1980) resolved form as an independent parameter of roundness and surface texture. Sneed and Folk (1958) considered form as an overall grain shape and introduced maximum projection sphericity based on three orthogonal axes.

Roundness of quartz-grains of the Siwalik sandstones ranges from subrounded to angular. The younger sandstones from SB possess subangular to angular grains (ρ=1.54-2.97) compared to the older sandstones from NB possessing mostly subrounded to subangular grains (ρ=2.02-3.35). There is a tendency of older sandstones to possess grains with high roundness and sphericity. The overall variation trends of roundness and maximum projection sphericity are roughly decreasing up-section (Fig. 5). This is attributed to textural immaturity of the younger sediments. However, both shape attributes were affected to some instances by reaction of cement with grains during diagenesis. Such reaction is remarkable in sandstones from SB (Fig. 6a). Therefore, the shape of quartz attained during sedimentation could have been somewhat modified by post-depositional changes.

Trask sorting coefficient

The Siwalik sandstones are well sorted (So=1.33) to very poorly sorted (So=3.46). Most of the sandstones are poorly sorted to moderately-well sorted and few well sorted to very poorly sorted. The sorting gradually diminishes up-section (So values increase, Fig. 5). Older sandstones from NB are fairly well sorted (Fig. 6b) compared to those from the SB (Fig. 6a). It suggests relatively low gradient and efficient reworking of the older sediments and high gradient and rapid sedimentation without much sorting of the younger sediments of the Siwalik Group.

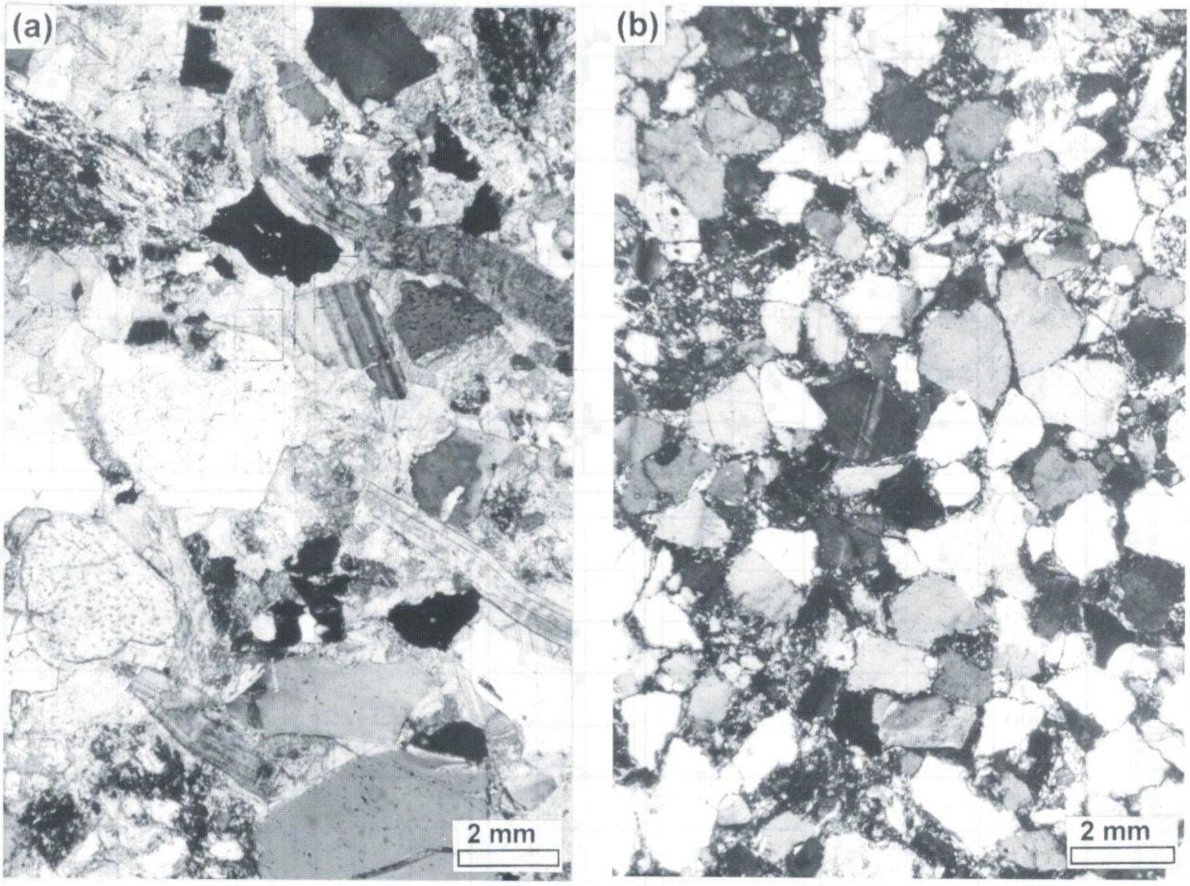

Fig. 6: Photomicrographs of the Siwalik sandstones: (a) Reaction rims developed around grains due to replacement by ferroan calcitic cement and therefore destruction of shape signature in some grains. Micas show preferred orientation. The mica in the upper right corner shows ductile deformation. (b) Well sorted grains in subarkose of the Ru (NB) in which cements are mostly ferruginous, and less argillaceous and siliceous

Grain Orientation Factor

GOF ranges between 1.22 and 3.45 showing fluctuating trend. Some sandstones from NB posses low GOF (1 to 2) and show rearrangement of grains under compaction. In some sandstones therein, authigenic micas exhibit fabric of preferred arrangements between highly interlocked framework constituents. Such preferred-orientation fabric was probably produced during deep burial diagenesis where authigenic micas tend to arrange perpendicular to the greatest principal stress axis. Other sandstones from NB show less preferred orientation fabric, as they possess fine grains, having high sphericity and well sorting.

Sandstones with large amount of pelitic rock fragments and micas tend to exhibit preferred orientation (Fig. 6a) which can be attributed to depositional fabric. The latter would be modified later by overburden pressure, as indicated by deformed micas (Fig. 6a). As mica and pelitic rock fragments are often ductile, sandstones composing microlaminae produced by such grains, possess ductile behavior upon loading (Tamrakar et al. 1999). Some sandstones, although composing substantial micas and pelitic rock fragments, show random arrangement of poorly sorted grains, and possess disordered fabric. Poorly sorted and randomly oriented grains in sandstones from Rl and the Amlekhganj Formation suggest rapid deposition of sediments.

Packing proximity and packing density

Packing reflects the mutual and spatial relationships among the grains. The concept of packing can be resolved into two basic aspects which Kahn (1956) proposed Packing Proximity (PP) and Packing Density (PD). PP is the ratio of number of grain-to-grain contacts in the traverse to the total number of contacts encountered in the traverse. PD is measured as a ratio of total no of grain intercepts to the traverse length and is concerned with closeness or spread of grains. Both packing proximity and packing density are expressed in percentage.

