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PETROFACIES IMPLICATION FOR THE LOWER SIWALIK FORELAND BASIN EVOLUTION, KUMAUN HIMALAYA, INDIA

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ABSTRACT

The Lower Siwalik sequence, 300-900 m thick, is made up of light green - brown buff sandstone interbedded with greyish brown-maroon coloured fine-grained horizons. The sequence is composed of quartz, lithic grains, mica and feldspars. The submature sandstone present from base to 500 m level is fine-grained (.15-.25mm), has argillaceous-siliceous cement, while the mature sandstone present above this level is dominantly medium-grained (.25-.35mm), shows preburial (phreatic zone) diagenesis and is calcite (sparitic) cemented. The sandstone is classed as sublithicarenite which becomes calcareous near the top of the sequence. Mottled siltstone succession (interfluve deposits) are well sorted having ferron cement, shows cryptoturbation and calcrete development. The Mudstone succession (flood plain deposits) is immature, ill sorted having subangular to angular silt and fine-sand sized grains set in muddy matrix. The provenance is recycled orogen-fold/thrust belt comprising metamorphic, granitoid and sedimentary suits. The petrographic analysis reveals that initially, the Lower Siwalik Foreland Basin was deep, narrow and actively subsiding, and with continued sedimentation became wider and slowly subsiding. The sedimentation took place under episodic tectonism and sub-humid climatic conditions.

Key words: Petrofacies, Lower Siwalik, Foreland Basin, Kumaun Himalaya.

INTRODUCTION

Petrogrpahic analysis of clastic sedimentary rocks is a useful approach to unravel basin evolution in plate tectonic context, source area lithology (provenance), intensity of orogen (tectonic activity) and subsequent unroofing by erosion (Dickinson and Suczek, 1979; Mack, 1984; Dickinson, 1985; Ingersoll, 1990). On the other hand, some workers paid attention to other factors such as climate, relief and chemical weathering responsible for sandstone genesis, compositional varaitions, variations in the detrital fragment population and textural parameters (Basu, 1976; Mack, 1981; Suttner and Dutta, 1986; Johnson, 1990). However, mechanical before final deposition and abrasion - omision of labile rock fragments is a major factor responsible to shape the clastic rock texture. Moreover, all kinds of clastic rock signatures, especially climatic and weathering, can be dramatically modified during post depositional diagenesis (Wilson and McBridge, 1988; McBridge, 1985, Mc Bridge Bridge *et al.,* 1991; Blatt, 1992).

A key element of the foreland basin is their syntectonic character. In the foreland basin set up, sediment fill directly responds to overriding thrust plane tectonics (ramp) and their unroofing - erosion in response to climatic changes (Critelli and Ingersoll, 1994; Critelli and

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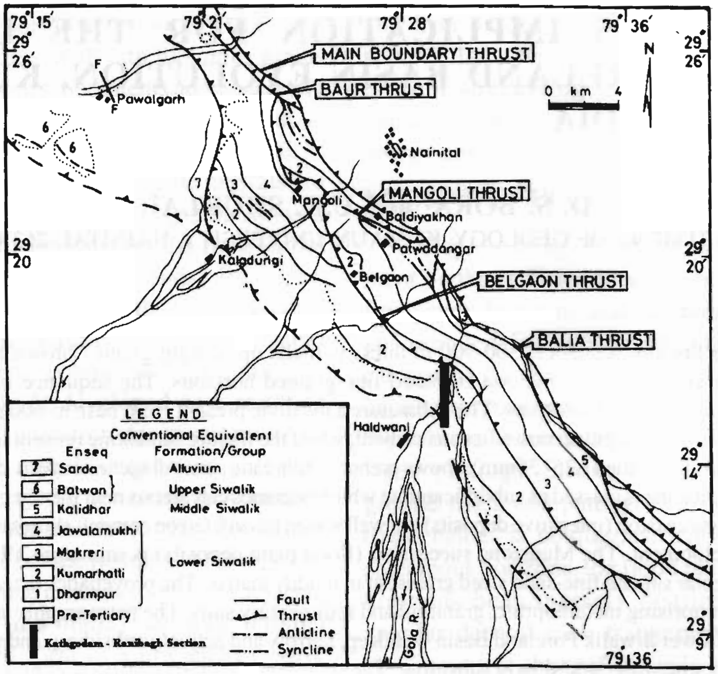


Fig. 1. Geological map of the study area showing location of Kathgodam - Ranibagh section (modified after Rangarao *et al.*, 1976).

Garzanti, 1994; DeCelles, *et al.,* 1998). This process leads to time progressive shift in the locus of deposition and subsidence, and give rise to the concept of migrating fore deep (Espezo and Lopezgamunde, 1994) studies on Siwalik foreland basin have received attention for petrographic investigations since a long back to unravel the thrust fold orogeny and subsequent unroofing, erosion and sedimentation in response to tectonic and climatic changes (DeCelles *et al.*, 1998). In the Indian part, the petrographical studies on the Siwalik rocks are quite sketchy, confined mainly to Jammu (Pandita and Bhat, 1995); Punjab (Tandon and Narayan, 1981); Himachal (Sikka *et al.*, 1962) and Uttaranchal sectors (Tandon, 1976; Prakash *et al.,* 1980; Kumar *et al.,* 1999; Kumar *et al.*, 2002). Nevertheless, probably because of difficult tectonic setting, intense deformation and non-availability of good outcrops, the Siwalik succession exposed in the study area around Nainital district, Kumaun Himalaya, has been ignored and no systematic investigation is available. Therefore, the present study focuses on petrographical aspects of the Lower Siwalik, representing most crucial earliest phase of foreland basin evolution in the Kumaun sector. Comments have been made on provenance, sandstone classification and petrofacies evolution. The approach has been helpful to unravel the variations in sediment source in response to thrust fold tectonics, climatic - weathering effect in the sediment fill, and post depositional diagenetic changes.

GEOLOGICAL SET-UP

Subduction related thrust tectonism has caused development of major thrust planes that differentiated Himalaya into five litho-tectonic

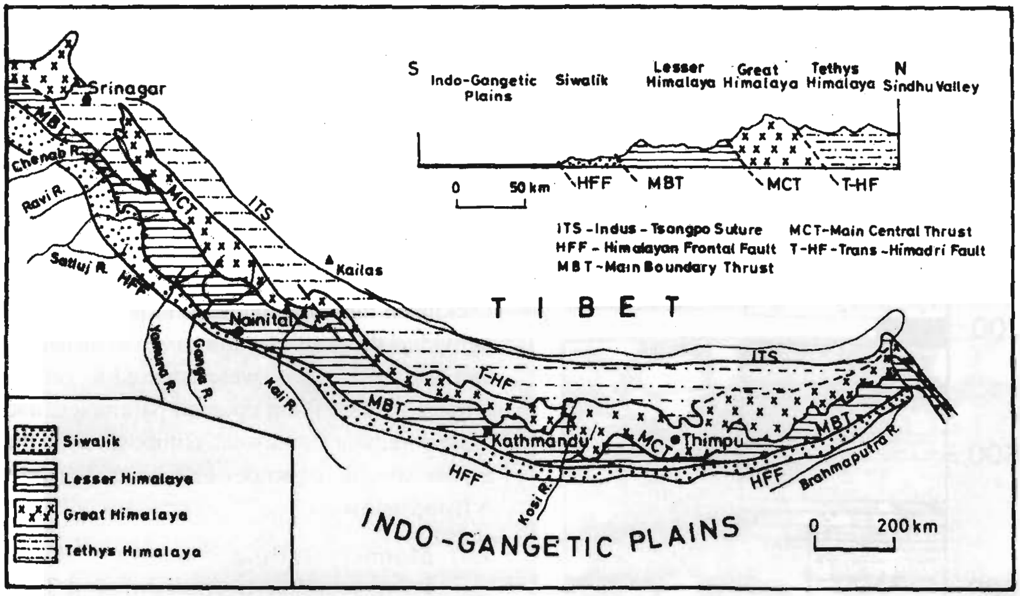


Fig. 2. Gelogical map of the Himalaya showing major lithotectonic provinces separated by bounding thrust planes (modified after Valdiya, 1998).

