Provenance of the Late Neogene Siwalik sandstone, Kumaun Himalayan Foreland Basin: Constraints from the metamorphic rank and index of detrital rock fragments

POONAM JALAL^{1,*} and SUMIT K GHOSH²

¹*Department of Geology, H.N.B. Garhwal University, Srinagar 246 174, India.*

²*Wadia Institute of Himalayan Geology, Dehradun 248 001, India.*

**Corresponding author. e-mail: jalal.poonam@gmail.com*

An understanding about lithology, tectonics and unroofing history of provenance is mostly drawn from the compositional and textural parameters of the detrital fragments. We here use different metamorphic ranks (Rm) and metamorphic index (MI) values of rock fragments present in Late Neogene Siwalik sandstone of the Ramganga sub-basin to infer the provenance history. The study indicates maximum contribution from metamorphic ranks 1 and 2 (Rm1 and Rm2; meta-sedimentary and very low grade metamorphic rocks) and minimum from metamorphic rank 4 (Rm4; high metamorphic grade rocks). The metamorphic index (MI) values range from 118 to 224, with an average of 186. The meta-sedimentary and very low-grade metamorphic rock fragments are derived from the Lesser Himalayan domain. The medium-to-high grade metamorphic fragments are derived from the Lesser Himalayan Crystalline bodies. The abundance of Rm2 and Rm3 detrital modes suggest the exhumation of crystalline bodies of the Ramgarh and Almora most likely occurred prior to 7 Ma and subsequently the source area shifted and resulted abundant supply of Rm1 fragments due to the upliftment along Main Boundary Thrust around 5.55 Ma.

1. Introduction

Detrital modes are a powerful tool for understanding the source of a package of sedimentary rocks for its lithology, climate, relief, and unroofing history (Basu *et al* 1975; Dickinson 1985, 1988; Ingersoll 1990; DeCelles 1998, 2001; Ghosh *et al* 2009). The more commonly used approach is to use the Gazzi–Dickinson method (Zuffa 1985) of point counting and plotting the data on a QFL diagram (Dickinson *et al* 1983). The operational classification of Dickinson (1970) does not take into account the great variety of metamorphic grains shed in abundance by collision orogens. The Himalaya

provides a type example of continent–continent collision and is a classical example of young collision orogen. The preserved sedimentary record of fluvial Siwalik succession is an important repository for decoding the provenance history of the Himalayan orogen. The volumetrically significant metamorphic rock fragments variably shed in Himalayan Foreland Basin (HFB) by the advancing crystalline thrust sheets reflect their unroofing history. An accurate provenance diagnosis in these settings requires all relevant information about the metamorphic evolution and structural level of parent rocks that can be retrieved from the texture and composition of detrital grains. The pioneering

Keywords. Provenance; Late Neogene; Siwalik sandstone; Ramganga sub-basin; metamorphic rank; metamorphic index.

work to infer the degree of metamorphism of source rocks from detrital polycrystalline quartz grains was done by Young (1976) but did not achieve the level of fine resolution that Garzanti and Vezzoli (2003) obtained. A classification of metamorphic grains in sand and sandstones has been proposed with an aim of enhancing data reproducibility among operators and the potential of bulk petrography in provenance studies (Garzanti and Vezzoli 2003). It has been broadly used to assess the average metamorphic grade of the source area (Garzanti and Vezzoli 2003; Garzanti *et al* 2004). Such an approach may be particularly useful for provenance analysis of foreland basin clastic wedges (Garzanti and Vezzoli 2003; Garzanti *et al* 2004, 2007).