PP and PD vary from 11 to 72% and 59 to 94%, respectively. Sandstones from NB possess higher PP and PD than those from SB (Table 1). It indicates that grains in older sandstones are in closely packed and frequently in contact with another grains compared to those in the younger sandstones. In the latter, low PP and PD are due to occlusion of pores and replacement of grains by cement.

Consolidation factor

Consolidation factor (Pcc), which is expressed as a percentage of theoretical consolidation (Bell, 1978), is defined as

$$Pcc = \frac{5Su + 4Cc + 3Lo + 2Ta + Fl}{500} 100$$

where, Su = % sutured contacts, Cc = % concavo-convex contacts, Lo = % long contacts, Ta = % tangential contacts and Fl = % float contacts or non-contact.

Pcc varies between 23 and 65%. Decreasing trends of Pcc from the older to the younger sandstones can be clearly observed (Table 1) and indicate that the older sandtones are more consolidated than the younger ones.

COMPOSITION

The Siwalik sandstones show wide range of composition (Table 2). Framework constituents dominate often, however cement forms a remarkable component in the younger sandstones.

Framework

The total framework grains range between 46 and 75%. In majority, volume of the framework grains is contributed predominantly by quartz, which varies from 23 to 66%. Quartz grains are polycrystalline (up to 20%) to monocrystalline (20 to 61%). The monocrystalline quartz grains are undulosed and few non-undulosed. Polycrystalline quartz also includes chert. The quartz content is fairly high in sandstones from the Rapti Formation of NB but there is no distinct trend of variation of recalculated quartz as well as polycrystalline quartz in stratigraphic level (Table 2 and Fig. 7).

The total feldspar content ranges from 3 to 16%. Feldspars are of both K-feldspar and plagioclase varieties. They occur in almost all the sandstones and there is no distinct trend of decrease or increase of each variety. However, K-feldspar exceeds plagioclase in majority of the sandstones.

Lithic fragments are of quartz-mica tectonite, quartz-mica aggregate, quartz-mica-feldspar aggregate, and argillite-shale. The former varieties appear more frequently in the younger rocks of SB. They are often metamorphic and rarely sedimentary and crystalline rock fragments.

Lithic fragments vary from 0 to 25% and increase in proportion in sandstones from Ru (SB) and the Amlekhganj Formation. Similar increase of lithic fragments were suggested by Tokuoka et al. (1986), Hisatomi (1992) and Dhital et al. (1995).

Micas form remarkable proportion in the Siwalik sandstones, and range between 1 and 18%. Chlorite and muscovite are common constituents in sandstones from the Rapti Formation of NB. Biotite increases in proportion in coarse-grained sandstones of the Amlekhganj Formation. Tokuoka et al. (1986) and Hisatomi (1992) mentioned increase in mica content from the older to younger units of the Siwalik Group in west Central Nepal. Dense minerals form minor constituents in studied sandstones.

Matrix

Matrix varies from 0 to 18% of the modal composition of sandstones. It ranges from 3 to 18% in sandstones from the Rapti Formation (NB) and from 1 to 10% in sandstones from Rl (SB). In sandstones from the Amlekhganj Formation, matrix