provinces, Sub-Himalaya (Siwalik), Lesser Himalaya, Higher Himalaya and Tethys Himalaya (Gansser, 1964) (figs. 1, 2). South vergent major thrust planes of high structural dips (40° - 70°) separate all these units. The Lesser Himalayan rocks, comprising quartz arenites, diamictites and carbonate-shale sequences, and the lave flows of spilitic affinity, are delimited in the north by the Main Central Thrust (MCT), which has separated them from a variously metamorphosed slab of central crystalline rocks forming the glaciated Higher Himalaya. The Lesser Himalayan sequence shows multiphase deformation, and a thrust contact with Neogene Siwalik succession along MBT. The Siwalik rocks in turn are thrut over the Piedmont zone, the northern most geomorphic element of Gangetic plain, along Himalayan Frontal Fault (HFF) (Nakata, 1972; Valdiya, 1988).

The Lower Siwalik succession in the study area is 300 - 900 m thick (fig. 2). The sequence is made up of compact, fine-grained, multistoried sandstone alternating with thick grey to maroon, muddy - siltstone horizons. The sandstone horizons are on an average 5-15 m thick, and show a varied distribution through space and time. In contrast to channel related flood plain deposits, thickly developed (8-43 m thick) muddy fine-grained horizons represent sedimentation in interfluve setting, which is an independent domain of sedimentation, not related to active channel processes (Singh *et al.,* 1999; Shukla and Bora, 2000; Sharma *et al.,* 2001).

METHODOLOGY

For petrographic study 50 smaples were collected from fresh, unweathered and tectonically undisturbed outcrops, systematically from oldest to youngest horizons in Kathgodam-Ranibagh section (fig. 3). Samples are collected from three major fluvial sub environments, namely Sandstone Succession

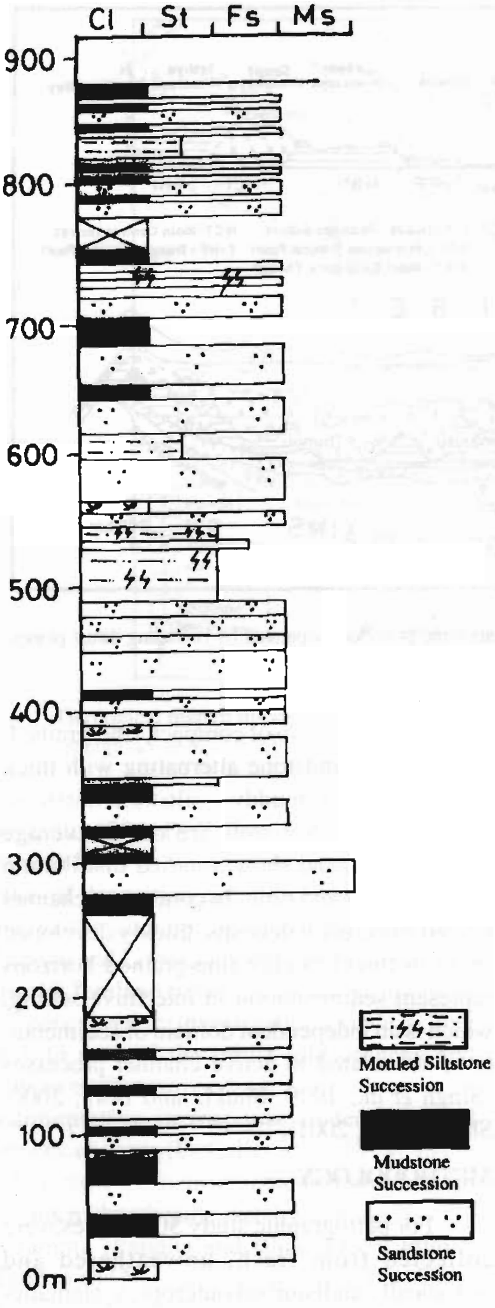


Fig. 3. Generalised litholog of the Kathgodam - Ranibagh section showing vertical variation of sandstone, mudstone and mottled siltstone successions.

(channel environment), Mottled Siltstone Succession (Interfluve environment) and Mudstone Succession (Flood plain environment). In the sandy successions, samples are preferentially collected from mid portion of the sand bodies, and eleven representative slides have been subjected to detailed model counting techniques (*cf.* Raynold *et al.,* 1993). The point counting technique is used following Gazzi - Dickinson method (Ingersoll *et al.,* 1984). In individual thin section, grain size was measured and 400 - 600 points were counted to get the reliable results. Point counted parameters and most dominant framework composition in the Lower Siwalik sequence of Kumaun Himalaya is listed below.

1. Monocrystalline quartz (Qm); Polycrystal-line quartz (Qp); and Total quartzose grain (Qt) = Qm + Qp
2. Lithic sedimentary - metasedimentary grain (Ls, including sandstone, siltstone, argillite, carbonate, chert, slate); Lithic metamorphic grain (Lm, including schist, foliated quartz, phyllite); and Total lithic grain (Lt = Lm + Ls).
3. Potash feldspar (K, including orthoclase, microcline, perthite); Plagioclase feldspar (P, including albite, oligoclase); and Total feldspar (Ft = P + K).
4. Cement (silicic, argillic and calcic)
5. Matrix (Mixture of clay minerals, mica, micrite and iron oxide)

In addition, mica and iron oxide minerals are also taken into account. For provenance modelling Qm-F-Lt and Qp-F-Lt ternary fields are used after recalculating the coordinate values to hundred percent (*cf.* Dickinson and Suczek, 1979; Dickinson,1 985).

SANDSTONE SUCCESSION

The sandstone of the Lower Siwalik are composed of quartz, lithic grain, micas and

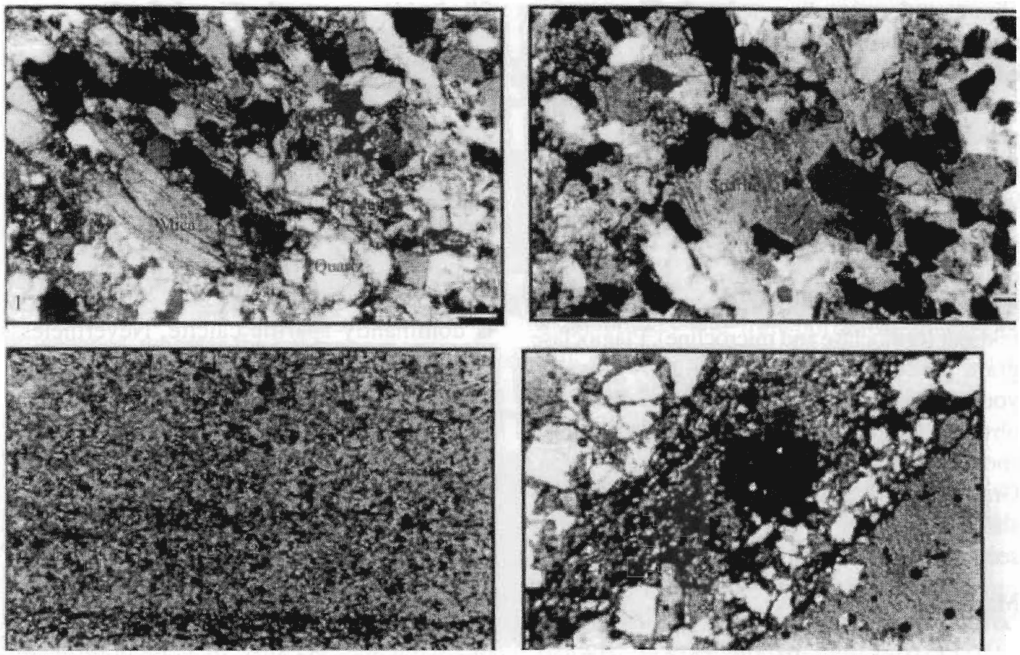


Plate I- Sandstone compostion at lower level in the sequence (Quartz grain, Lithic grains, Mica and Matrix); 2. Sandstone compostion at upper level in the sequence (Quartz and Lithic grains floating in sparitic cement); 3. Compostion of well sorted siltstone in Mottled siltstone Succession; 4. Photomicropgraph of silty-sandy units in Mudstone succession. Bar length is 1 mm. View is in crossed nicol.