The temporal variation of the detrital modes suggests episodic tectonism related to the thrusting activity. Information regarding the timing of thrusting events are summarised in table 1. The Ramganga sub-basin has a unique characteristic

of a near source provenance as compared to other sub-basins except the Kangra sub-basin, and thus possesses a good preservation of detrital modes. Few efforts have been made towards deciphering its petrographic character as sublithic arenite to lithic arenite (Tandon 1976). Misra and Valdiya (1961), Tiwari and Yadav (1993) and Bora and Shukla (2005) collectively referred as metamorphic and granitic rocks of Lesser Himalaya as the provenance. Recently, Jalal *et al* (2011) have attempted to characterize and decipher the provenance history of Late Neogene Siwalik sandstone of the Ramganga sub-basin based on the detrital modes. The present study carried out on the sandstone dominated Middle Siwalik (7.7–4.5 Ma; Kotlia *et al* 2001) succession is exposed along the Baliagad–Gaula River (BGR) section of the Ramganga sub-basin (figure 1a and b). The main objective of this paper is to understand the tectonic history of the source area using metamorphic ranks (Rm) and metamorphic index (MI) parameters.

Table 1. Major tectonic events recorded in the source area, Himalayan orogen.

Thrusting activity	Timing	Reference
Main Central Thrust		
Main Central Thrust	~23 Ma	Hodges <i>et al</i> (1996); Hubbard and Harrison (1989)
Dadeldhura Thrust Nepal (became active)	21–15 Ma	DeCelles <i>et al</i> (2001)
Main Central Thrust (initial phase of activity)	20 Ma	Thakur (1992); Buslov (2004)
Main Central Thrust (activity)	17 Ma	Walker <i>et al</i> (1999)
Chail Thrust, Kangra (activity)	16 Ma	Raiverman (1997)
Ramgarh Thrust, Nepal (activity)	~15–11 Ma	Pearson and DeCelles (2005)
Ramgarh Thrust, Nepal (activity)	~12–5 Ma	DeCelles <i>et al</i> (2001)
Dadeldhura Thrust, Nepal (activity)	11 Ma	DeCelles <i>et al</i> (1998)
Chail Thrust, Kangra (activity)	11 Ma	Kumar <i>et al</i> (2011); Sinha <i>et al</i> (2008); Ghosh <i>et al</i> (2009)
Main Central Thrust, Nepal (activity and brittle phase)	9–7 Ma	Macfarlane (1992)
Main Boundary Thrust		
Thrust sheet movement	~45 Ma	Raiverman (1997); Dubey <i>et al</i> (2001)
Initiation of Thrust	10 Ma	Meigs <i>et al</i> (1995)
Reactivation of Thrust	8.0 Ma	Valdiya (1999)
Initiation of Thrust	6.5 Ma	Burbank and Reynolds (1988)
Activities	5.5 Ma and 5 Ma	Kumar <i>et al</i> (2011); Ghosh and Kumar (2000); Hisatomi (1990); DeCelles (1998, 2001)
Other Activities		
Erosion and upliftment of Higher Himalaya	11–7.50 Ma	Valdiya (1999)
Emplacement of Crystalline Nappe	7.50 Ma	Ghosh and Kumar (2000)
Upliftment and subsequent erosion of Higher Himalayan Crystalline	7.65 Ma	Sangode <i>et al</i> (1999)
Lesser Himalayan duplex development	~12.5 Ma	DeCelles (2001)

Figure 1. (a) Different sub-basins of Himalayan Foreland Basin (Raiverman 2002). The Ramganga sub-basin is shown in the box. (b) Geological map of the Ramganga sub-basin, Kumaun Himalaya showing different lithotectonic units (modified after Raiverman 2002).

2. Geological background

The Himalaya is differentiated into four lithotectonic provinces, i.e., Tethys Himalaya, Higher Himalaya, Lesser Himalaya and Sub-Himalaya (Siwalik) or Himalayan Foreland Basin (HFB) divided by major structural discontinuities.