Table 1: Sedimentary parameters of samples

Formation/	Member	Sample No.	Stratigraphic level m	Structure	Colour	DOI	Grain Size (ϕ) *M_z	Grain Size (ϕ) *M_d	Grain Shape ρ	Grain Shape ψ_p	Trask Sorting Coefficient, So	Grain Orientation Factor	PP %	PD %	Pcc %
Rapti Formation (North Belt)	Lower Member	1H1	51	Ms	yellowish grey	2	2.13 (F)	2.15	2.8 (SA)	0.79 (HS)	1.58 (MWS)	1.98	62.0	94.0	55.4
		H1	327	Cp	grey	2	2.11 (F)	2.11	2.32 (SA)	0.78 (HS)	1.35 (WS)	1.81	67.0	91.0	65.2
		H2	337	Ms	green grey	2	2.80 (F)	2.89	3.5 (SR)	0.78 (HS)	2.15 (PS)	3.10	60.0	92.0	59.6
		H3	510	Cp	green grey	3	3.01 (VF)	3.02	3.18 (SR)	0.76 (HS)	1.35 (WS)	2.65	52.0	85.0	53.8
		H4	585	Cp	yellowish grey	3	1.74 (M)	1.75	3.06 (SR)	0.76 (HS)	1.40 (MWS)	2.82	62.0	92.0	60.8
	Middle Member	1H2	802	Cp	green grey	4	2.97 (F)	2.97	2.02 (SA)	0.73 (MS)	1.40 (MWS)	2.46	61.0	89.0	48.6
		1H3	843	Ms	green grey	4	2.55 (F)	2.66	2.58 (SA)	0.78 (HS)	1.98 (MWS)	2.43	56.0	90.0	58.2
		1H4	852	Cp	light grey	4	2.15 (F)	2.14	3.08 (SR)	0.76 (HS)	1.61 (MWS)	2.45	64.0	94.0	64.4
		H5	1173	Ms	yellowish grey	2	3.12 (VF)	3.16	2.16 (SA)	0.71 (MS)	1.40 (MWS)	2.23	54.0	89.0	54.8
	Upper Member	H6	1243	Cr	grey	3	2.64 (F)	2.75	3.35 (SR)	0.79 (HS)	1.40 (MWS)	1.46	72.0	94.0	61.4
		H7	1278	Ms	yellowish grey	2	2.77 (F)	2.82	3.28 (SR)	0.81 (HS)	1.54 (MWS)	1.95	61.0	93.0	55.0
		H15	1352	Ms	green grey	3	2.76 (F)	2.81	2.26 (SA)	0.70 (MS)	1.50 (MWS)	3.57	68.0	89.0	60.8
		H16	1386	Ct-Ms	light grey	2	2.54 (F)	2.61	2.93 (SA)	0.82 (HS)	1.33 (WS)	3.32	54.0	90.0	52.8
		H8	1561	Ms	yellowish brown	2	2.44 (F)	2.48	2.93 (SA)	0.78 (HS)	1.37 (WS)	3.09	44.0	91.0	46.0
		H17	1648	Cp	yellowish grey	2	2.58 (F)	2.65	2.37 (SA)	0.77 (HS)	1.39 (WS)	3.03	58.0	92.0	50.4
		H18	1785	Cp	yellowish grey	2	1.53 (M)	1.44	2.65 (SA)	0.78 (HS)	1.45 (MWS)	2.13	71.0	95.0	60.8
Rapti Formation (South Belt)	Upper Member	H21	122	Cp	light grey	3	1.44 (M)	1.40	2.11 (SA)	0.71 (MS)	2.65 (PS)	1.72	34.0	78.0	36.6
		H22	168	Cp	light grey	3	1.96 (M)	1.96	1.72 (A)	0.71 (MS)	2.58 (PS)	2.86	33.0	72.0	33.4
		H23	185	Cp	light grey	2	2.07 (F)	2.03	2.48 (SA)	0.74 (MS)	2.68 (PS)	1.88	46.0	83.0	36.0
		H24	203	Ct	light grey	3	1.72 (M)	1.61	1.89 (A)	0.68 (MS)	3.46 (VPS)	1.92	36.0	75.0	32.4
		H25	252	Ms-Ct	light grey	4	0.95 (C)	0.90	1.94 (A)	0.64 (LS)	2.68 (PS)	2.58	22.0	72.0	28.4
		H26	296	L	light grey	3	2.74 (F)	2.79	2.68 (SA)	0.72 (MS)	1.77 (MWS)	3.45	37.0	73.0	31.4
		H27	338	Cp-L	light grey	4	0.78 (C)	0.71	2.26 (SA)	0.69 (MS)	2.63 (PS)	2.06	31.0	78.0	30.6
		H28	365	Ct	yellowish grey	2	0.99 (C)	0.92	2.97 (SA)	0.75 (MS)	2.55 (PS)	2.98	52.0	83.0	37.2
		H30	474	Cp-L	light grey	3	0.99 (C)	0.91	2.55 (SA)	0.73 (MS)	2.32 (PS)	2.21	31.0	83.0	31.9
		H32	504	Cp	grey	3	1.08 (M)	0.98	2.57 (SA)	0.74 (MS)	2.41 (PS)	1.22	29.0	70.0	31.0
Amlekhganj Formation (South Belt)		H33	639	Cp-Ct	grey	2	1.22 (M)	1.19	2.77 (SA)	0.79 (HS)	2.05 (PS)	1.42	47.2	77.0	39.3
		H34	692	Ms	light grey	4	1.05 (M)	0.96	2.91 (SA)	0.74 (MS)	1.90 (MWS)	2.24	31.8	80.0	32.1
		H36	835	Ct-Cp	light grey	3	1.01 (M)	0.93	2.67 (SA)	0.76 (HS)	1.87 (MWS)	1.73	33.8	79.0	33.3
		H38	970	Cp	light grey	4	1.05 (M)	0.97	2.48 (SA)	0.74 (MS)	3.45 (VPS)	1.44	32.4	73.0	31.1
		H40	1100	Cp	light grey	4	0.99 (C)	0.92	2.38 (SA)	0.76 (HS)	2.20 (PS)	1.58	33.8	78.0	31.0
		H41	1208	Cp	light grey	3	1.07 (M)	0.98	2.16 (SA)	0.76 (HS)	2.68 (PS)	2.55	46.5	80.0	34.0
		H42	1299	Cp-L	light grey	2	0.94 (C)	0.88	2.33 (SA)	0.65 (MS)	1.51 (MWS)	1.99	25.0	70.0	26.6
		H43	1350	Cp-L	light grey	4	1.05 (M)	0.97	2.12 (SA)	0.75 (HS)	1.51 (MWS)	2.45	19.6	60.0	25.6
		H44	1450	Cp-L	light grey	3	0.87 (C)	0.83	2.44 (SA)	0.73 (MS)	1.42 (MWS)	2.87	14.2	61.0	23.4
		H45	1505	Cp-L	light grey	4	0.77 (C)	0.72	2.22 (SA)	0.71 (MS)	1.52 (MWS)	2.00	17.4	64.0	25.5
		H46	1519	L	light grey	4	0.88 (C)	0.84	1.99 (A)	0.75 (HS)	2.13 (PS)	2.35	22.2	65.0	25.6
		H47	1543	Cp-L	grey	4	0.77 (C)	0.51	1.97 (A)	0.69 (MS)	3.45 (VPS)	2.31	23.4	68.0	26.5
		H48	1573	Cp-L	grey	4	1.16 (M)	1.07	1.96 (A)	0.77 (HS)	1.70 (MWS)	1.59	23.6	60.0	27.8
		H49	1609	Cp-L	light grey	3	0.84 (C)	0.81	2.43 (SA)	0.75 (HS)	2.16 (PS)	2.51	20.0	62.3	25.8
		H50	1650	Cp	light grey	4	0.91 (C)	0.86	1.93 (A)	0.74 (MS)	1.42 (MWS)	2.13	18.6	72.0	25.7
		H51	1668	Cp	light grey	4	0.96 (C)	0.89	1.54 (A)	0.71 (MS)	1.42 (MWS)	2.04	16.8	61.0	24.8
		H52	1684	Cp	light grey	4	0.99 (C)	0.94	1.74 (A)	0.69 (MS)	2.55 (PS)	3.00	17.0	59.0	24.4
		H53	1890	Cp-L	yellowigh grey	2	0.86 (C)	0.83	1.94 (A)	0.66 (MS)	2.30 (PS)	1.64	33.7	72.7	30.2

Structure: Ms = massive, L = laminate/ horizontal bedded, Cp = planar cross-bedded/laminated, Ct = trough cross-bedded and Cr = ripple cross-laminated,

Grain size: C = coarse, M = medium, F = fine and VF = very fine; DOI = Degree of induration; 2 = weakly indurated, 3 = indurated, 4 = strongly indurated (Henriksen et al. 1999)

$\phi = -\log_2 d$, where d = size in mm; * corrected size: VF = very fine-grained, F = fine-grained, M = medium-grained, and C = coarse-grained; VPS = very poorly sorted, PS = poorly sorted, MWS = moderately well sorted, and WS = well sorted; A = angular, SA = subangular and SR = subrounded; HS = high sphericity, MS = moderate sphericity and LS = low sphericity