feldspars in their decreasing order of abundance. The quartzose grains include both monocrystalline and polycrystalline grains and constitutes 50% - 60% of the bulk composition (Plate I, fig. 1) Monocrystalline quartz shows complete extinction, and is the most dominant detrital component, constituting 50% - 60% of the total population. Polycrystalline quartz grain constitutes just 2% - 5% of the bulk composition and shows wavy extinction. These grains are usually fractured and larger than the other grains. Within larger graines, the smaller grains are randomly packed with intracrystalline boundaries (Plate I). Most of the grains are sub-angular to sub-rounded. However, few grains are well rounded and show a distinct clay rim around them. Vaculose filling and fluid-mineral inclusions in the grain are rare. The overgrowth and grain boundary corrosion is also rare.

Lithic grains constitute 7% - 17% of total framework composition. It includes both sedimentary and metamorphic grains (Plate I, fig. 1). These grains show a wide variation in size and shape with well defined boundaries. Lithic sedimentary grains constitute 1% - 3% of total composition and include dominantly argillite and siltstone, however, rarely chert and carbonate grains are also present. Lithic metamorphic grains constitute nearly 6%-15%, including dominantly mica schist, foliated quartz, gneisses and phyllite. The lithic sedimentary grains are commonly squeezed and smashed forming pseudo-matrix.

Biotite and muscovite combined together constitutes 2%-10% of total detrital composition (Plate I, fig. 1). However, biotite dominates over muscovite, especially muscovite decreases up section. The mica grains are tabular to lath like and show preferred alignment forming discrete bands. These grains are bent, squeezed and crumpled. The intensity of bending varies in different transects of individual thin section. Their alter nation and sericitization is a common feature. In some sand bodies, these grains are almost absent.

The feldspar grain population is very small, constituting just 1%-5% of the total detrital framework (Plate I, fig. 1). The plagioclase feldspar dominates over the potash feldspar (orthoclase and microcline). Plagioclase grain percentage increases slightly towards younger horizon, however no such change is obvious for potash feldspars. Feldspar grain shows distinct boundary with little corrosion. Grains are broken along twin laminae and also show alteration to clay minerals, forming secondary matrix.

Matrix

Petrography of the Lower Siwalik sequence demarcates two distinctly different modes of matrix and cement emplacement. From base to about 500 m level, sandstone contains variable matrix ranging form 9% to 10%. The matrix is fine-grained and filled between the interstices of the larger grains in squeezed form. It is dominantly made up of mixture of argillitic rock fragments, quartz, micas and iron oxides. The flaky mica grains show preferred alignment, bending around grains and clay seam development. The matrix is primary as well as secondary (pseudo matrix). Many mica grains are sericitized and feldspar grains are altered to clay minerals. The mechanical and chemical compaction is responsible to produce secondary matrix. This argillaceous matrix might have created some primary porosity in this part, which would have been dramatically reduced due to mechanical compaction. However, no edivence of secondary porosity is observed. Characteristically, the sequence lying above 500 m level is almost devoid of the matrix content, except some clay content mixed with micrite is present in the interstices. The pore spaces are filled with cement only (Plate I, fig. 2).

Cement

From base to about 500 m level, cement is poorly developed, and is muddy to siliceous in nature constituting (7% - 10%) of the bulk composition (Plate I(2)). In contrast, from 500 m to 900 m level, sandstone has dominantly carbonate cement (Plate I, fig. 2). The cement representation ranges from 20% - 30%. Cement is dominantly sparitic calcite. Nevertheless, occasionally micritic cement is present with muddy matrix. The micritic cement is microcrystalline to cryptocrystalline in nature. The carbonate cement is present in two forms. Dominantly it is filling the grain interstices (drusy); and occasioanlly individual grains are floating in the cement (poikilotopic). Cement is displacive in nature, however, sometimes replacement is also observed. In this part of the sequence, because of cementation, the primary porosity is completely hindered. Nevertheless, occasional alteration and replacement may have imparted secondary porosity to the rock (*cf.* Schmidt and Mc Donald, 1979; Surdam *et al.,* 1989).

Texture

The Lower Siwalik sand bodies are made up of fine to medium-grained (0.15-0.35 mm) sand. Grains are sub-rounded to sub-angular, showing point as well as tight grain contacts. Larger grains forming the framework, are better rounded than the smaller ones present in the matrix. Some recycled quartz grains show well defined boundary marked by clay rim precipitation around them. Well rounded shape of these grains can be attributed to their recycled origin. The rocks show moderate to well-sorted texture.

In the lower levels of the sequence (up to 500 m levels), appreciable amount of matrix (3% - 10%) is present in the interstices of the grains. At this level matrix is primary as well as secondary. Characteristically, two different types of sand bodies are observed based on texture and mineral composition. In one case, grains are comparatively smaller, lithic fragments and mica grains set into matrix are common. Whereas in others, quartz grains are larger, fractured and better rounded, and mica content is comparatively less. The rock fragments are mostly shale and schist. The detrital grains are set into muddy matrix and argillaceous cement. The former case may indicate metamorphic provenance, whereas the latter one may imply metamorphic - sedimentary provenance.

Above 500 m level, sequence is well sorted and matrix content is almost missing. The cement is mostly sparitic and muddy micritic in nature (Plate I, fig. 2). The mica content decreases and biotite dominates, however, platy laths are comparatively smaller. In general, sandstone of the Lower Siwalik sequence is sub-mature to mature in nature, and the rocks show fitted-grain and floating grain textures (Plate I, figs. 1, 2).

It is believed that the degree of compositional modification is a function of intensity of chemical weathering and distance of transportation. Loss of rock fragments, feldspar and muscovite grains during fluvial transport has been extensively documented. High gradient streams tend to disintegrate rock fragments into their constituent mineral. In the Lower Siwalik sequence, abundance of rock fragments, muddy matric and occasional mineral - fluid inclusions in quartz grains, particualrly at lower levels in the sequence, may suggest short distance of transportation. Subangular to subrounded grain shape, moderate sorting and submature texture, further, supports the contention of small transportation of the sediments. These inferences lead to the conclusion that probably provenance was not much distant from the depositional basin. The transportation energy, as evidenced by grain-size and dimension of associated bed forms, seems to range between 0.2-1.5 m/s (cf. Ashley, 1990).

Above 500 m level in the section, matrix is almost absent, sorting, roundness and maturity is improved. Mica grains become considerbaly smaller in size. The rocks are dominantly carbonate cemented (Plate I, fig. 2). These parameters may imply that as compared to the lower levels, the sediments were transported for a much longer distance. The rivers were probably larger in dimension with increased water budget and transportation energy. In turn, it may suggest that the basin might have been widened through time.

MOTTLED SILTSTONE SUCCESSION

In the Mottled Siltstone Succession, representing interfluve sedimentation (Singh *et al.*, 1999; Shukla and Bora, 2000), samples for petrogrpahic analysis were collected from channelised silty sandstone (Imch), well-sorted siltstone (Iwd), lenticular sandy siltstone (Ick) and banded calcrete (Ip) lithofacies. In general, the lithofacies of interfluve succession are micaceous and matrix-rich with high content of iron oxide.