The Lesser Himalaya is delimited by Main Central Thrust (MCT) in the north and Main Boundary Thrust (MBT) in the south (figure 1a). In the Kumaun sector, Almora thrust sheet forms a major crystalline body of the Lesser Himalaya (figure 2) and is marked equivalent to Dadeldhura thrust sheet of western Nepal (DeCelles *et al* 2001). The Almora Group consists of medium- to high-grade metamorphics (Joshi and Tiwari 2004). At the base of Almora thrust sheet, the Lesser Himalayan crystalline rocks (Ramgarh Group) crop out as a narrow belt separated by Ramgarh Thrust (RT;

Shrestha 1987). The Ramgarh Group consists of low-grade metamorphic rocks up to green schist facies. The Ramgarh Thrust places the Ramgarh Group of rocks above the Lesser Himalayan strata of Jaunsar (Chandpur, Nagthat and Blaini formations) and Mussoorie (Krol Formation) Group (Valdiya 1980). Sediments of the Jaunsar Group show late stage diagenesis to very low-grade metamorphism and lie in contact with Siwalik sediments to its southern extremity by the MBT (figure 2). The adjoining Amritpur Granite is deformed and provides a basement for the overlying rocks (Pandey *et al* 2005).

The HFB lies between MBT in the north and Himalayan Frontal Thrust (HFT) in the south. It thins laterally to the south and coarsens upward from sandstone–mudstone (Lower Siwalik) to sandstone dominated (Middle Siwalik) and finally to conglomerate–sandstone–mudstone (Upper Siwalik) succession. The HFB is divided into a number of sub-basins (figure 1a) by several basement highs (Raiverman *et al* 1983) separated from each other by pre-existing lineaments (Virdi 1979). The Ramganga sub-basin (RSB) marks the western sector of the HFB bounded by north-western and south-eastern ends by Haridwar–Rishikesh and Tanakpur spurs, respectively.

3. Methodology

Twenty eight sandstone samples were selected from the magnetostratigraphically constrained measured BGR section (Jalal *et al* 2011; figure 3, p. 126) to understand the temporal behaviour of the sandstones. These sandstone samples were studied following the traditional method (Basu *et al* 1975; Mack and Suttner 1977) for counting the different detrital grains with main focus on the lithic ($L < 62.5 \mu$) and rock ($Rf > 62.5 \mu$) fragments (Garzanti and Vezzoli 2003, table 1, p. 835). Metamorphic grains were subdivided into five metamorphic ranks (Rm) according to their textural behaviour (recrystallization, cleavage and schistosity; Garzanti and Vezzoli 2003). For each sample, average rank is expressed by a metamorphic index (MI) ranging from 100 (very low rank lithic fragments, such as slate, meta-siltstone or meta-basalt) to 500. In the present study, the lithic/rock fragments unidentifiable under any rank falls within the transition zone as siltstone *versus* meta-siltstone, sandstone *versus* meta-sandstone and mudstone are avoided. However, the metaquartzite fragments are considered within Rm4 rank owing to quartz fabric representing degree of recrystallization which falls under similar grade as described by Kurhl (1996) and Stipp *et al* (2002). Further, we have considered the grain-size of the

Figure 2. Geological map of the Lesser Himalayan Crystalline bodies (Kumaun Lesser Himalaya) showing various litho-tectonic units (modified after Valdiya 1980) and the possible combinations of metamorphic rank present in the source area.

metamorphic rock fragment as a proxy for transportation distance, as being its most labile nature, cannot survive during long distances. The reason for this argument is that the metamorphic rock occupies in both far Higher and near Lesser Himalayan domains and its source site prediction may be made through the grain-size parameters.

4. Sandstone petrography

The sandstones of BGR section share a greater affinity towards sublithic to lithic arenite ($Q_{78}F_5Rf_{17}:Mx_7$) type (table 2; figure 3). Quartz averages about 66% of the total framework. Monocrystalline type dominates over the polycrystalline type. Undulose extinction and peripheral corrosion are the common features observed in quartz detritals. Feldspar constitutes 4% of the total framework. It is mostly unaltered with nearly equal amount of potash feldspar (55%) and plagioclase feldspar (45%). The rock fragments contribute about 14% of the framework. They consist

of abundant subangular to subrounded sedimentary/metasedimentary ($Rfs - 87\%$, including shale, siltstone, sandstone, chert, mudstone, argillite, siliciclastic, and limestone); common metamorphic ($Rfm - 12\%$ including metaquartzite, phyllite, gneiss and schist) and rare igneous ($Rfi - 0.18\%$) fragments. Mica detritals are mostly tectonised and contribute 3%. Matrix constitutes 6% of the total framework components. Cement constitutes 6% (mainly calcareous) of the total framework components of the sandstones. The dense minerals include mainly zircon, garnet, tourmaline and opaque grains.