Table 2: Composition of sandstones and mineralogical indices

Formation/ Member		Sample	Framework Grains (%)													Matrix	Cement (%)					Void	%QFL			Clan	Mineralogical Indices		
			Qm	Qp	Q	P	K	F	Lm	Ls	L	M	D	Mc	Total	(%)	Cfc	Cf	Cs	Ca	Ct	(%)	Q	F	L		CMI	(Cfc +Cs)/Ct	MMI, %
Rapti Formation (North Belt)	Lower Member	1H1	37	12	49	3	3	6	5	2	7	1	1	0	64	12	1	0	7	8	15	9	79	10	11	SL	0.6	0.53	327
		H1	47	5	52	1	4	5	3	1	4	2	1	0	64	3	7	10	6	3	26	7	85	9	7	SA	3.9	0.48	415
		H2	38	10	48	6	8	14	4	1	5	4	1	0	72	17	0	1	3	3	7	4	72	21	7	FG	0.2	0.43	200
		H3	32	0	32	4	5	9	1	1	2	15	2	0	60	9	10	1	7	8	26	4	74	21	5	SA	1.9	0.65	114
		H4	47	8	55	2	2	4	8	1	9	3	3	1	75	12	3	3	2	1	9	4	81	6	13	SL	0.4	0.56	275
	Middle Member	1H2	40	1	41	5	2	7	1	0	1	18	1	0	68	11	0	0	15	5	20	1	84	14	2	SA	1.4	0.75	152
		1H3	61	5	66	2	3	5	3	0	3	3	1	0	78	5	9	1	3	3	16	1	89	6	5	SA	2.4	0.75	547
		1H4	53	6	59	1	2	3	7	0	7	2	0	0	71	5	0	10	6	3	19	5	85	5	10	SL	1.2	0.32	482
		H5	30	2	32	2	6	8	2	0	2	15	1	0	58	13	0	2	4	15	21	8	76	19	5	SA	0.3	0.19	123
	Upper Member	H6	33	3	36	5	3	8	5	0	5	8	1	0	58	16	2	1	5	9	17	9	73	16	10	FG	0.4	0.41	164
		H7	47	3	50	5	7	12	2	0	2	5	1	0	70	9	0	0	5	7	12	9	78	19	3	SA	0.6	0.42	250
		H15	39	0	39	0	9	9	1	0	1	16	1	0	66	18	0	2	2	2	6	10	79	19	1	FG	0.1	0.36	144
		H16	48	5	53	1	5	6	4	0	4	3	1	0	67	10	0	4	6	8	18	5	84	9	7	SA	0.6	0.35	383
		H8	46	2	48	5	5	10	2	0	2	3	0	0	63	8	0	14	5	4	23	6	80	17	3	SA	0.6	0.22	320
		H17	35	2	37	5	8	13	3	1	4	3	0	0	57	6	2	8	5	14	29	8	69	24	7	SA	1.2	0.24	185
		H18	34	20	54	6	2	8	9	2	11	3	1	0	77	5	1	1	4	5	11	7	74	11	15	SL	1.0	0.45	235
Rapti Formation (South Belt)	Upper Member	H21	26	15	41	3	5	8	13	1	14	5	1	0	68	2	21	1	0	1	23	6	65	13	22	SL	11.3	0.90	151
		H22	24	7	31	4	8	12	9	1	10	8	2	0	62	1	32	0	0	0	32	4	59	22	20	SA	28.9	0.99	100
		H23	37	7	44	1	5	6	4	0	4	4	0	0	58	4	24	4	1	3	32	6	82	10	8	SA	7.1	0.79	309
		H24	24	10	34	4	4	8	19	1	20	5	1	0	68	1	28	1	1	0	30	1	55	13	32	LA	23.3	0.96	99
		H25	18	18	36	3	5	8	19	1	20	2	1	0	67	1	25	0	0	0	25	7	56	13	31	LA	40.4	0.97	117
		H26	23	0	23	3	0	3	0	0	0	19	0	0	45	10	34	3	3	1	41	4	87	13	0	SA	3.6	0.90	104
		H27	25	13	38	3	4	7	23	1	24	3	1	0	73	1	23	0	0	0	23	3	55	10	35	LA	22.5	1.00	107
		H28	28	4	32	4	11	15	10	1	11	12	1	0	71	2	14	7	0	1	22	5	55	26	19	AA	7.4	0.63	80
		H30	30	5	34	4	12	16	16	1	17	8	2	0	78	2	14	0	0	0	14	6	51	24	25	LA	7.3	1.00	79
		H32	23	4	27	1	8	9	13	2	15	11	1	0	63	3	21	2	0	2	26	9	53	18	29	LA	6.8	0.82	73
Amlekhganj Formation (South Belt)		H33	25	3	28	5	4	9	1	0	1	12	3	0	53	6	29	0	0	0	29	12	74	24	3	SA	4.8	1.00	112
		H34	27	13	40	4	4	8	14	0	14	2	1	1	66	1	31	0	0	0	31	1	64	14	23	SL	26.4	1.00	149
		H36	32	6	38	2	6	8	10	0	10	7	2	0	65	1	27	0	0	0	27	7	68	14	18	SL	21.9	0.98	141
		H38	20	7	27	1	10	11	13	1	14	9	1	0	62	2	33	0	0	1	34	2	53	21	27	LA	16.8	0.97	78
		H40	26	9	35	3	4	7	15	1	16	4	1	0	63	1	32	0	0	1	33	3	61	12	28	LA	34.0	0.98	126
		H41	28	7	35	2	6	8	9	1	10	10	2	0	65	1	30	0	0	1	31	3	66	15	19	SL	30.0	0.96	118
		H42	30	7	37	2	6	8	6	1	7	5	3	0	60	1	30	0	0	1	31	8	72	15	13	SA	50.4	0.98	164
		H43	23	6	29	5	9	14	7	1	8	7	2	0	59	1	37	0	0	1	38	1	57	27	16	AA	33.9	0.97	98
		H44	24	11	35	3	5	8	9	3	12	6	1	0	61	1	34	0	0	1	35	2	64	14	22	SL	34.4	0.97	133
		H45	26	9	35	3	4	7	9	1	10	9	1	0	62	1	31	0	0	0	31	6	67	13	20	SL	31.0	1.00	130
		H46	24	8	32	4	6	10	8	2	10	9	1	0	62	1	33	0	0	1	34	3	62	19	19	SL	32.9	0.97	108
		H47	25	5	30	7	8	15	6	2	8	8	2	0	63	1	34	1	0	0	35	1	57	28	15	AA	47.3	0.98	94
		H48	30	8	38	4	8	12	6	3	9	6	3	1	68	1	29	0	0	0	29	2	65	20	15	SA	33.1	0.98	129
		H49	27	6	33	5	7	12	9	4	13	5	3	0	67	1	31	0	0	1	32	1	57	21	22	SL	37.4	0.97	100
		H50	31	11	42	6	5	11	3	1	4	3	9	0	69	1	27	0	0	1	28	2	74	20	6	SA	31.1	0.97	155
		H51	27	7	34	3	8	11	11	1	12	6	3	0	66	1	32	0	0	0	32	1	59	20	21	SL	26.0	1.00	106
		H52	29	6	35	4	5	9	9	1	10	6	3	0	63	3	33	0	0	0	33	1	65	17	19	SL	11.7	1.00	121
		H53	25	7	32	3	4	7	10	1	11	9	1	1	61	3	26	1	0	1	28	8	65	15	21	SL	8.4	0.92	114

Qm = Monocrystalline quartz; Qp = Polycrystalline quartz; Q = Total quartz = Qm + Qp; K = K-feldspar; P = Plagioclase; F = Total feldspar = K + P; Lm = Metamorphic lithic fragment; Ls = Sedimentary lithic fragments; L = Total lithic fragments = Lm + Ls + volcanic lithic fragments (not accounted); M = Mica; D = Dense mineral; Mc = Miscellaneous; Total framework = Q + F + L + M + D + Mc; Cfc = Ferroan calcitic cement; Cf = Ferruginous cement; Cs = Siliceous cement; Ca = Argillaceous cement; Ct = Total cement = Cfc + Cf + Cs + Ca; Q%QFL = (Q/QFL)100; F%QFL = (F/QFL)100; L%QFL = (L/QFL)100; CMI = Strong cement versus matrix index; MMI = Modified maturity index diminishes and varies between 0 and 6% (Fig. 7) showing a remarkable variation trend. The amount of matrix is high in fine-grained sandstones from the Rapti Formation of NB.