In calcareous horizons of interfluve deposits the detrital grains are bounded by micritic calcite, and shows irregularly distributed patches of sparite. Irregularly oriented sparitic veins of varied dimension cut across randomly in micritic matrix. Occasionally, veins occur in isolation with minor tapering off-shoots. Such microfabric is common both in modern and ancient calcretes (*cf.* Wright and Tucker, 1991; Tandon *et al.*, 1998). Micrite forms through nucleation of closely spaced carbonate crystallites depending on supersaturation threshold (Wright, 1992; Khadkikar *et al.*, 1998). The sparitic veins with well developed calcite grains seems to be precipitated along shrinkage cracks, and subsequently cemented by pore filling sparite. However, smaller off-shoots tapering toward one end might be fillings created by rootlets.

The well sorted siltstone horizons are made up of quartz, small lath like mica grains and lot of iron oxides. Sediments are moderately to well-sorted (Plate I, fig. 3). The ferruginous cement fills the interstices. Howere, along micro fractures and pores sparitic clacite crystals are well developed. The detrital fragment shows a preferred alignment. Broadly the rock shows an array of unorganised bands, fractures/ burrows that are filled with comparatively coarser grained sediment than the ground matrix. The blocky patches of coarse material are spheroidal peds developed as a result of expansion and contraction due to soil moisture variation. The small, carbonate globules encased within clay and iron oxide are common, which may be the result of clay illuviation around in situ carbonate nodules. Alternatively, the small carbonate nucleus might be gathering mass around it in a muddy substrate through rolling back and forth in a low energy wave affected environment like small pond etc. However, sometimes these spherical globules also resemble with warm (annelid) excreta. Cryptoturbation is the ubiquitous feature of these horizons, evidenced through patchy homogenisation of preferred aligned ground mass. Actively filled burrows showing U and J shaped grain-alignment are common.

The lenticular sandy siltstone horizons are composed of quartz subordinate mica fragments with abundant matrix content showing organised alignment. The detrital grains are having plane to point contact. The rock is poorly sorted and matrix is dominantly composed of micritic calcite, mica and iron oxides. Usually iron oxides are dispersed throughout in the matrix, however, it also shows dark patchy concentration.

The channelised silty sandstone lithofacies is made up of monocrystalline silt and fine-sand sized quartz grains with subordinate mica grains showing alignment. Texture of the rock is immature to sub mature and illsorted. Matrix is made up of clay minerals and iron oxides. Quartz grains are usually subangular. Occasionally blocky peds are present suggesting marked soil moisture variation. The textural parameters reflect low energy environment.

MUDSTONE SUCCESSION

Representing the flood plain environment, in the mudstone succession, only silty - fine sandy horizons and calcareous horizons are sampled for petrographic analysis. The calcareous horizons are dominantly made up of micritic matrix and detrital grains. Sparite crystals are common along micro fracture and loose partings. Strong iron staining in the ground mass and patchy distribution of iron oxide haloes is ubiquitous. Unlike interfluve calcareous horizons, the flood plain calcareous horizons bear sparsely distributed, highly angular detrital rock frangement as well as clayey matrix that reflect episodic sediment influx through high energy currents.

The silty lithofacies of overbank environment are matrix rich, made up of clay, iron oxide and micrite. Lithology is poorly sorted, containing monocrystalline and subangular quartz grains (Plate I, fig. 4). The mica grains are showing preferred alignment reflecting their deposition through unidirectional low energy currents. The poorly sorted silt-fine sand-sized quartz grains are set into muddy matrix and show microscopic interbedding with muddy matrix. These horizons also contain small micrometer scale spherical globules, similar to mottled silty horizons of interfluve deposits that owe their origin as animal excreta, clay illuviation or mass gathering around a nucleus.

SANDSTONE DIAGENESIS

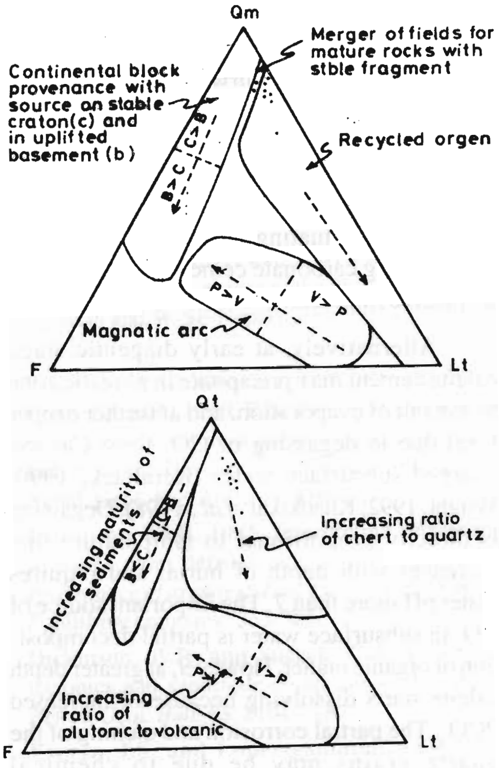
The degree of lithification depends on cement to grain contact (McDonald and Surdam, 1984). Increased amount of pore filling by matrix or cement may reduce the primary porosity. Below 500 m level in the sequence, sediments are rather immature and pore spaces were filled with primary and secondary matrix (pseudo-matrix). The cementing material is dominantly argillaceous, present as pore space filling. However, occasionally siliceous cement is also present. Because of higher matrix content at the lower levels, the decreased porosity might have restricted movement of pore fluids and precipitation of cement during the early diagenetic stage (cf. Wislon and McBridge, 1988). However, during subsequent deep burial, mechanical compaction squeezed the matrix and bent the flaky minerals that caused pseudo-matrix and argillaceous cement development. Subsequently, chemical compaction followed that produced clay seams, stylolites etc. at deeper levels. Some part of silica cement might have released because of feldspar and lithic grain alteration during their diagenetic transformation to clay minerals. This siliceous cement might have precipitated under acidic conditions during the later stages of diagenesis under deep burial. Abundance of primary matrix might have prohibited calcite cementation at the lower level, however its absence may also be a result of decarbonatisation during deep burial diagenesis. It results decarboxylation reaction in contained organic material. The released CO_2 combines with subsurface waters to form acidic solutions. The large volume of dissolved Mg^{2+}, Ca^{2+}, HCO^{3-}, and CO_3^{2-} ions may migrate upward during compaction and precipitate again as carbonate cement at higher level (Surdam *et al.,* 1989).

In contrast, above 500 m level, mature sediments lacking matrix were deposited and got cemented with carbonate material. The effect of mechanical compaction does not show any signature in the upper part of the sequence. It seems that due to improved porosity, pore fluids had opportunity to precipitate the cementing material presumably as phreatic zone carbonate cement in pore spaces. Therefore, the cement seem to be early diagenetic in origin. This sparitic calcite cement exceeds up to 40% and forming floating grain texture (poikilotopic). It seems that the pore fluids had high concentration of carbonate cement forming calcareous sandstone. The Ca+ charged surface as well as subsurface water might have been repeatedly fluctuating into porous sand and precipitating carbonate cement. The cement is displacive in nature.

Alternatively, at early diagentic stage calcite cement may precipitate in phreatic zone as a result of evaporation, and at further deeper level due to degassing of CO_2 from Ca^+ ion charged subsurface water (Retallack, 1990; Wright, 1992; Khadkikar *et al.,* 1998). Degassing is directly proportional to temperature that increases with depth of burial and requires water pH more than 7. The important source of CO_2 in subsurface water is partial decomposition of organic matter. However, at greater depth calcite starts dissolving because of increased PCO_2. The partial corrosion and etching of the quartz grains may be due to chemical compaction. Moreover, subsurface water chemistry, having pH conditions of 7-9, at a diagenetic temperature of 100°C and burial depth of 2000 - 3000 m also causes silica - calcite replacement. Under higher PCO_2, calcite quartz interaction depth decreases and lies at 40 - 130°C at a burial dpeth of 1500-3000 m (Hesse, 1987).

