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MICROFABRICS OF THE SIWALIK GROUP SANDSTONES, CENTRAL NEPAL SUB-HIMALAYA: CLUES TO POST-DEPOSITIONAL CHANGES

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ABSTRACT

Sandstones from the Siwalik Group of Central Nepal Sub-Himalaya were studied for microfabrics. Interlocking microfabric, packing microfabric, preferred orientation microfabric, authigenic microfabric and deformation microfabric were assessed in order to reconstruct post-depositional changes in sandstones and understanding nature of intergranular volume reduction in sandstones. Sandstones from north belt (NB) are closely packed and are much consolidated, whereas sandstones from south belt (SB) are loosely packed with weak grain contacts and strong cementing. Sandstones from NB were subjected to deep burial diagenesis, in which little initial cementation was followed by progressive compaction. Sandstones from SB underwent mechanical compaction followed by extensive carbonate cementation. Development of microfabrics and pore-reduction are due largely to compaction in sandstones from NB, but those in the sandstones from SB are due mainly to cementation and less to compaction.

Key words: Microfabrics, diagenesis, cementation, sandstone, Siwalik Group

MICROFABRICAS DE LAS ARENISCAS DEL GRUPO SIWALIK, SUB-HIMALAYA DE NEPAL CENTRAL: CLAVES PARA CAMBIOS POST-DEPOSICIONALES

RESUMEN

Las areniscas del Grupo Siwalik del Sub-Himalaya de Nepal Central han sido estudiadas para establecer sus microfábricas: Microfábrica de interdigitización, microfábrica de empaquetamiento, microfábrica de orientación preferancial, microfábrica autigénica y microfábrica de deformación fueron evaluadas con el fin de reconstruir cambios post-deposicionales en areniscas y entender la naturaleza de la reducción de volúmen intergranular en areniscas. Las areniscas del cinturón norte (NB) son muy empaquetadas y mucho más consolidadas, mientras que las areniscas del cinturón sur (SB) son pobremente empaquetadas con contactos entre granos débiles y fuerte cementación. Las areniscas del NB fueron sometidas a diagénesis de enterremiento profundo, en las cuales poca cementación inicial fue seguida por campactación progresiva. Las areniscas del SB experimentaron compactación mecánica seguida por cementación extensiva de carbonato. El desarrollo de microfábricas y la reducción de poros son debidas principalmente a la compactación en areniscas del NB, pero aquellas en las areniscas del SB son debidas principalmente a la cementación y menos a la compactación.

Palabras claves: Microfábricas, diagénesis, cementación, arenisca, Grupo Siwalik

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INTRODUCTION

The Siwalik Group is a thick fluvial sequence of mainly mudstone, sandstone and conglomerate of middle Miocene to early Pleistocene epoch developed in the fore land basin. Sediments were derived from uplifting Himalayas in the north (Chaudhri, 1982; Critelli and Ingersoll, 1994; DeCelles et al., 1998; Tamrakar, 1998). Continuous burial of sediments led to lithification of sediments.

Primary microfabrics alter during diagenesis, but in some cases, they preserve as relicts. Compaction, physico-chemical deformation and cementation usually modify depositional texture of sandstone and produce diagenetic microfabrics, which are useful in inferring evolutionary trend of post depositional changes in sandstones. Moreover, degree of packing and cementation, which diminish depositional porosity, may influence stiffness of sandstones. The present paper deals with microfabrics of sandstones, their variability and their signatures in interpreting post-depositional changes.

GEOLOGICAL SETTING

The study area is located in the Siwalik Group (FIGURE 1), which is divisible into north belt (NB) and south belt (SB) separated by the Central Churia Thrust. The strata of the Siwalik Group extend roughly NW-SE and are being folded by thrusting. The group ranges in age from 14 to <2 Ma (Gautam & Rõsler 1999) and constitutes about 5500 m thickness which is divisible into five units; the Rapti, Amlekhganj, Churia Khola and Churia Mai formations (Sah et al. 1994) in ascending order. The Rapti Formation exposes mainly in NB, while the uppermost part of the Rapti Formation, Amlekhganj Formation, Churia Khola Formation and Churia Mai Formation crop out in SB only (Tamrakar et al. 2002).

The Rapti Formation comprises fine- to medium-grained sandstone and mudstone (FIGURE 2). In SB, the Rapti Formation exhibits medium- to coarse-grained 'salt-and-pepper' sandstone associated with few mudstone. The Amlekhganj Formation comprises multistoreyed, medium-to coarse-grained 'salt-and-pepper' sandstone (FIGURE 2). The Churia Khola and the Churia Mai formations compose mainly of conglomerate and minorly of sandstones and mudstone. Sandstones distribute extensively in the Rapti and Amlekhganj formations and crop out well along the riverbanks from where stratified-selective sampling was made (FIGURE 3).

METHODS

Thin slices of forty-four sandstones were petrographically analysed. Grain size was measured following Harrel & Erikson (1979). Roundness and sorting were assessed using comparison charts of Power (1953) and Beard & Weyl (1973), respectively. Thin sections were stained for k-feldspar, and carbonate minerals using Chayes's (1952) and Dickson's (1966) methods, respectively. Each thin section was counted for 800 points using Gazzi-Dickinson's point-counting method (Dickinson 1970; Ingersoll et al. 1984). The cement and pore were also included in the counts. Packing indices, grain orientation factor, deformation fabrics and authigenic fabrics were assessed for the thin slices using a polarizing microscope.

TEXTURE AND COMPOSITION

Sandstones are very fine- to coarse-grained with subangular to subrounded and well to very poorly sorted grains (TABLE 1). They are texturally immature to submature. Quartz predominates other clasts and ranges from 23 to 66%. Monocrystalline quartz exceeds polycrystalline one. Feldspar (K-feldspar and plagioclase) and lithic fragments vary from 3 to 16% and 0 to 24%, respectively. K-feldspars often exceed plagioclase. Lithic fragments of quartz-mica tectonite, quartz-mica aggregate, quartz-mica-feldspar aggregate, argillite shale and some carbonate grains occur. Micas constitute muscovite, biotite and chlorite, altogether varying from 1 to 19%. Sandstones are subarkose followed by sublitharenite, lithic arenite, arkosic arenite and feldspathic graywacke (FIGURE 4) in diminishing abundance.