Cement

Four kinds of cement that were recognised in sandstones, were calcareous, ferruginous, siliceous and argillaceous. Calcareous cement (ferroan calcite) occurs mostly as pore filling (Fig. 8a) but some as replacing cement as indicated by poikilotopic fabric (Fig. 8a). Little cement also produces as the development of reaction rims around grain boundaries. Labile grains are extensively replaced by ferroan calcitic cement. Siliceous cement mostly occurs as a syntaxial overgrowth and a pressure solution between grains. Sutured contacts produce such binding cement after dissolving grains boundaries by pressure and then lead to the grain interlocking (Houseknecht 1984 and 1987). Ferruginous cements are of limonite and hematite, which occur as coats over grains or as isolated patches (Fig. 8c). Argillaceous cement occurs mostly between grains as thin coats of clay minerals and micas, and as a pore filling fines binding the grains (Fig. 8d).

The amount of total cement varies between 6 and 41% and increases gradually up-section (Fig. 7). Sandstones from SB are almost entirely cemented by ferroan calcitic cement except few samples in which ferruginous, siliceous and argillaceous cements occur in minor amount. Contrarily, the sandstones of NB are cemented dominantly by argillaceous, siliceous and/or ferruginous cement (Table 2). The exception applies to the samples H1, H3 and 1H3 in which ferroan calcitic cement dominates over other kinds of cement.

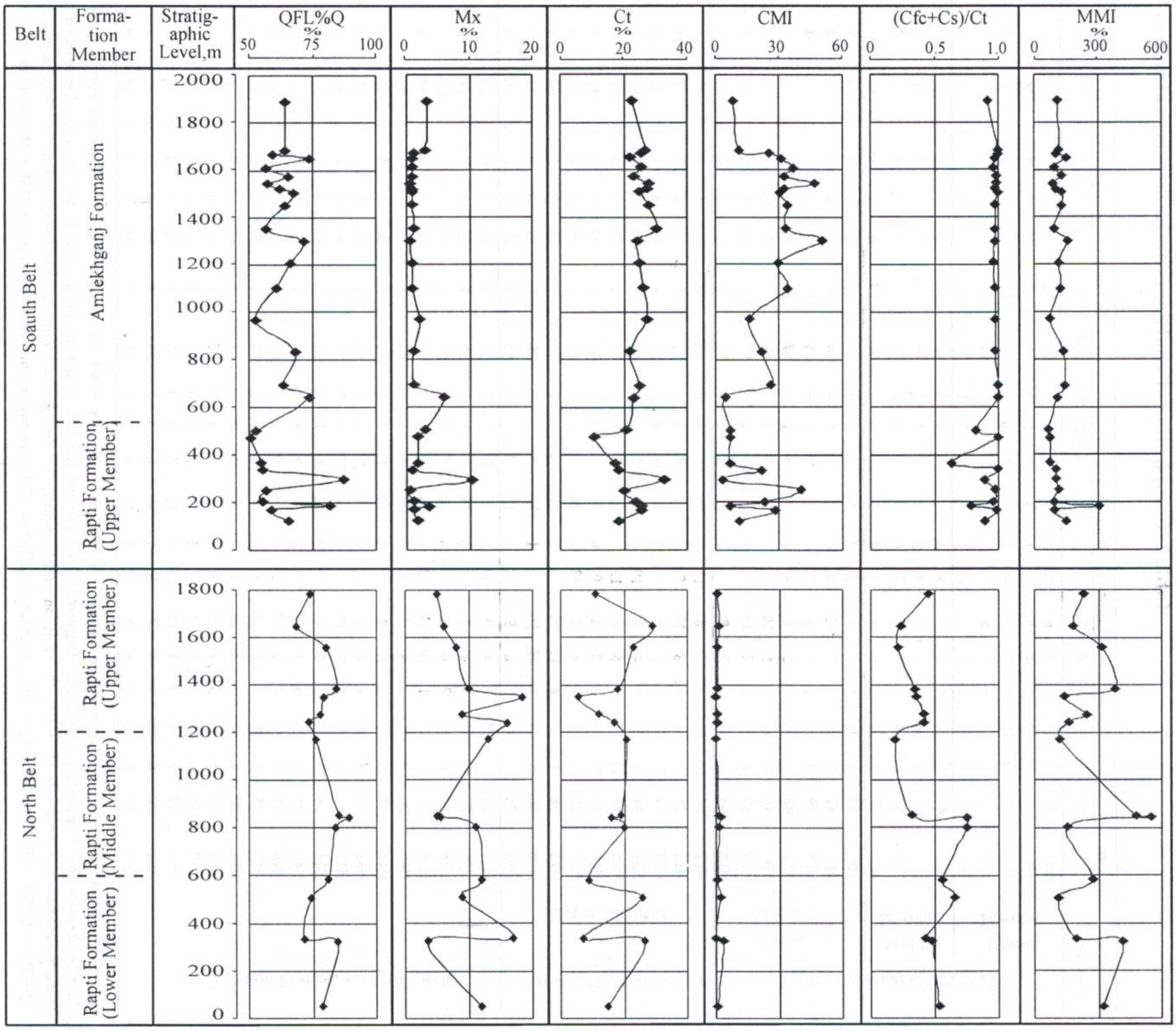

Fig. 7: Stratigraphic variation trends of some compositional parameters and mineralogical indices