PROVENANCE

Eleven representative thin sections of sand bodies collected from lower to upper stratigraphic levels in Kathgodam - Ranibagh section have been studied for modal analysis. The point counted values of different petrographic parameters is listed in table 1, and the recalculated values are plotted in ternary diagrams Qm-F-Lt and Qt-F-Lt following Dickinson and Suczek, (1979) and Dickinson, (1985). These plots do not show any systematic variation in the provenance field (figs. 4, 5).



Figs. 4 and 5. Provenance plot in Qm - F - Lt and Qt - F - Lt diagrams showing recycled orogen source rocks (After Dickinson,1985).

The results fall in a cluster concentrating toward dominant quartz and quartz - lithic grain edge (figs. 4, 5). However, few plots also fall along quartz - feldspar edge of standard triangular diagram. These results show almost similar provenance fields in different diagrams. Both the diagrams clearly point to a recycled orogen source. Besides this, the sandstone is quartzolithic (Qt - Lt) with low feldspar and negligible volcanic grains. This indicates that the Lower Siwalik sandstone of study area falls in quartzolithic petrofacies, which is characteristic sequence in the last phase of petrofacies evolution of the foreland basin (Schwab, 1986).

The recycled orogen was probably constituted of varied suit of rocks comprising metamorphic, granitic and sedimentary rocks. Fine-grained quartz grains with undulose extinction can release from various rocks, such as phyllite, schist, gneiss etc, however, medium-grained quartz is most likely released from crystalline granites and granite gneisses. The most abundant vaculose free monocrystalline grains imply crystalline granite to granite gneiss source rock. The polycrystalline quartz grains of varied size are most likely derived from the metamorphic source rock. Furthermore, smaller sized quartz grains packed within a bigger polycrystalline grains support the view of their metamorphic origin. Rare fluid inclusions in quartz grains may suggest that they might have been derived from quartz veins of crystalline rock. Few well-rounded quartz grains with clay rim boundary indicate their recycled origin from

Table 1: Average modal analysis values of framework composition in selected sand bodies.

Height	Qm	Qp	Qt	Ls	Lm	Lt	P	K	Ft	Mica	Feo	Cem.	Mat.
50m	50	5	65	3	10	13	1	1	2	10	1	--	9
280m	60	4	64	2	8	10	1	1	2	2	1	12	9
320m	62	3	65	3	7	10	1	--	1	3	1	10	10
350m	60	2	62	2	7	9	2	--	2	3	1	12	11
360m	63	3	66	1	6	7	1	1	2	3	1	10	11
550m	50	5	55	2	15	17	4	1	5	3	1	7	10
620m	55	5	60	1	12	13	2	1	2	2	1	21	--
660m	50	3	53	2	8	10	2	1	3	2	1	29	--
740m	55	3	58	2	6	8	2	1	3	2	1	28	--
850m	56	4	60	1	7	8	3	2	5	2	1	23	--
890m	55	5	60	2	8	10	2	1	3	2	1	24	--

sedimentary source rocks.

Next to quartz, the lithic grains composed of sedimentary and metamorphic rocks are well represented in the sandstones. The availability of rock fragment in clastic sedimentary rocks depends mainly on aerial extent of drainage basin, highland / lowland topogrpahy, susceptibility to chemical and mechanical destruction and size of the fragments. Therefore, the lithic fragments may imply interplay of above mentioned first two factors, where tectonism may be a dominating factor. However, their representation in abundance may also be related to climate factors and degree of transportation. A sub-humid climate and a relatively small distance of transport may support their survival. Abundance of rock fragments suggests that sediments were deposited within a distance of 75-80 km from the provenance (cf. Suttner *et al.,* 1981).

Mica is poor provenance indicator. Biotite can be released from a wide variety of crystalline rocks, however muscovite may suggest a metamorphic provenance. In case of the Lower Siwalik sediments, close association of mica grains with other detrital fragments of crystalline and metamorphic affinity reflects a similar mixed origin. Nevertheless, persistent bending of preferred aligned mica layers suggests strong mechanical compaction.

Granitoid rocks release plagioclase feldspar with ease along convergent plate margins when erosion and burial are rapid, whereas potash feldspar is released with ease in intracratonic setting. However, quiescent cratonic condition is also suitable for release of little plagioclase in total feldspar population (Dickinson and Suczek, 1979). Percentage of feldspar in sandstone depends on rate of tectonic activity and weathering - climatic conditions during their release and subsequent transportation, however much of these signatures are lost if they have undergone diagenetic alteration and replacement. Some alteration - replacement of feldspar grains noticed in thin sections indicate that these grains were also affected during post depositional diagenesis. However, their supply from source seems to be low.

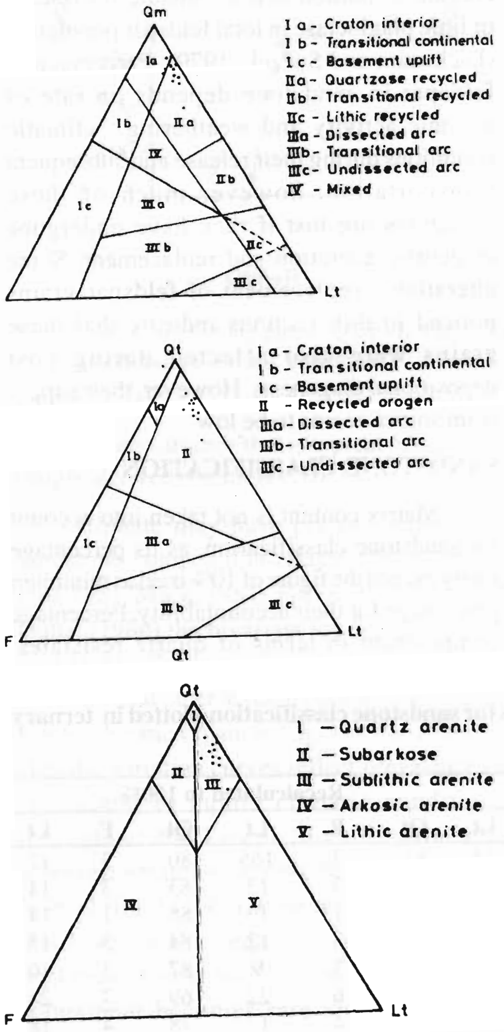
SANDSTONE CLASSIFICATION

Matrix content is not taken into account for sandstone classification, as its percentage rarely exceed the figure of 10% used as minimum percentage for their accountability. Percentage composition in terms of quartz resistates,

Table 2: Computed - recalculated to 100% values for sandstone classification plotted in ternary diagrams.

	Computed value						Recalculated to 100%					
Depth	**Qt**	**F**	**Lt**	**Qt**	**F**	**Lt**	**Qt**	**F**	**Lt**	**Qt**	**F**	**Lt**
50m	65	2	13	60	2	13	81	3	165	80	3	17
280m	64	2	10	60	2	10	84	3	13	83	3	14
320m	65	1	10	62	1	10	86	1	13	85	1	14
350m	62	2	9	60	2	9	85	3	12	84	3	13
360m	66	2	7	63	2	7	88	3	9	87	3	10
550m	55	5	17	50	5	17	71	6	22	69	7	24
620m	60	3	13	55	3	13	79	4	17	78	4	18
660m	53	3	10	50	3	10	80	5	15	79	5	16
740m	58	3	8	55	3	8	84	4	12	83	5	12
850m	60	5	8	56	5	8	82	7	11	81	7	12
890m	60	3	10	55	3	10	82	4	14	81	4	15

feldspar and rock fragments were recalculated to 100% from a list of all compositional data (Table 2), and plotted in ternary diagrams of sandstone classifications given by Dikinson, (1985) and Pettijhon *et al.* (1987) (figs. 6, 7, 8). Based on modal composition data, plotted in ternary plotting diagrams Qm-F-Lt and Qt-F-Lt the Lower Siwalik sandstone of the studied area falls in sublithicarenite plot (figs. 6, 7, 8). Nevertheless, above 500m level, based on abundance of carbonate cement, rock may be classed as calcareous sublithicarenite.