Matrix ranges from 0 to 18%. It occurs as grain coating and pore filling, in sandstones from NB, but often as feldspar, quartz and micas associated with clasts in those of SB. Total cement varies from 6 to 38%. Ferroan calcitic cement often occurs as replacing and pore-filling. They also fill most of the fractures in grains. Siliceous cement occurs as grain boundary dissolution. Ferruginous cement occurs as irregular pore-filling patches, grain coats and bridge between grains. Argillaceous cement occurs as authigenic development of clays and chlorites, which also bridge grains in sandstones from NB. Argillaceous cement over total

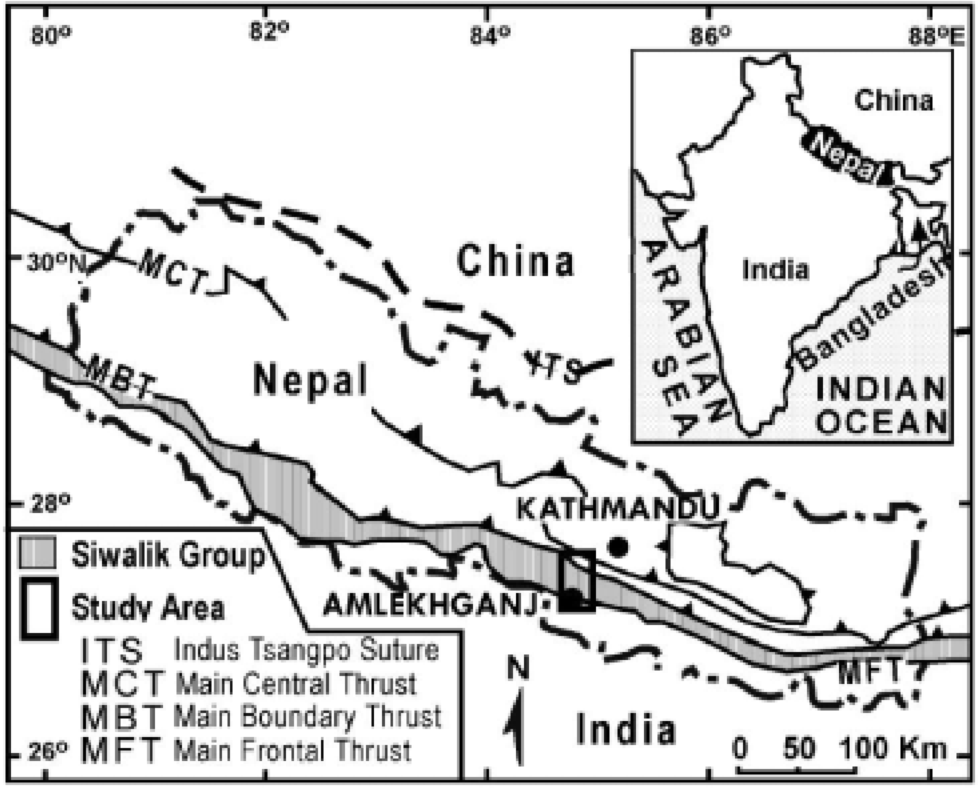

FIGURE 1. Location map of study area.

cement (Ca/Ct) ranges from 0 to 0.17 and is often high in sandstones from NB, and low in those from SB. Strong cement over total cement (SCTC = (Cfc +Cs)/Ct) varies from 0.19 to 1.00 and is high in sandstones from the Amlekhganj Formation.

Optical voids range from 1 to 12%. They are primary (intergranular) and secondary. Grain fracture, rock fracture, and grain dissolution result in secondary voids in the studied sandstones.

MICROFABRICS

Primary and/or diagenetic features showing mutual and spatial relationship among components are treated as microfabrics. Authigenic fabrics are diagenetic fabrics, which are formed by cementation, replacement and overgrowth, and deformation.

Interlocking microfabrics

Sutured (Su), concavo-convex (Cc), long (Lo), tangential (Ta) and floating (Fl) contacts (after Taylor, 1950) were considered contact types (FIGURE 5). Su and Cc contacts show considerable compaction of the sediment while Ta and Fl contacts represent minor compaction (Bell, 1978). Grain-to-grain contact (G-G), grain-to-cement contact (G-C), grain-to-matrix contact (G-M) and grain-to-void contact (G-V) were taken as contact nature. Interlocking microfabrics are important in revealing extent of packing and grain interlocking.

Consolidation factor (Pcc), which is expressed as percentage of theoretical consolidation (Bell, 1978), concavo-convex index (CCI) as an indicator of compaction, and degree of strong over weak contact (SOWC) were calculated using relations shown in TABLE 2.

Sandstones from NB often contain Su contact (FIGURE 6a), whereas those from SB lack it (TABLE 3) and comprise Fl contact commonly (FIGURE 6b). In the latter, Ta and Fl contacts increase at the expense of Su, Cc and Lo contacts. G-G, G-M and G-V decreases up-section (TABLE 3). Instead, G-C increases remarkably.

TABLE 1. Textural and compositional data of the Siwalik sandstones from Central Nepal.