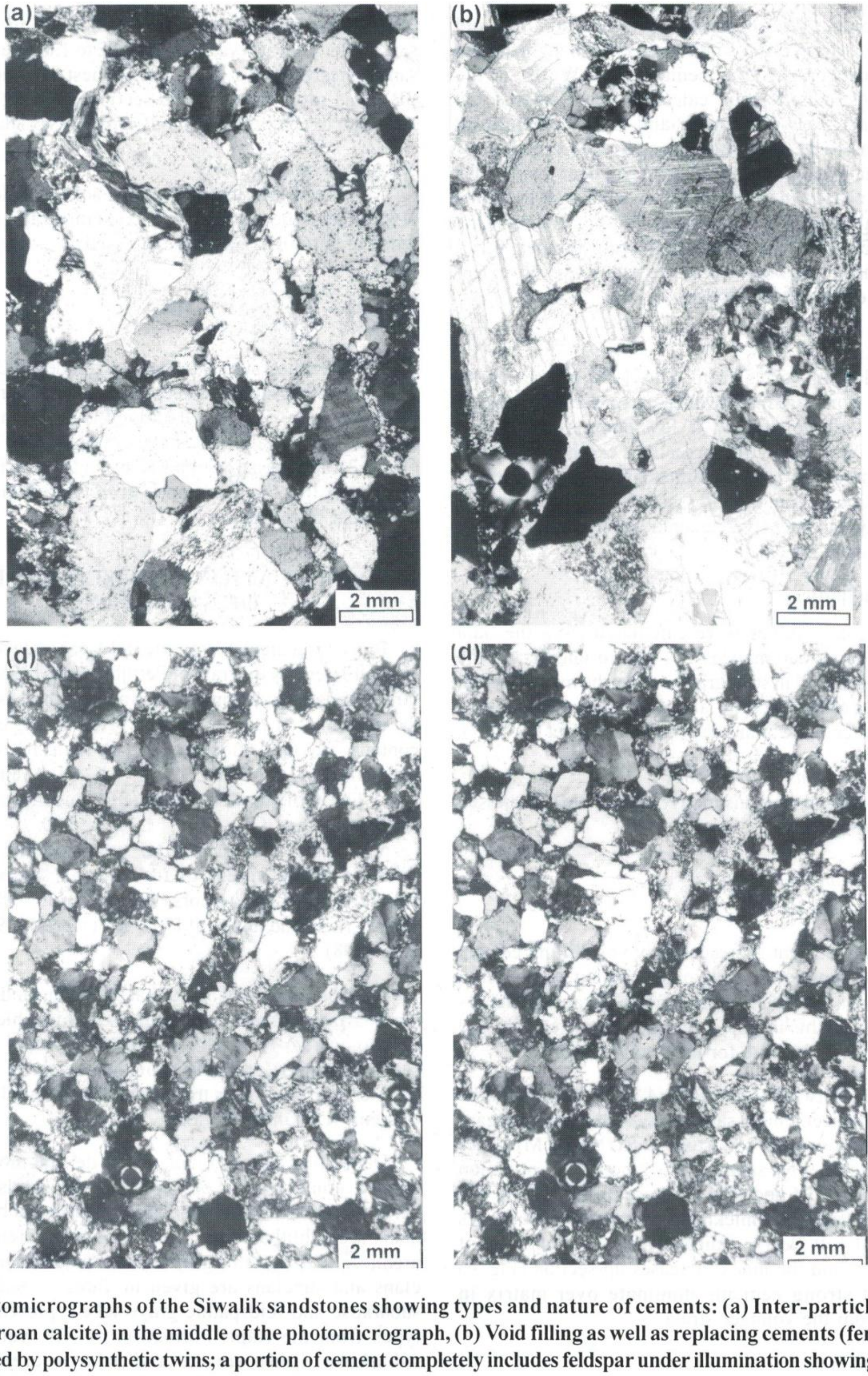

Fig. 8: Photomicrographs of the Siwalik sandstones showing types and nature of cements: (a) Inter-particle void filling cement (ferroan calcite) in the middle of the photomicrograph, (b) Void filling as well as replacing cements (ferroan calcite) characterised by polysynthetic twins; a portion of cement completely includes feldspar under illumination showing poikilotopic fabric, (c) Cementation by ferruginous and siliceous cements; the former occurs as an irregular patch between grains and as grain coating whereas the later as a result of pressure solution, and (d) Cementation by argillaceous material usually occurring as thin coating among grains therefore bridging the grains, and less commonly producing irregular patches

Closer contacts among grains, pressure solution and authigenic growth in older sandstones exhibit significance of compaction compared to cementation. Whilst in the younger sandstones, ferroan calcitic cement extensively occludes space between grains and thus, cementation process seems to be important process. The variation of cementing material from the older to younger sandstones may indicate change in depositional environments from one of acidic to alkaline and oxidizing condition. Similarly the change in diagenetic environment having greater burial pressure to one of lower burial pressure with active movement of fluid in the younger sandstones.

Void

The total void varies from 1 to 12% of the modal composition. Voids are mainly inter-particle and fracture in nature. The volume of void is low compared to other components. Assessment of thin sections exhibits that inter-granular volume was reduced either by greater degree of interlocking due to compaction (as in the case of the older sandstones) or by extensive cementation (as in the case of the younger sandstones).

Mineralogical indices

Mineralogical indices were calculated from the data obtained in the modal analysis in order to understand the ranges and variability in stratigraphic level the mineralogical maturity, cement-matrix ratio and ratio of ferroan calcitic cement and siliceous cement over the total cement (Table 2).

Strong Cement versus Matrix Index

The strong cement versus matrix index (CMI) proposed herein is expressed as

$$CMI = \frac{\%StrongCement}{\%MatrixContent}$$

where % strong cement represents any void filling cement or authigenic syntaxial overgrowth cement or pressure solution cement, which strongly bind the grain as well as matrix in rock. In this instance, ferroan calcitic cement and siliceous cement substitute for the strong cement.

CMI ranges between 0.11 and 50.4, being highest for the ferroan calcitic cemented sandstone of the Amlekhganj Formation, and lowest for sandstone of Rl (NB). CMI varies between 0.1 and 3.9 for sandstones of the Rapti Formation (NB) and between 3.6 and 40.4 for those from Ru (SB). For the sandstones from the Amlekhganj Formation CMI ranges from 4.8 to 50.4. It clearly indicates that variation trend of CMI is distinct and the index increases up-section (Fig. 7) showing that strong cements dominate over matrix in sandstones from the younger strata.

(Cfc + Cs)/Ct ratio

The ratio of ferroan calcitic cement and siliceous cement (Cfc + Cs) to total cement content (Ct) represents abundance of strong cement out of the total binding material in sandstone. The ratio varies from 0.22 to 1.00, being lowest in sandstones from Ru (NB) and highest in sandstone from SB. This ratio increases up-section showing contrasting variation trends between sandstones of NB and SB.

Modified Maturity Index

Modified Maturity Index (MMI) of Mcbride and Picard (1987) that is the modified version of mineralogical maturity index of Pettijohn (1984) is expressed as

$$MMI = \frac{Quartz + Chert}{OtherClasts} x100(\%)$$

MMI is almost similar to the Quartz Index of Okada (1966) which does not take into account of chert grain. The index reflects relative abundance of durable grains in sandstones. MMI of the Siwalik sandstones ranges from 73 to 547% (Table 2). The variation trend of this index is striking (Fig. 7) and shows that the sandstones from NB are more matured than those from SB.