5. Metamorphic index and rank

The metamorphic index (MI) is an approach towards understanding the collision orogens in depth and expresses the different participated metamorphic weight percentages categorized under five metamorphic ranks (Rm) 1, 2, 3, 4 and 5 (table 3) multiplied by 1, 2, 3, 4 and 5, respectively

Table 2. Detrital rock fragments under different metamorphic ranks (Rm) for the 7.7–4.5 Ma BGR Siwalik Sandstone of the BGR section, Ramganga basin.

Sample no.	St. ht. and age	Recalculated QFR			Metamorphic rank and index				
		Qr	Fr	Rfr	Rm1	Rm2	Rm3	Rm4	MI
S-1	1070 (4.5 Ma)	91	2	7	51	17	30	2	183
S-4	1060	91	1	8	43	28	29	0	186
S-6	1030	93	3	3	87	4	9	0	123
S-8	1012	83	5	11	64	17	15	4	159
S-11	995	79	8	13	55	36	9	0	154
S-14	975	76	1	23	52	35	9	5	167
S-19	934	71	6	22	73	20	7	0	135
S-21	900 (~5.10 Ma)	78	2	21	56	25	13	5	167
S-20	895	83	2	14	34	24	35	8	217
S-27	890	70	5	25	37	37	17	9	198
S-25	885	73	6	21	27	39	13	20	203
S-24	865	67	5	28	34	24	28	14	222
S-28	860	80	1	19	56	21	23	0	167
S-31A	825	71	6	23	25	38	17	19	230
S-32	820	76	5	18	49	28	11	12	187
S-33	815	92	3	5	80	10	11	0	131
S-32 c	760 (~5.55 Ma)	88	4	7	45	33	22	0	177
S-32 cc	630 (~5.90 Ma)	78	4	17	42	0	54	4	221
S-32d	580	82	6	13	49	14	26	11	200
S-35	518	58	11	31	72	15	9	4	145
S-37	495	75	5	20	46	17	37	0	191
G-3	438	70	6	24	46	14	40	0	195
G-4	390	79	9	12	41	10	46	1	213
S-40	350	81	3	17	56	15	24	5	179
S-50	330	71	6	22	28	5	64	4	244
S-51	280 (~6.95 Ma)	73	7	21	37	10	51	3	220
G-8	50	60	5	36	88	7	6	0	118
G-9	20 (~7.7 Ma)	95	2	3	31	7	49	13	244
Average		78	5	17	50	20	25	5	185
Std. dev.		10	2	8	17	11	16	6	35

St. ht.: Stratigraphic height in meter, Qr: recalculated quartz, Fr: recalculated feldspar, Rfr: recalculated rock fragments, Rm1: metamorphic rank 1, Rm2: metamorphic rank 2, Rm3: metamorphic rank 3, Rm4: metamorphic rank 4, and MI: metamorphic index.

(for details refer to Garzanti and Vezzoli 2003). It ranges from 100 (only rank 1 lithic fragments) to 500 (only rank 5 rock fragments) and classifies the metamorphic rock fragments on the basis of increasing degree of recrystallization and progressive formation of cleavage and schistosity into ranks from 1 to 5. To make the classification effective and to avoid complications this technique limits itself by considering the only two fundamental variables, composition and grade.

Based on the metamorphic rank approach (Garzanti and Vezzoli 2003), the lithic and rock fragment (figure 4) populations of the Late Neogene (~7.7–4.5 Ma) sandstones are segregated under five ranks excluding the fragments within transitional zone (figure 4a) and expressed in terms of metamorphic index. The temporal variability observed within the metamorphic rank 1 to 4 (Rm1

to Rm4) and metamorphic index (MI) values of the metamorphic rock fragments are abstracted in table 2 and shown in figures 4 and 5.