Formation		Sample	*M_z			Framework Grains (%)					Matrix	Cement (%)					Void	%QFL					
	Member		(φ)	ρ	So	Q	F	L	M	Mc	(%)	Cfc	Cf	Cs	Ca	Ct	(%)	Q	F	L	Clan	Ca/Ct	SCTC
Rapti Formation (North Belt)	Lower Member	1H1	2.13	2.8	1.58	49	6	7	1	1	12	1	0	7	8	15	9	79	10	11	SL	0.53	0.53
		H1	2.11	2.32	1.35	52	5	4	2	1	3	7	10	6	3	26	7	85	9	7	SA	0.12	0.48
		H2	2.80	3.50	2.15	48	14	5	4	1	17	0	1	3	3	7	4	72	21	7	FG	0.43	0.43
		H3	3.01	3.18	1.35	32	9	2	15	2	9	10	1	7	8	26	4	74	21	5	SA	0.31	0.65
		H4	1.74	3.06	1.40	55	4	9	3	4	12	3	3	2	1	9	4	81	6	13	SL	0.11	0.56
	Middle Member	1H2	2.97	2.02	1.40	41	7	1	18	1	11	0	0	15	5	20	1	84	14	2	SA	0.25	0.75
		1H3	2.55	2.58	1.98	66	5	3	3	1	5	9	1	3	3	16	1	89	6	5	SA	0.16	0.75
		1H4	2.15	3.08	1.61	59	3	7	2	0	5	0	10	6	3	19	5	85	5	10	SL	0.16	0.32
		H5	3.12	2.16	1.40	32	8	2	15	1	13	0	2	4	15	21	8	76	19	5	SA	0.71	0.19
	Upper Member	H6	2.64	3.35	1.40	36	8	5	8	1	16	2	1	5	9	17	9	73	16	10	FG	0.53	0.41
		H7	2.77	3.28	1.54	50	12	2	5	1	9	0	0	5	7	12	9	78	19	3	SA	0.58	0.42
		H15	2.76	2.26	1.50	39	9	1	16	1	18	0	2	2	2	6	10	79	19	1	FG	0.29	0.36
		H16	2.54	2.93	1.33	53	6	4	3	1	10	0	4	6	8	18	5	84	9	7	SA	0.43	0.35
		H8	2.44	2.93	1.37	48	10	2	3	0	8	0	14	5	4	23	6	80	17	3	SA	0.17	0.22
		H17	2.58	2.37	1.39	37	13	4	3	0	6	2	8	5	14	29	8	69	24	7	SA	0.48	0.24
		H18	1.53	2.65	1.45	54	8	11	3	1	5	1	1	4	5	11	7	74	11	15	SL	0.45	0.45
Rapti Formation (South Belt)	Upper Member	H21	1.44	2.11	2.65	41	8	14	5	1	2	21	1	0	1	23	6	65	13	22	SL	0.04	0.90
		H22	1.96	1.72	2.58	31	12	10	8	2	1	32	0	0	0	32	4	59	22	20	SA	0.00	0.99
		H23	2.07	2.48	2.68	44	6	4	4	0	4	24	4	1	3	32	6	82	10	8	SA	0.10	0.79
		H24	1.72	1.89	3.46	34	8	20	5	1	1	28	1	1	0	30	1	55	13	32	LA	0.01	0.96
		H25	0.95	1.94	2.68	36	8	20	2	1	1	25	0	0	0	25	7	56	13	31	LA	0.01	0.97
		H26	2.74	2.68	1.77	23	3	0	19	0	10	34	3	3	1	41	4	87	13	0	SA	0.02	0.90
		H27	0.78	2.26	2.63	38	7	24	3	1	1	23	0	0	0	23	3	55	10	35	LA	0.02	1.00
		H28	0.99	2.97	2.55	32	15	11	12	1	2	14	7	0	1	22	5	55	26	19	AA	0.04	0.63
		H30	0.99	2.55	2.32	34	16	17	8	2	2	14	0	0	0	14	6	51	24	25	LA	0.00	1.00
		H32	1.08	2.57	2.41	27	9	15	11	1	3	21	2	0	2	26	9	53	18	29	LA	0.09	0.82
Amlekhganj Formation (South Belt)		H33	1.22	2.77	2.05	28	9	1	12	3	6	29	0	0	0	29	12	74	24	3	SA	0.00	1.00
		H34	1.05	2.91	1.90	40	8	14	2	2	1	31	0	0	0	31	1	64	14	23	SL	0.00	1.00
		H36	1.01	2.67	1.87	38	8	10	7	2	1	27	0	0	0	27	7	68	14	18	SL	0.01	0.98
		H38	1.05	2.48	3.45	27	11	14	9	1	2	33	0	0	1	34	2	53	21	27	LA	0.02	0.97
		H40	0.99	2.38	2.20	35	7	16	4	1	1	32	0	0	1	33	3	61	12	28	LA	0.02	0.98
		H41	1.07	2.16	2.68	35	8	10	10	2	1	30	0	0	1	31	3	66	15	19	SL	0.03	0.96
		H42	0.94	2.33	1.51	37	8	7	5	3	1	30	0	0	1	31	8	72	15	13	SA	0.02	0.98
		H43	1.05	2.12	1.51	29	14	8	7	2	1	37	0	0	1	38	1	57	27	16	AA	0.03	0.97
		H44	0.87	2.44	1.42	35	8	12	6	1	1	34	0	0	1	35	2	64	14	22	SL	0.02	0.97
		H45	0.77	2.22	1.52	35	7	10	9	1	1	31	0	0	0	31	6	67	13	20	SL	0.00	1.00
		H46	0.88	1.99	2.13	32	10	10	9	1	1	33	0	0	1	34	3	62	19	19	SL	0.03	0.97
		H47	0.77	1.97	3.45	30	15	8	8	2	1	34	1	0	0	35	1	57	28	15	AA	0.01	0.98
		H48	1.16	1.96	1.70	38	12	9	6	4	1	29	0	0	0	29	2	65	20	15	SA	0.01	0.98
		H49	0.84	2.43	2.16	33	12	13	5	3	1	31	0	0	1	32	1	57	21	22	SL	0.03	0.97
		H50	0.91	1.93	1.42	42	11	4	3	9	1	27	0	0	1	28	2	74	20	6	SA	0.03	0.97
		H51	0.96	1.54	1.42	34	11	12	6	3	1	32	0	0	0	32	1	59	20	21	SL	0.00	1.00
		H52	0.99	1.74	2.55	35	9	10	6	3	3	33	0	0	0	33	1	65	17	19	SL	0.00	1.00
		H53	0.86	1.94	2.30	32	7	11	9	2	3	26	1	0	1	28	8	65	15	21	SL	0.02	0.92

* corrected size: Harrel & Erikson (1979); Mz = Mean grain size; So = Trask sorting coefficient

Q = Total quartz = Qm + Qp; F = Total feldspar = K + P; L = Total lithic fragments = Lm + Ls + volcanic lithic fragments (not accounted); M = Mica; Mc = Miscellaneous; 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; SCTC = (Cfc+Cs)/Ct; SL = Sublitharenite; SA = Subarkose; AA = Arkosic arenite; LA = Lithic arenite; FG = Feldspathic graywacke

TABLE 2. Indices of interlocking microfabrics and definition.