CLASSIFICATION AND NOMENCLATURE OF SANDSTONES

Plots of recalculated quartz, feldspar and rock fragment over QFL ternary diagram of Pettijohn et al. (1987) show that three sandstones belonged to wackes whereas the rest of the other plotted as arenites (Fig. 9) depending on the matrix content. The QFL modes of Ru, Rm and Rl from NB are respectively Q_{72-85} F_{6-21} L_{5-13}, Q_{76-89} F_{5-19} L_{2-10} and Q_{73-84} F_{9-24} L_{1-15}. The QFL modes of Ru (SB) and the Amlekhganj Formation are Q_{51-87} F_{10-26} L_{0-35} and Q_{53-74} F_{12-28} L_{3-28}, respectively. Almost similar quartzolithic to quarto-feldspathilithic modes of the Siwalik sandstones were exhibited by several authors (Tokuoka et al. 1986; Hisatomi 1992; Critelli and Ingersoll 1994; Dhital et al. 1995; DeCelles et al. 1998).

It is observed from Fig. 9 that the older sandstones (NB) are quartzo-feldspathic and quartzo-lithic which gradually shift to quartzo-feldspathilithic components in the younger sandstones (SB) probably showing change in provenance from craton interior or transitional continental to recycled orogenic (Dickinson 1985).

Depending on the abundance of detrital modes, type of cement content and void content, the sandstones were categorized into five major clans and further sub-clans. Five clans are sublitharenite, subarkose, lithic arenite, arkosic arenite, and feldspathic graywacke (Table 3). Description of clans and subclans are given in Table 3. Sublitharenite, subarkose and feldspathic graywacke represent sandstone types from the Rapti Formation of NB. Sublitharenite, subarkose, lithic arenite and arkosic arenite are the sandstones from the Rapti Formation (SB) and the Amlekhganj Formation.

Table 3: Petrographic subdivisions of the Siwalik sandstones

Clan	Sub-clan		Characteristics
1. Sublitharenite (SL)	SL-I	Ferroan calcitic cemented sublitharenite	They are massive, horizontal bedded to planar cross-bedded, medium- to coarse-grained, ferroan calcitic cemented, and light grey sublitharenites. They are strongly indurated. Matrix varies from 1 to 3% while void is very low approaching 1% thus showing clast-supported fabric. Grains are moderately well sorted to poorly sorted. Quartz grains are subangular to angular. Texturally sandstones are submature.
	SL-II	Ferroan calcitic cemented sublitharenite with considerable void	They are massive, planar cross-bedded to laminated to trough cross-bedded, medium- to coarse-grained, ferroan calcitic cemented, micaceous, and yellowigh to light grey sublitharenites. They are weakly to strongly indurated having few matrix and more voids (3-8%). Grains are moderately well sorted to poorly sorted showing usually subangular quartz. Texturally, sandstones are submature.
	SL-III	Siliceous-ferruginous cemented sublitharenite	They are massive, planar cross-bedded, fine- to medium-grained, siliceous-ferruginous cemented, and yellowish to light grey sublitharenites. They are weakly indurated to indurated and are comprised of remarkable matrix (5-12%) and voids (4-8%). Grains are moderately well sorted with sub-rounded quartz. They are texturally immature to submature.
	SL-IV	Siliceous-argillaceous cemented sublitharenite	Sub-clans are massive, horizontal bedded to planar cross-bedded, fine- to medium-grained, siliceous-argillaceous cemented, and yellowish grey sublitharenites. They are weakly indurated with considerable matrix (7-9%) and voids (5-12%). Grains are moderately well sorted with subangular quartz and rocks are texturally immature to submature.
2. Subarkose (SA)	SA-I	Ferroan calcitic cemented subarkose	Sub-clans are massive, planar cross-bedded to laminated, medium- to coarse-grained, ferroan calcitic cemented, and light grey subarkoses. They are indurated to strongly indurated poorly with low matrix content and voids. Grains are sorted to moderately well sorted. Quartz grains are subangular to angular. They are texturally submature.
	SA-II	Ferroan calcitic cemented subarkose with considerable voids	They are massive, trough to planar cross-bedded and laminated, medium- to coarse-grained, ferroan calcitic cemented, micaceous, and light grey subarkoses. They are weakly indurated with slightly high matrix and void. Grains show poor to moderately well sorting with subangular quartz. They are texturally immature to submature.
	SA-III	Ferroan calcitic cement dominant subarkose	They are medium-bedded to massive, planar cross-bedded to laminated, fine-grained, ferroan calcitic-cement dominated, micaceous and light grey subarkoses. Sandstones are weakly indurated to indurated with with moderate matrix and void. Grains are poorly to moderately well sorted with subangular quartz grains. They are texturally immature to submature.
	SA-IV	Ferruginous-siliceous-argillaceous-ferroan calcitic cemented subarkose	Sub-clans are thick-bedded to massive, horizontal bedded to planar cross-bedded, very fine- to fine-grained, ferruginous-siliceous-argillaceous-ferroan calcitic cemented, micaceous, and green grey subarkoses. They are indurated to strongly indurated having moderate matrix and void. Grains show moderately well to well sorted. Quartz grains are subangular to subrounded. Texturally, sub-petrofacies are immature to submature with textural abnormality.
	SA-V	Argillaceous-siliceous cemented subarkose	Sub-clans are massive, planar cross-bedded, fine-grained, argillaceous-siliceous cemented, micaceous, and green grey subarkoses. They are strongly indurated, though they have high matrix content. Void is around 1% Grains show moderately well sorted. Quartz grains are subangular. They are immature showing textural anomalies.
	SA-VI	Argillaceous cement dominant subarkose	They are massive, horizontal bedded to planar cross-bedded to trough cross-bedded, very fine- to fine-grained, argillaceous-cement cominated, and yellowish grey subarkoses. They are weakly indurated with moderately high matrix (6-13%) and void (5-9%). Grains are well to moderately well sorted with subangular to subrounded quartz. They are immature and texturally abnormal.
	SA-VII	Ferruginous cement dominant subarkose	They are massive, horizontal to planar cross-bedded, fine-grained, ferruginous-cement dominated, and yellowish brown to grey subarkoses. The sub-petrofacies are weakly indurated with moderate matrix (3-8%) and void (6-7%). Grains are well sorted. Quartz grains are mostly subangular. They range from mature to immature (texturally anomalous).
3. Lithic arenite (LA)			Lithic arenites are massive, planar to trough cross-bedded, horizontal bedded and laminated, medium- to coarse-grained ferroan calcitic cemented, and light grey lithic arenites. They are indurated to strongly indurated with low matrix (1-3%) but moderate void (1-9%). Grains show remarkably poor to very poor sorting. Quartz is subangular to angular. They are submature.
4. Arkosic arenite (AA)	AA-I	Ferroan calcitic cemented arkosic arenite	They are massive, planar cross-bedded to laminated, medium- to coarse-grained, strongly indurated, ferroan calcitic cemented, and light grey arkosic arenites. They are indurated to strongly indurated with low matrix and void, and texturally submature. Grains are moderately well to very poorly sorted. Quartz grains are subangular to angular.
	AA-II	Ferruginous-ferroan calcitic cemented arkosic arenite	They are massive, palanar to trough cross-bedded, coarse grained, ferruginous-ferroan calcitic cemented, micaceous, and yellowish grey arkosic arenites. They are weakly indurated with low matrix (2%) and moderate void (5%). Grains are poorly sorted. Quartz grains are subangular. They are texturally submature.
5. Feldspathic graywacke (FG)			Feldspathic graywackes are thick-bedded to massive, ripple cross-laminated to laminated, fine-grained, siliceous-argillaceous cemented, and grey to green grey feldspathic graywackes. Sub-petrofacies are weakly indurated to indurated with high matrix (16-18%) and void (4-10%). Grains are poorly to moderately well sorted. Quartz grains are subrounded to subangular. They are texturally immature showing anomalous results.