Figs. 6, 7 and 8. Sandstone classification plot in Qm - F - Lt and Qt - F - Lt diagram after Dickinson (1985; Fig. 6, &0, and Pettijhon *et al.* 1987, Fig. 8), falling in sublithicarenite field.

GRAIN SIZE DISTRIBUTION

The grain-size distribution has been studied in the thin sections subjected to modal count analysis. Grain size analysis has been carried out through direct measurement from microscope eyepiece scale (Table 3). Vertical variation in grain size through the Lower Siwalik sequence, exposed along Kathgodam-Ranibagh section, are shown in figure 9. Grain size data shows that the sandstone bodies of the Lower Siwalik sequence are dominantly madeup of fine to medium grained sand having an average grain size of 0.25 mm. However, grain-size varies from a minimum of 0.16 mm to

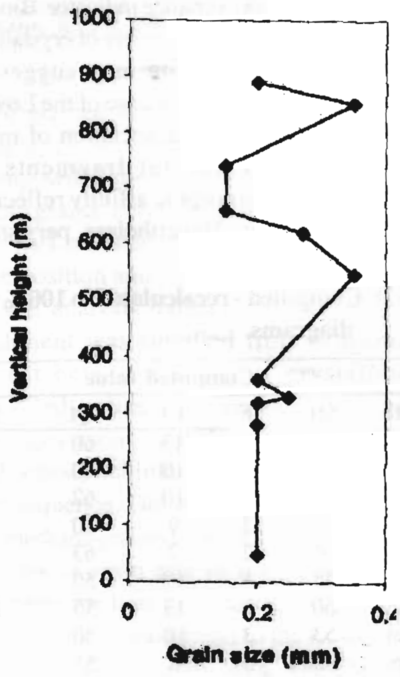


Fig. 9. Up section grain size variation in the Lower Siwalik sequence.

Table 3: Up section variation in grain size values.

Height (m)	Max. (mm)	Min. (mm)	Average
50	0.36-0.25	0.15	0.20
280	0.25-0.30	0.15	0.20
320	0.22-0.25	0.15	0.20
330	0.30-0.35	0.20	0.25
360	0.25-0.30	0.10	0.20
550	0.45-0.55	0.25	0.35
620	0.35-0.30	0.10	0.25-0.30
660	0.22-0.25	0.07	0.15
740	0.30-0.25	0.10	0.15
850	0.47-0.60	0.22	0.35
890	0.25-0.30	0.10	0.20

maximum of 0.60 mm. Moreover, two sand bodies located at 550 m and 850 m levels in the sequence are composed of medium grained sand of 0.35 mm size.

The temporal grain size variation is diagnostic,and shows variable trends. From basement to about 300 m level, fine-grained sand size hangs around an average size of 0.20 mm. From 300 m to about 500 m level, grain size gradually increases to medium grained sand (average 0.35 mm). Above 500 m level, grain size is highly variable ranging between fine to medium grained sand, varying between 0.15-0.35 mm; the average grain size is 0.25 mm. These medium-scale coarsening and finning upward trends can be attributed to basin progradation and retrogradation events (*cf.* Paola *et al.*, 1992).

TECTONIC - CLIMATIC INFLUENCE

Following Putnam, (1982), Qt/Lt, Qm/Lt, Qm/Qp and Qp/Ls ratios are plotted against the vertical thickness (Fig. 10). The plots show fluctuating trends that imply episodic tectonism through time within the Lower Siwalik sequence (fig. 10). Characteristically, between 0-300 m and 700-900 m levels, the Qm/Lt ratios are low, indicating tectonism in the provenance, releasing lithic grains in abundance. Whereas, intervening thickness between 300 - 700 m level, exhibiting fluctuating trend, implies episodic tectonism. Similarly, Qm/Qp and Qp/Ls ratios re quite variable (fig. 10), especially Qp/Ls ratio

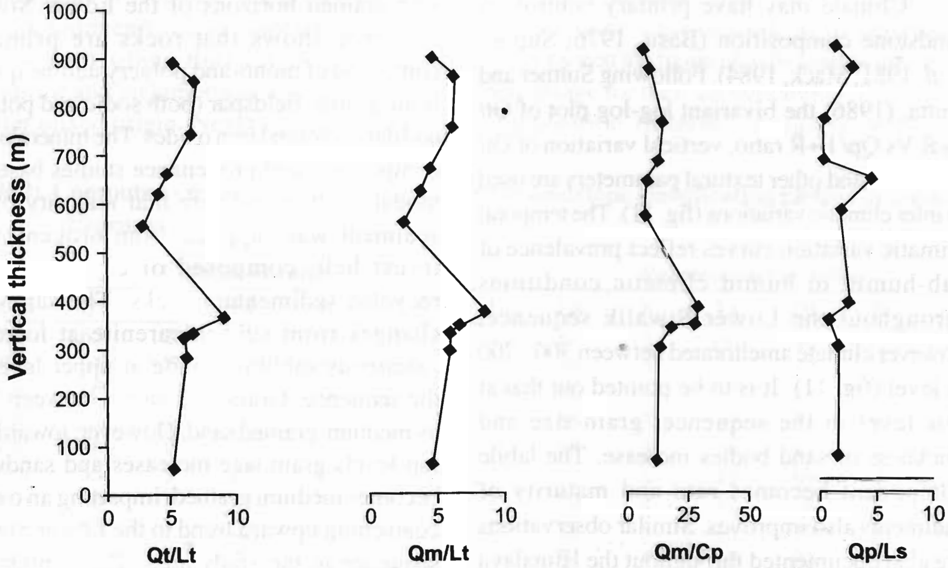


Fig. 10. Vertical variation in grain ratio plots of Qt/Lt, Qm/Lt, Qm/Qp, Qp/Ls showing episodic tectonic conditions and recylced orogen provenance.

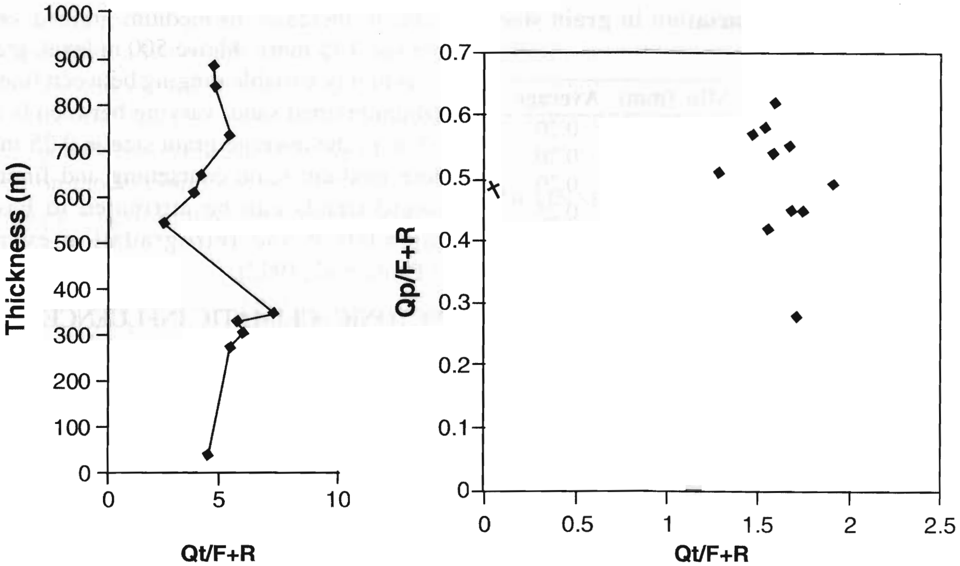


Fig. 11. Bivariant log-log plot of QT/F+R VS Qp/F+R and vertical variationin Qt/.F+R ratio. Plots indicate sub-humid climatic conditions

shows more variance that is typical of recycled orogen derived sediments (Dickinson, 1985).