Indices of interlocking microfabrics	Definition
Consolidation factor	$Pcc = \frac{5Su + 4Cc + 3Lo + 2Ta + Fl}{500} 100$
Concavo-convex index	$CCI = \frac{Gc}{G\text{-}G} 100\%$
Strong over weak contact	$SOWC = \frac{Su + (G\text{-}G)}{Ta + L + (G\text{-}V) + (G\text{-}M)} 100$

Pcc ranges from 23 to 65% and CCI from 0 to 47%. Pcc and CCI exhibit diminishing up-section trends (TABLE 3). These indicate that sandstones from NB have undergone substantial compaction compared to those from SB.

SOWC varies in a wide range from 0.78 to 6.04 and shows a fluctuating trend in vertical level. Higher values of Su contact and G-C respectively in sandstones from NB and SB give this trend.

Packing proximity and packing density

Packing proximity (Pp) and packing density (Pd) of Kahn (1956) are illustrated in FIGURE 7. Pp and Pd vary from 11 to 72% and 59 to 94%, respectively. Usually, high Pp and Pd are obtained in sandstones from NB than in those from SB (TABLE 2). It indicates that grains in older sandstones are in frequent contacts and are closely packed (FIGURE 6a), compared to those in the younger sandstones (FIGURE 6b).

Preferred orientation fabric

Elongate grains (micas and pelitic rock fragments), which have their length/width ratio often exceeding 2, were measured for acute angular differences, and then grain orientation factor (GOF) was calculated based on an angle factor proposed by Howarth & Rowland (1986). GOF varies from 1.22 to 3.45, being low in sandstones from NB, which is attributed to rearrangement of grains under compaction. Some fifty percent of sandstones from SB exhibit low GOF suggesting that they are rather depositional or modified during early phase of diagenesis.

Deformation fabric

Bended micas, squeezed micas or pelitic rock fragments and fractured grains all show mechanical deformation fabrics (FIGURE 8a). Such deformational fabrics preserve evidence of compaction during shallow to deep burial diagenesis (Liu, 2002). Chemical deformation involves pressure solution of grains. Deformational fabrics are observed in sandstones from both NB and

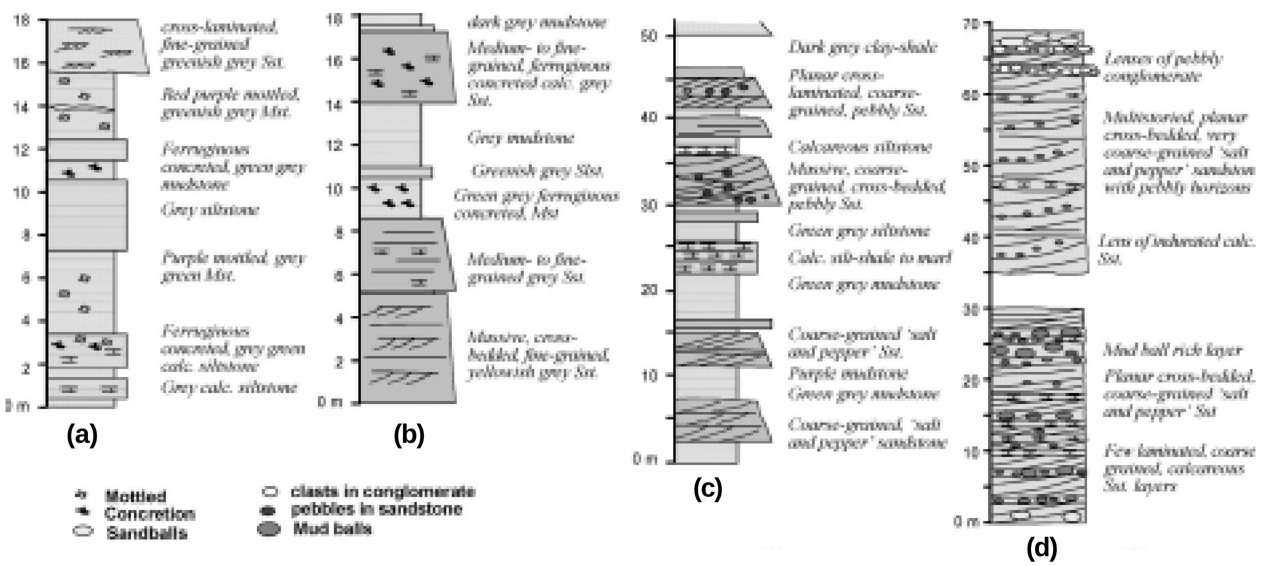

FIGURE 2. Columnar sections of the Rapti Formation and Amlekhganj Formation; (a) Rapti Lower Member at the left bank of the Pantale Khola, (b) Rapti Middle Member at the right bank of the Rapti River, north of the Rapti Bridge in Hetauda, (c) Rapti Upper Member at the right bank of the Dudhaura Khola and (d) Amlekhganj Formation at the at the right bank of the Chure Khola.