5.1 Metamorphic rank 1

Detrital grains of Rm1 constitute nearly 50(±17)% of the total rock fragment population and represented mainly by meta-siltstone, meta-sandstone, meta-chert, and meta-argillite fragments (figure 4b). The grain-size ranges from fine- to medium-grained (0.13–0.52 mm, avg. 0.24 mm). Temporally, the Rm1 varies from 25 to 90%. Overall, it shows gradual upward increasing trend till 775 m (~5.45 Ma) with variability mainly between 30 and 70 quartz percent. However, from 775 m upward and till 900 m (~5.45–5.10 Ma), it shows

Figure 3. (a) Classification of the 7.7–4.5 Ma Siwalik Sandstone (following Pettijohn *et al* 1987) of the BGR section. (b) Ternary plot showing the relative distribution of the sedimentary (Rs), metamorphic (Rm), igneous (Ri) rock fragments, and majority of the samples plot on the Rm–Rs end.

Table 3. Characteristic features of the metamorphic rock/lithic fragments and assigned metamorphic ranks (Rm; based on Garzanti and Vezzoli 2003) in Late Neogene Siwalik Sandstone of BGR section, Ramganga sub-basin.

Grade (Rm)	Texture	Phyllo-silicates	Metamorphic rank	Present study
None	Unoriented	Clay minerals	Rm0	Unmetamorphosed sedimentary and volcanic rock fragments
Very low	Rough cleavage	Illite, chlorite	Rm1	Meta-siltstone, meta-sandstone meta-chert, meta-carbonate
Low	Strong cleavage	Sericite	Rm2	Phyllite, strongly cleaved quartz with mica aggregate, quartz sericite with strong cleavage
Medium	Schistosity	Tiny micas	Rm3	Low-grade mica schist, quartz-mica schist
High	Crystals <62.5 μm	Muscovite	Rm4	Muscovite gneiss lithic fragment, muscovite-schist lithic fragment
Very high	Crystals >62.5 μm	Biotite	Rm5	–

MI= $Rm1/Rm \times 100 + Rm2/Rm \times 200 + Rm3/Rm \times 300 + Rm4/Rm \times 400 + Rm5/Rm \times 500$.

Rm: sum of all metamorphic ranks, MI: metamorphic index.

decreasing trend (figure 5) and thereafter relative increasing trend up to 1012 m (~ 4.75 Ma) is discernable.

5.2 Metamorphic rank 2

Detrital grains of Rm2 include mainly phyllite, strongly cleaved quartz mica aggregate and quartz sericite lithic fragment (figure 4c) comprises $20(\pm 11)\%$. The grain-size ranges from very fine- to medium-grained (0.10–0.33 mm; avg. 0.23 mm). Rm2 contributes 7–15% till 630 m (~ 5.90 Ma) level, except around 350 m (~ 6.7 Ma), where it shows slightly increasing trend up to 17% (figure 5).

A conspicuous increasing trend from 775 m (5.45 Ma), to 1000 m (~ 4.85 Ma) and thereafter reversal of trend is noticed. The trend Rm2 is nearly similar to Rm1 till 600 m (~ 6 Ma) but thereafter it is reverse. The maximum concentration is noticed at 760 m (~ 5.55 Ma); 995 m (~ 4.80 Ma) coupled with the increase in grain size (0.20–0.33 mm).

5.3 Metamorphic rank 3

Detrital grains of Rm3 constitute nearly $25(\pm 16)\%$ of the total rock fragment population and is represented by mica schist with well developed

Figure 4. Photomicrographs of different metamorphic rock fragments classed under different metamorphic ranks (Garzanti and Vezzoli 2003) from the 7.7–4.5 Ma Siwalik Sandstone of BGR section, (a) Meta-sandstone representing the detritals within the transitional zones (Lt), (b) meta-sandstone showing metamorphic rank 1 (Lm1), (c) strongly cleaved phyllite representing metamorphic rank 2 (Lm2), (d) mica schist with well developed schistosity representing metamorphic rank 3 (Lm3), (e) muscovite schist (crystals $<62.5\ \mu\text{m}$) is classified under metamorphic rank 4 (Lm4), and (f) metaquartzite (crystals $>62.5\ \mu\text{m}$) is classified under metamorphic rank 4 (Rm4). All photomicrographs are in XN.