Climate may have primary control on sandstone composition (Basu, 1976; Suttner *et al*, 1981; Mack, 1984). Following Suttner and Dutta, (1986) the bivariant log-log plot of Qt/ F+R Vs Qp/ F+R ratio, vertical variation of Qt/ F+R ratio and other textural parameters are used to infer climatic variations (fig. 11). The temporal climatic variation curves reflect prevalence of sub-humid to humid climatic conditions throughout the Lower Siwalik sequence, however climate ameliorated between 300 - 700 m level (fig. 11). It is to be pointed out that at this level in the sequence, grain-size and thickness of sand bodies increase. The labile component becomes rare and maturity of sediments also improves. Similar observations are also documented throughout the Himalaya (Sahni and Mitra, 1980; Quade and Cerling, 1995; Nakayama and Ulak, 1998).

BASIN EVOLUTION

The petrographic analysis of sand and fine grained horizons of the Lower Siwalik sequence shows that rocks are primarily composed of mono-and polycrystalline quartz, lithic grains, fieldspar (both sodic and potasic) and dark coloured iron oxides. The mineralogical composition and provenance studies based on modal analysis indicate that majority of the sediment was supplied from orogenic fold thrust belt, composed of crystalline and recycled sedimentary rocks. The sandstone changes from sublithicarenite at lower to calcareous sublithicarenite at upper levels in the sequence. Grain size varies between fine-to-medium-grained sand. However, towards the top levels grain size increases and sandstone becomes medium grained, imparting an overall coarsening upward trend to the Lower Siwalik sequence in the study area. The Qm/Qp and Qp/Ls plots suggest variable sediment supply through time, which can be attributed to episodic reactivation of source terrain. Q-t/F+R vs Qp/F+R plots suggest dominantly subhumid climatic conditions with enough water budget in the rivers to transport the sediments for longer distances. The palaeocurrent in the Lower Siwalik sequence is directed towards SE indicating sediments transport from north. On the basis of bulk composition two distinctly different types of drainages originating from metamorphic and sedimentary-metamorphic terrain respectively, have contributed the sediments to the Lower Siwalik Foreland Basin.

Abundance of matrix, poor sorting and rather immature texture of the snadstones in the lower levels (below 500 m) indicate less transport and proximity to the source terrain. At this level, abundance of lithic fragments imply deposition within a distance of 75-80 km from the source. Up in the section maturity, rounding and sorting improve considerably suggesting a much longer distance of transport and expansion of basin of sedimentation. The diagenitic texture shows two dominant modes of cementation. In the lower levels, the mechanical compaction created pseudo-matrix. In the upper levels (above 500 m), the carbonate cement is related to phreatic zone precipitation under early diagenesis.

In the light of petrographic data it is believed that during middle to late Miocene, enormous terrigenous sediments shed into the Lower Siwalik foreland basin situated south to the Lesser Himalaya along Main Boundary Thrust. The differential tectonic upliftment of various lithotectonic units along thrust plains had primary control on detritus sediment supply (DeCelles *et al.*, 1998; Garzanti, Critelli and Ingersoll, 1996; Najman and Garzanti, 2000). Situated between MBT and MCT, the Lesser Himalayan belt, composed of carbonates, siliciclastics, argillites, phyllites, schist and orthogneiss had released most of the sedimentary and metasedimentary lithic grains through reactivation and erosion along intracrustal boundary thrust. However, the central crystalline made up of amphibolite grade schist, orthogneiss, paragneiss and tertiary leucogranites, might had primary control to supply feldspar and most of the lithic metamorphic grains. Similar deductions have been made by Burbank, *et al.* (1996), and Kumar *et al.* (1999). In this section, sediments do not seem to have been contributed from southern cratonic bulge as there is not any major reversal in palaeocurrent trend that may indicate sediment drained from south to north.

In response to active thrust sheet loading in the orogen, in the beginning the basin was narrow, deep and activley subsiding. The sediments were transported to a short distance, buried quickly and compacted. Later, with continued sedimentation, the basin became wider and slowly subsiding. The sediments were transported to a longer distance to gain maturity. Before burial, sediments underwent early diagenesis (preburial diagenesis) preferably under subhumid conditions.

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REFERENCES

Ashley, G.M. 1990. Classification of large scale subaqueous bedforms: a new look at an old problem *Jour. Sedim. Petrol.* **60**: 160-172.

Basu, A. 1976. Petrology of Holocene fluvial sands derived from plutonic source rocks: Implication to palaeoclimatic interpretation. *Jour. Sedim. Petrol.* **46**: 694-709.

Blatt, H. 1992. *Sedimentary Petrology*, 2nd ed. W.H. Freeman and Company, New York. 508 p.

Burbank, D.W., Beck, R.A. and Mulder, T. 1996. The Himalayan foreland basins. In: *The Tectonic Evolution of Himalaya,* (Eds, Yin, A. and Harrison, T.M.), Cambridge University Press: 149-188.

Critelli, S. and Garzanti, E. 1994. Provenance of the lower Tertiary Murree red beds (Haeara-Kashmir Syntaxis, Pakistan) and initial rising of the Himalayas. *Sedim. Geol.* **89**: 265-284.

Critelli, S. and Ingersoll, R.V. 1994. Sandstone petrology and provenance of the Siwalik group (NW Pakistan and W-SE Nepal). *Jour. Sedim. Res.* **A64**: 815-823.

DeCelles, P.G. Gehrels, G.E., Quade, G.E., Ojha, T.P. and Upreti, B.N. 1997. Neogene foreland basin deposits, erosional unroofing and the kinematic history of the Himalayan fold thrust belt., western Nepal. *Geol. Soc. Am. Bull.* **110**: 2-21.

Dickinson, W.R. 1985. Interpreting provenance relations from detrital modes of sandstone. In: *Provenance of arenites, (Eds.* Zufa, G.G.), D. Reidel Publishing company: 333-361.

Dickinson, W.R. and Suczek, C.A. 1979. Plate tectonics and sandstone composition. *Am. Assoc. Petrol. Geol. Bull.* **63**: 2164-2182.

Espezo, I.S. and Lopez-gamundi, O.R. 1994. Source versus depositional control on sandstones and modern sand. (Indus transect, India and Pakistan). *Geol. Soc. Am. Bull.* **108** : 631-642.

Ganesh, A. 1964. *Geology of the Himalayas.* Interscience Publication, John Wiley, London. Hesse, R. 1987. Selective and reversible carbonate silica replcaement in lower cretacesus carbonate bearing turbidites of eastern Alps. *Sedimentology,* **34**: 1055-p77.

Ingersoll, R.V. 1990. Actualistic sandstone petrofacies: Discriminating modern and ancient source rocks. *Geology,* **18**: 733-736.

Ingersoll, R.V., Bullard, T.F., Ford, F.L., Grimm, J.P., Pickle, J.D. and Sares, S.W. 1984. The effect of grain size on detrital modes: a test of Gazi - Dickinson point counting method. *Jour. Sedim. Petrol.* **54**: 103-116.

Johnson, M.J. 1990. Tectonic versus chemical weathering controls on the composition of fluvial sands in tropical environments. *Sedimentology,* **37**: 713-726.