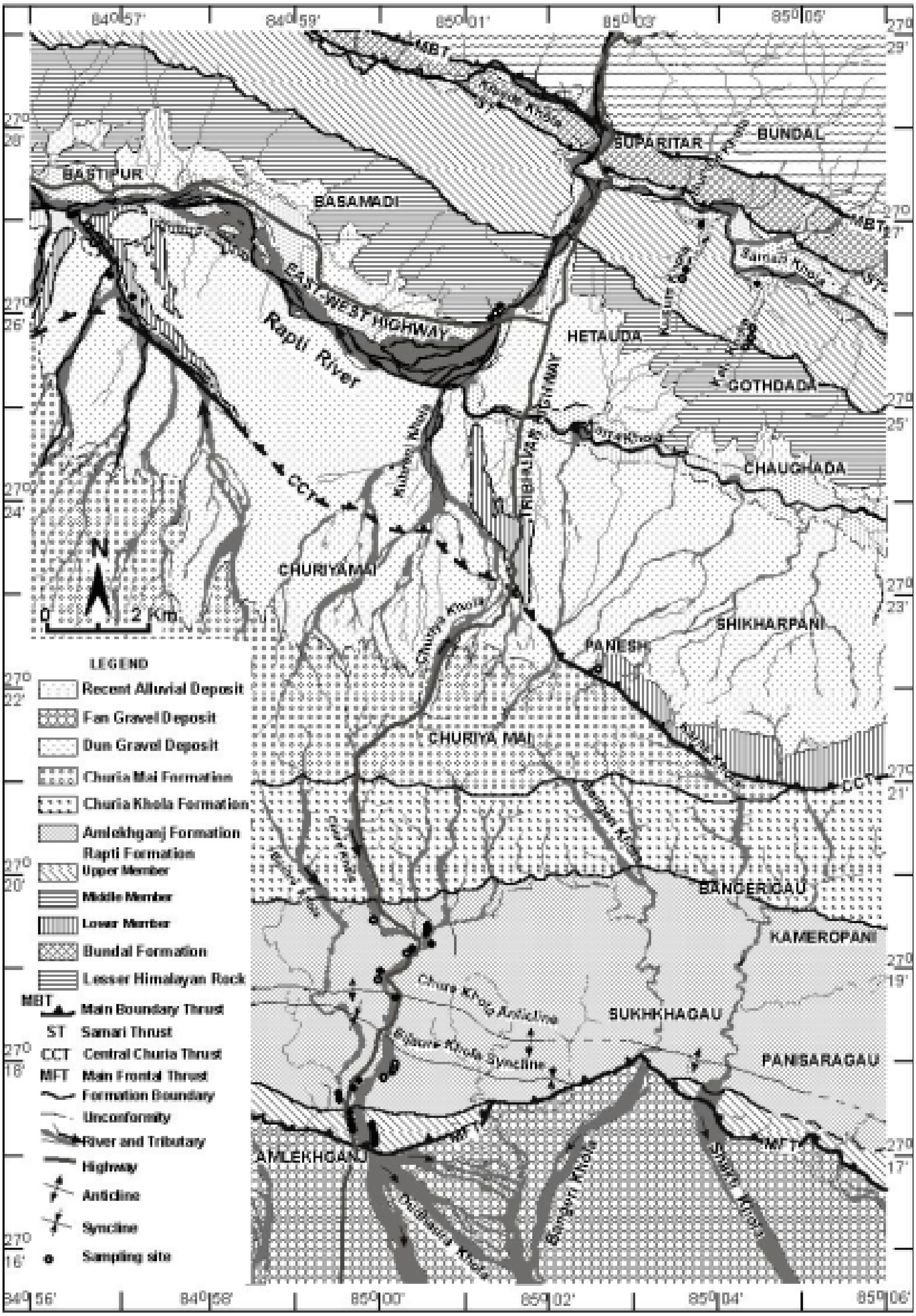

FIGURE 3. Sample locations in the Siwalik Hills.

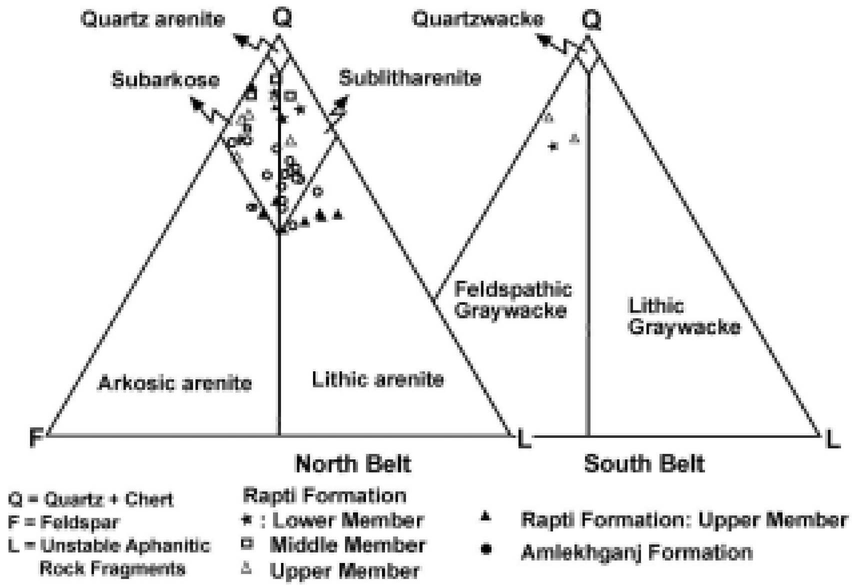

FIGURE 4. Plots of the Siwalik sandstones in QFL-ternary diagram of Pettijohn et al. (1987).

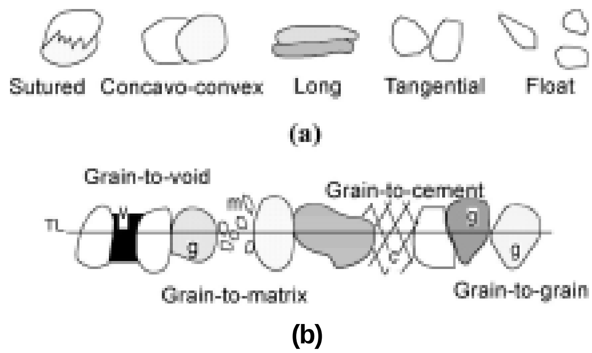

FIGURE 5. (a) Showing contact types, and (b) Grain-to-grain and grain-to-other constituent contacts (TL = traverse line; c = cement; v = void; g = grain; m = matrix).

SB. In NB, sandstones exhibit notable compaction and pressure solution, which suggest deep burial diagenesis. Sandstones from the Amlekhganj Formation virtually lack pressure solution. However, they contain few concavo-convex contacts between grains, brittle grain fractures and ductile deformation (FIGURE 8a) indicating that these sandstones have undergone substantial compaction prior to pervasive cementation.

Authigenic fabric

Fabrics of new minerals and related features generated in situ are grouped into authigenic fabric. Overgrowth fabric (FIGURE 8b) is seen in sandstones from NB. Clay mineral authigenesis is observed in samples from NB, where it occurs as patch and bridge between grains. Iron oxide cements are developed as coating and patch. Pore filling calicitic (ferroan) cement (FIGURE 8a) is very well developed in sandstones from SB. Such cements show mosaics of sparry calcite. Grain fractures (secondary pores) are often filled with calcite cement (FIGURE 8c) in all samples. Some sandstones from NB show heterogenous distribution (as patches) of carbonate cements. Such distribution of cement may indicate precipitation in secondary pores. Replacement fabric is pronounced in sandstones from SB in which poikilotopic and ghost fabrics are also developed (FIGURE 8d). These authigenic microfabrics suggest pervasive carbonate cementation and replacement obliterating depositional signature in sandstones.