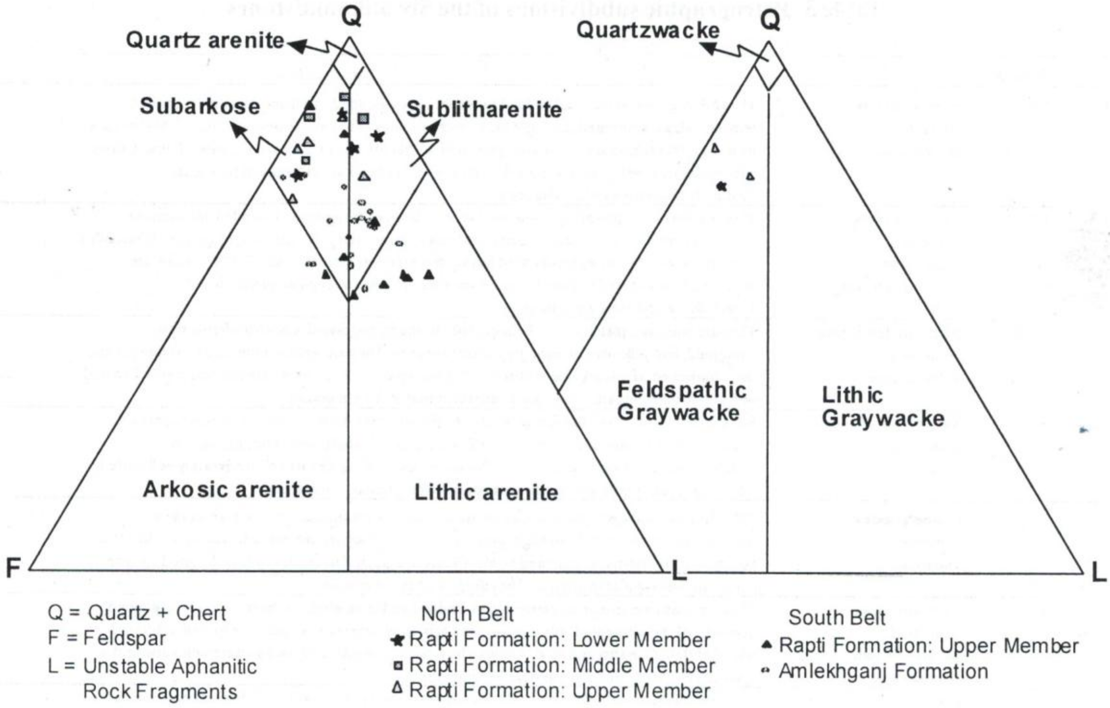

Fig. 9: QFL-ternary diagram representing composition of the Siwalik sandstones

SANDSTONE VERSUS TEXTURE AND FABRIC

Considering abundance of matirx, both arenite and wacke are distinguhised among the Siwalik sandstones. Out of forty-four sandstone samples analysed, fifteen are sublitharenite, sixteen are subarkose, three are feldspathic graywacke, three are arkosic arenite and seven are lithic arenite. Although distribution of sandstone types is irrespective of stratigraphic level, lithic arenites and arkosic arenites are restricted to younger stratigraphic levels (Ru (SB) and the Amlekhganj Formation) whereas feldspathic greywacke to the Rapti Formation of NB. Even though sandstones from different stratigraphic levels belong to the same clan, they differ in aspects of texture and fabric. If sublitharenite and subarkose, which occur both in the older and younger stratigraphic levels, are considered, sandstones of older strata from NB are finer grained, more rounded and sphered, better sorted and have higher packing indices than those from the younger strata of SB.

Feldspathic graywackes are fine-grained, siliceous-argillaceous cemented, matrix supported, and texturally immature rocks distributed in Ru and Rm of NB. They have high PP, PD and Pcc values.

Arkosic arenite and lithic arenites are much similar to each other in terms of texture and fabric. However, lithic arenites show more preferred grain-orientation. Both arkosic arenite and lithic arenites are massive bedded, medium- to coarse-grained, texturally submature and less packed.

CONCLUSIONS

(1) Variation trend of mean grain size is quite remarkable as grain size gradually increases up-section. Similarly, sorting becomes significantly poorer up-section. Roundness and maximum projection sphericity slightly decrease up-section. However, the trends of DOI and GOF are highly fluctuating. Highly cemented and interlocked sandstones tend to possess high value of DOI. The lower values of GOF are exhibited either by younger sandstones with high pelitic fragment and mica contents or by older sandstones subjected to more burial compaction.

(2) The variation trend of recalculated quartz, matrix and mineralogical indices are very promising in distinguishing the older sandstones from the younger ones. The recalculated quartz, MMI and matrix content decrease up-section and produce contrasting trends between sandstones of NB and SB. Contrarily, the total cement, CMI and the ratio of strong cement over total cement increase drastically up-section, allowing petrographic distinction of sandstones from NB and SB.

(3) The majority of the younger sandstones are cemented mainly with ferroan calcitic cement occluding inter-particle pores whereas the older sandstones are poorly cemented by ferroan calcite but the cements in them more commonly occur as thin grain coats, irregular patches and as localized pressure solution.

(4) Sandstones of NB are more packed and consolidated as shown by high degree of PP, PD and Pcc. In these sandstones compactional process must have played important role in reducing intergranular volume. Sandstones of SB exhibit comparatively low degree of packing indices but show high proportion of cement, which fills pore and replaces grains. In these younger sandstones, pervasive cementation probably led to final reduction in intergranular volume.

(5)Detrital modes of QFL and proportion of matrix distinguish five major sandstone clans; sublitharenite, subarkose, arkosic arenite, lithic arenite and feldspathic graywacke. The former three clans are further classified into thirteen sub-clans based on type of cement content and void content.

(6)Lithic arenites and arkosic arenites distribute in SB whereas feldspathic graywackes in NB. Sublitharenites and subarkoses occur both in NB and SB. Although sublitharenites and subarkoses distribute irrespective of stratigraphic levels, these sandstones from older strata (from NB) differ in texture and fabric with younger sandstones (from SB).

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