Khandkikar, A. S., Merh, S.S., Malik, J.N. and Chamyal, L.S. 1998. Calcrete in semi arid alluvial systems: formative pathways and sinks. *Sedim. Geol.* **116**: 251-260.

Kumar, R., Ghosh, S.K. and Sangode, S.J. 1999. Evolution of a Neogene fluvial system in a Himalayan foreland basin India. In: A Macfarlane, R.B. Sorkhabi and J. Quade Eds., Boulder Colarado. *Geol. Soc. Am. Spec. Publ.* **328**: 239-256.

Kumar, R., Ghosh, S.K., Sangode, S.J. and Thakur, V.C. 2002. Manifestation of Intra-Foreland thrusting in the Neogene Himalayan basin fill. *Jour. Geol. Soc. India,* **59**: 547-560.

Mack, G.H. 1981. Composition of modern stream sands in a humid climate derived from a low grade metamorphic and sedimentary foreland fold thrust belt of north Georgia. *Jour Sedim. Petrol.* **51**: 1247-1258.

Mack, G.H. 1984 Exceptions to the relationship between plate tectonics and sandstone composition. *Jour. Sedim. Petrol.* **54**: 212-220.

McBridge, E.F. 1985. Diagenetic processes that effect provenance determinations in sandstones. In *Provenance of arenites* (Eds Zuffa, G. G.), NATO, Advance Study Institute, Ser. C., Mathematical and Physical Sciences. **148**: 95-113 Dordrechdt, D. Reidel Publishing company.

McBridge, E.F., Diggs, T.N. and Wilson, J.C. 1991. Compaction of Wilcox and Carrizo sandstones (Pliocene-Eocene) to 4420m, Texas Gulf coast. *Jour. Sedim. Petrol.* **61**: 73-85.

McDonald, D.A. and Surdam, R.C. 1984. Clastic Diagenesis. *Am. Assoc. Petrol. Geol. Mem.* **37**: 434p.

Najman, Y. and Garzanti, E. 2000. Reconstructing early Himalayan tectonic evolution and palaeogeography from Tertiary foreland basin sedimentary rocks, northern India. *Geo. Soc. Am. Bull.* **112**: 435-449.

Nakata, T. 1972 Geomorphic history and crustal movements of the foot hills of Himalaya: *Inst. of Geography,* Tohuku Univ. Sendai. p. 162-164.

Nakayama, K. and Ulak, P. D. 1998 Evolution of the fluvial styles in the Siwalik group in the foothills of the Nepal Himalaya. *Sedim. Geol.* **125**: 205-224.

Pandita, S.K. and Bhat, G.M. 1995. Petrogrpahic and facies evaluation of Middle and Upper Siwalik subgroup boundary, Jammu. *Jour. Geol. Soc. India,* **46**: 369-374.

Paola, C., Heller, P.L. and Angevine, C.L. 1992. The large scale dynamics of grain size variation in alluvial basin, 1: Theory, *Basin Res.* **4**: 73-90.

Prakash, B., Sharma, R.P. and Roy, A.K. 1980. The Siwalik group (molasse) sediments shed by collision of continental plates. *Sedim. Geol.* **25**: 127-159.

Pettijhon, F. J., Potter, P. E and Siever, R. 1987. *Sand and Sandstone*. Springer Verlag, New York, 574p.

Putman, P.E. 1982. Fluvial channel sandstone within upper Mannville (Albian) of Lloydminster area, Canada - Geometry, petrography and palaeogeographic implications. *Am. Assoc. Petrol. Geol. Bull.* **66**: 436-459.

Quade, J. and Cerling T.E. 1995. Expansion of C_4 grasses in the late Miocene of northern Pakistan: evidence from stable in the palaeosol. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **115**: 91-116.

Raynold, V., Ingersoll, R.V., Andrea, G., Kretchmer and Valles, P.K. 1993. The effect of sampling scale on actualistic sandstone petrofacies. *Sedimentology*, **40** : 937-953.

Retallack, G.J. 1990. *Soils of the past - An Introduction to Palaeopedology.* Unwin Hyman, Boston.

Sahni, A. and Mitra, H.G. (1980) Neogene palaeobio-geography of the Indian subcontinent with special reference to fossil vertebrate. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **31**: 39-62.

Schmidt, V. and McDonald, D.A. (1979). Texture and recognition of secondary porosity in sandstone, In: *Aspects of Diagenesis* (Eds. Schoole, P.A. and Schluger, P.R.), *SEPM Spec. Publ.* **26**: 175-208.

Schwab, F.L. 1986. Sedimentary "singatures" of foreland basin assemblages: real or counter fit? In: *Foreland basins* (*Eds.* Allen, P. A. and Homewood. P.), *Int. Assoc. of Sed. Spec. Publ.* **8**: 395-410.

Sharma, S., Sharma, M. and Singh, I.B. 2001. Facies charactersitics and cyclicity of lower Siwalik sediment, Jammu area: a new perspective. *Geol. Mag.* **138**(4): 455-470.

Shukla, U. K. and Bora, D. S. 2000 Identification of Interfluve (Doab) deposits in the lower Siwalik succession of Kumaun Himalaya: Their tectonic and palaeoclimatic significance. *Symp. on Neogene climate of Indian Ocean and Indian subcontinent,* I.I.T. Khargpur, 39 p.

Sikka, D.B., Saxena, M.N., Bhatia, S.B. and Jain, S.P. 1961. Occurrence of greywackes in lower Siwaik, Simla hills. *Nature,* 192: 61.

Singh, I. B., Srivastava, P., Sahrma, S., Sahrma, M., Singh, D. S., Rajagopaln, G. and Shukla, U. K. 1999. Upland Interfluve (Doab) deposition: An alternative model to muddy overbank deposits. *Facies,* **40**: 197-210.

Suttner, L.J. and Dutta, P.K. 1986. Alluvial sandstone composition and palaeoclimate, I. Framework mineralogy. *Jour. Sed. Petrol.* **56**: 329-345.

Suttner, L.J., Basu, A. and Mack, G.H. 1981. Climate and origin of quartz arenite. *Jour. Sedim. Petrol.* **51**: 1235-1246.

Surdam, R.C., Crossey, L.J., Hagen, E.S. and Heasler, H.P. 1989. Organic - inorganic interactions and sandstone diagenesis. *Am. Assoc. Petrol. Geol. Bull.* **73:** 1-23.

Tandon, S.K. 1976. Siwalik sedimentation in part of Kumaun Himalaya, India. *Sedim. Geol.* **16**: 131-154.

Tandon, S.K. and Narayan, D. 1981. Calcrete conglomerate, case hardened conglomerate and cornstone - a comparative account of pedogenic and non pedogenic carbonate from the continental Siwalik group, Punjab, India. *Sedimentology,* **28**: 353-367.

Tandon, S.K., Andrews, J.E. and Mittal, S. 1998. Shrinkage and sediment supply control on multiple calcrete profile development: a case study from the Maastrichtian of central India. *Sedim. Geol.* **119**: 24-45.

Valdiya, K.S. 1988. The tectonics and evolution of the central sector of Himalaya. *Phil, Trans. Royal Soc. London,* **A326**: 151-175.

Wilson, J.C. and Mc Bridge, E.F. 1988. Compaction and porosity evolution of Pliocene sandstones, Ventera basin, California. *Amer. Assoc. Petroleum Geologists Bull.* **72**: 664-681.

Wright, V.P. 1992. Plalaeopedology: stratigraphical relationship and empirical models In: *Weathering, Soils and Palaeosols* (Eds. Martini, I.P., Chesworth, W.), Elservier, Amsterdam, p. 475-499.

Wright, V.P. and Tucker, M.E. 1991. Introduction. In: *Calcrete* (Eds. Wright V.P. and Tucker, M.E.), Int, Assoc. Sedimentol. Reprint, **2**: 1-22.