SEQUENCE OF MICROFABRICS DEVELOPMENT

Paragenetic sequence of sandstones from NB and SB differs in some aspects (FIGURE 9). The former exhibits quartz overgrowth, pressure solution and packed fabrics, which suggests initial silica cementation, progressive burial to a greater depth and pressure solution. Some of the preferred orientation developed by authigenic micas probably formed during deep burial diagenesis. Carbonate cement, which occurs as patch, could be late and could have cemented sandstones in which pore fluid could move easily due to development of secondary pores during the late phase. Therefore,

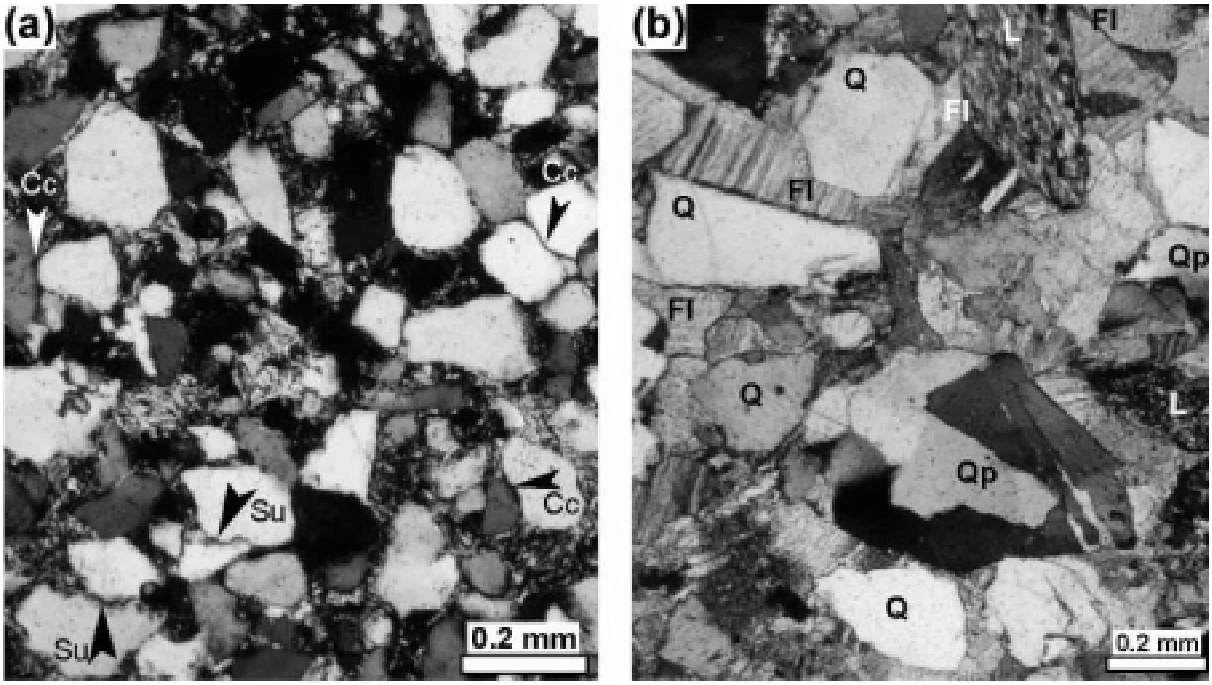

FIGURE 6. Photomicrographs of the Siwlaik sandstones showing contacts and packing microfabrics. (a) Sutured and concavo-convex contacts in sandstone from NB and (b) Float contact and loose packing of grains in sandstones from SB showing low Pp, Pd and Pcc.

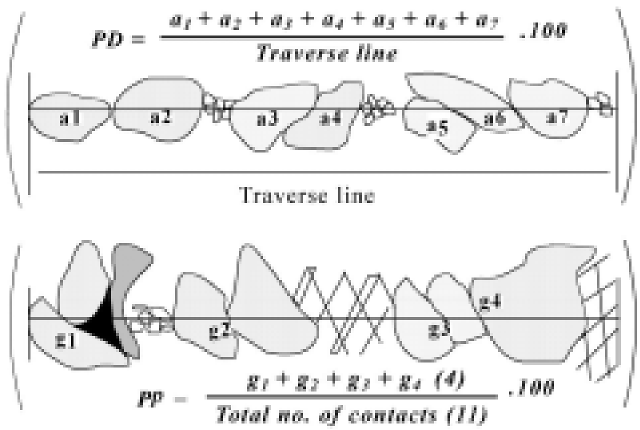

FIGURE 7. Schematic diagrams showing method of determining packing density and packing proximity (after Kahn, 1956).

these sandstones underwent deep burial diagenesis, and carbonate cements could be introduced at shallower depth after the uplift of the strata.

Sandstones from SB exhibit extensive carbonate cementation, replacement of siliceous grains and some mechanical grain deformation, but lack pressure solution and sutured contacts. Fl, Ta and Lo contacts dominate over Cc contact in these sandstones. Cements also fill fractured grains. In these sandstones, the weaker grains deformed initially in the early phase of diagenesis. As the brittle grain fracturing requires more stress than ductile grain deformation (Stone & Lumsden, 1984), the sediment could have buried under overburden stress, and grains could have readjusted to become closer. The Ta and Lo contacts, which formed initially, perhaps modified to Cc contacts during further compaction with increased depth of burial. Mechanical deformation and grain rearrangement could have occurred at the early phase because fractures in grains, which were filled by cement, were produced prior to cementation. Carbonate cement subsequently filled integranular pores preventing much closer packing of grains. Because carbonate cement also has extensively replaced siliceous grains in all the sandstones, strata must be well connected to carbonate rich meteoric water. On the other hand, lack of evidences of authigenic micas, sutured contacts and pressure solution indicate that the sandstones of SB were not as deeply buried as the sandstones of NB.

TABLE 3. Microfabrics of packing and orientation.

Sample	Packing Microfabric											Petrographic Indices			Grain
No.	% Contact type					% Contact nature				PP	PD	Pcc	CCI	SOWC	Orientation
	Su	Cc	Lo	Ta	Fl	G-G	G-C	G-M	G-V	%	%	%	%		Factor
1H1	15	26	18	3	38	62	19	9	10	62	94	55	42	0.85	1.98
H1	36	22	7	2	33	67	25	4	4	67	91	65	33	3.59	1.81
H2	30	20	8	2	40	60	10	28	2	60	92	60	33	1.00	3.10
H3	26	15	9	2	48	52	35	11	2	52	85	54	29	2.54	2.65
H4	36	15	4	7	38	62	13	21	4	62	92	61	24	1.36	2.82
1H2	24	12	5	1	58	42	42	16	0	61	89	49	29	3.00	2.46
1H3	34	13	7	2	44	56	37	7	0	56	90	58	23	4.44	2.43
1H4	43	9	11	1	36	64	29	3	4	64	94	64	14	3.79	2.45
H5	21	25	7	1	46	54	28	11	7	54	89	55	46	1.88	2.23
H6	21	23	26	2	28	72	15	10	3	72	94	61	32	0.88	1.46
H7	19	18	21	3	39	61	21	13	5	61	93	55	30	0.95	1.95
H15	24	22	20	2	32	68	12	16	4	68	89	61	32	0.86	3.57
H16	20	17	16	1	46	54	26	14	6	54	90	53	31	1.24	3.32
H8	17	12	11	4	56	44	39	13	4	44	91	46	27	1.75	3.09
H17	13	20	17	6	44	58	38	2	2	58	92	50	34	1.89	3.03
H18	20	28	17	6	29	71	14	7	8	71	95	61	39	0.89	2.13
H21	0	16	17	1	66	34	64	0	2	34	78	37	47	3.20	1.72
H22	0	8	18	7	67	33	65	0	2	33	72	33	24	2.41	2.86
H23	0	10	14	22	54	46	49	2	3	46	83	36	22	1.20	1.88
H24	0	6	14	16	64	36	64	0	0	36	75	32	17	2.13	1.92
H25	0	5	10	7	78	22	76	0	2	22	72	28	23	4.00	2.58
H26	0	1	18	18	63	37	54	7	2	37	73	31	3	1.21	3.45
H27	0	6	10	15	69	31	66	0	3	31	78	31	18	2.29	2.06
H28	0	9	26	7	58	42	51	3	4	52	83	37	21	1.28	2.98
H30	0	7	14	10	69	31	65	1	3	31	83	32	24	2.36	2.21
H32	0	5	15	9	71	29	61	3	7	29	70	31	19	1.81	1.22
H33	0	14	21	12	53	47	38	12	3	47	77	39	30	0.78	1.42
H34	0	8	12	11	68	32	68	1	0	32	80	32	26	2.80	2.24
H36	0	8	17	9	66	34	61	2	3	34	79	33	23	1.94	1.73
H38	0	4	16	13	68	32	65	2	0	32	73	31	12	2.11	1.44
H40	0	3	15	16	66	34	65	1	0	34	78	31	9	2.03	1.58
H41	0	1	21	24	54	47	54	0	0	47	80	34	3	1.18	2.55
H42	0	1	7	17	75	25	72	0	3	25	70	27	3	2.67	1.99
H43	0	1	7	12	80	20	80	0	0	20	60	26	4	4.25	2.45
H44	0	0	3	11	86	14	86	0	0	14	61	23	0	6.04	2.87
H45	0	1	8	8	83	17	81	0	2	17	64	25	5	4.35	2.00
H46	0	0	6	16	78	22	76	1	2	22	65	26	0	3.10	2.35
H47	0	0	9	14	77	23	76	1	0	23	68	27	0	3.15	2.31
H48	0	1	14	9	76	24	75	2	0	24	60	28	4	3.11	1.59
H49	0	0	9	11	80	20	79	1	0	20	62	26	0	3.82	2.51
H50	0	1	9	9	81	19	81	1	0	19	72	26	3	4.32	2.13
H51	0	0	8	9	83	17	81	0	2	17	61	25	0	4.26	2.04
H52	0	0	5	12	83	17	83	0	0	17	59	24	0	4.88	3.00
H53	0	1	14	19	66	34	62	3	1	34	73	30	4	1.66	1.64

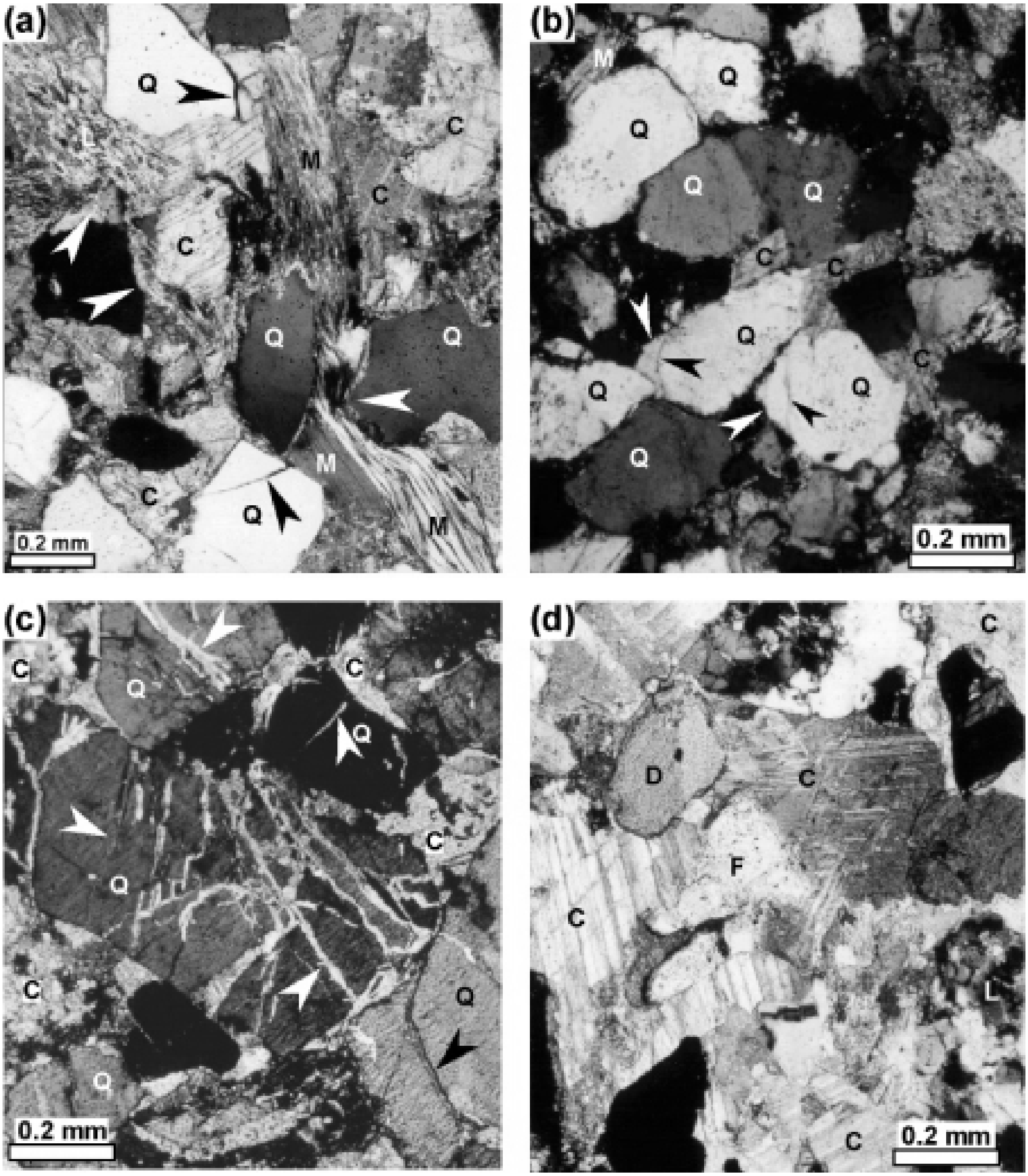

FIGURE 8. Photomicrographs showing deformational and authigenic fabrics. (a) Ductile and brittle deformation of grains; white arrows indicate squeezing of micas and black arrows indicate fractures in grains, (b) Syntaxial overgrowth of quartz (Q); white arrows indicate silica cement while black arrows indicate formal grain boundaries, (c) Fractures in quartz grains filled up by calcitic cement and some pore-filling cement between grains; black and white arrows indicate fractures with cement, and (d) Replacement fabric; poikilotopic fabric exhibited by replacement of feldspar (F) by calcite (C) (Q = quartz, C = calcite, L= lithic fragments and M = mica and D = tourmaline).

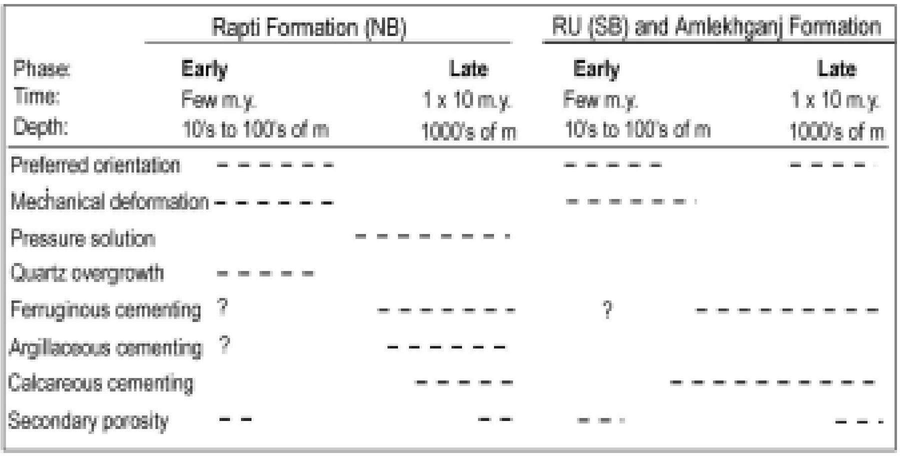

FIGURE 9. Generalized paragenetic sequence of fabrics in the Siwalik sandstones. Question marks denote probable occurrence.

CEMENTATION VERSUS COMPACTION ON MICROFABRICS DEVELOPMENT

Compaction and cementation are two important diagenetic processes that lead to consolidation of rocks. Whichever of these processes dominates in sandstone is the function of framework composition, texture, fluid circulation, quantity of cement, geothermal gradient, tectonic history and depth of burial (Houseknecht, 1984; Compton, 1991). Both compaction and cementation tend to reduce depositional porosity of sediments (Lundegard, 1992; Ehrenberg, 1995).

Void in sandstones tends to decrease as increase in cement and decrease in matrix. Also void tends to diminish with reduction in Pcc. This is the case in sandstones from SB that have low Pcc but have pervasive carbonate cement that exceeds all other types of cement.

Therefore, the cementation played important role in reducing intergranular volume in these sandstones.

Sandstones from NB exhibit most of the fabrics resulted by compaction, while cementation played little in development of fabrics. In these sandstones, the total amount of cement is little and matrix is high compared to that in sandstones from SB (younger sandstones). The tightly packed fabric, pressure solution and quartz overgrowths are characteristic features, which are not observed in the younger sandstones. High packing indices, pressure solution and preferred orientation in the older sandstones suggest intergranular volume reduction mainly by compaction. From early to late phase of diagenesis of these sandstones, compaction must have played major role and cementation subordinate role in reducing original voids in sediments. The overall clues (microfabrics, existing void and cement, and paragenetic sequence) suggest that the porosity reduction in the older sandstones was chiefly by compaction while that in younger sandstones was firstly by compaction and then by cementation.

CONCLUSIONS

(1) Sandstones from NB possess high Ca/Ct and high matrix content but low SCTC, while the reverse applies for the sandstones from SB.

(2) G-G, Su, Cc, Lo, Pd, Pp, Pcc and CCI diminish up-section but G-C, Ta and Fl increase indicating that the sandstones from NB are closely packed and are much consolidated, whereas the sandstones from SB are loosey packed, but with strong cement.

(3) SOWC is high in either strongly cemented sandstones from SB or in sandstones from NB with sutured contact. Similarly, GOF also varies widely and independently with stratigraphic level.

(4) Sandstones from NB were subjected to deep burial diagenesis, in which little initial cementation was followed by progressive compaction. Sandstones from SB were subjected to mechanical compaction followed by extensive carbonate cementation.

(5) Fabric developed and pores reduced due largely to compaction in sandstones from NB, but that in the sandstones from SB are due mainly to cementation and less to compaction.

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