schistosity, i.e., low grade mica schist, chlorite mica schist, quartz mica schist, and quartz with thick bands of micas (table 3; figure 4d). The grain-size ranges between 0.09 and 0.34 mm (avg. 0.20 mm). The main turning point is noticed around 600 m (~ 6 Ma). Unlike Rm1 and Rm2, the Rm3 detrital

grains show a wide range of variability (9–64%) from base up to 760 m (~ 5.55 Ma) and conspicuously narrowed (7 and 15%) further up section (figure 5). However, it is consistent between 825 and 885 m (~ 5.37 – ~ 5.15 Ma) and nearly matches with the trend of Rm2 (figure 5).

Figure 5. Temporal variation in the representative metamorphic components of 7.7–4.5 Ma Siwalik Sandstone of the BGR section. Rm1: metamorphic rank 1, Rm2: metamorphic rank 2, Rm3: metamorphic rank 3, Rm4: metamorphic rank 4, MI: metamorphic index.

5.4 Metamorphic rank 4

Detrital grains of Rm4 include high-rank metamorphic lithic fragments (with constituent crystal size $<62.5 \mu$) (figure 4e) and rock fragments (with constituent crystal size $>62.5 \mu$) (figure 4f). In the present case, the metaquartzite fragments becomes more useful. Rm4 (figure 5) is low (1–13%; avg. 5; SD ± 6) from base to 800 m (~ 5.40 Ma). However, its presence is promising above 800 m (~ 5.40 Ma) and it gains a maximum (20%) between 825 and 885 m (~ 5.37 – ~ 5.15 Ma) with an increased grain size of 0.35–0.48 mm. The main turning point also matches with Rm3.

5.5 Metamorphic index

It estimates an average metamorphic grade of the source rock and helps to ascertain a relation of the

detrital to its source. The MI values of the sandstones range from 118 to 224 (185 ± 35), its higher values are noticed between 825 and 885 m (~ 5.37 – ~ 5.15 Ma) and the minimum values between 934 and 1030 m (~ 5.05 – 4.75 Ma; figure 5). The temporal trend of the MI values follows an impulsive trend and shares a similitude mainly with the trend of the Rm3 and Rm4 (particularly between 800 and 1000 m; figure 5).

Further, an attempt has been made to test the dataset (table 4) by some statistical parameters (average and standard deviation). The datasets are grouped into two sets (table 4) based on age. In this case we have chosen the tie point around ~ 5.55 Ma, as during this time Himalayan orogen have recorded a major tectonic activity (table 1). However, due to paucity of data around ~ 7.5 Ma (table 2) similar test could not

Table 4. Temporal distribution and statistical values of metamorphic ranks (Rm) and metamorphic index (MI) for Siwalik Sandstone of the BGR section, Ramganga Basin (based on 20 selected samples).

Sample no.	Stratigraphic height	Rm1	Rm2	Rm3	Rm4	MI
S-1	1070 (4.5 Ma)	51	17	30	2	183
S-4	1060	43	28	29	0	186
S-6	1030 (4.75 Ma)	87	4	9	0	123
S-8	1012	64	17	15	4	159
S-14	975	52	35	9	5	167
S-19	934	73	20	7	0	135
S-21	900 (5.10 Ma)	56	25	13	5	167
S-25	885	27	39	13	20	203
S-28	860	56	21	23	0	167
S-32	820	49	28	11	12	187
S-32 c	760 (5.5 Ma)	45	33	22	0	177
Avg.		55	24	16	4	169
Std. dev.		16	10	8	6	23
S-32 cc	630 (5.90 Ma)	42	0	54	4	221
S-32d	580	49	14	26	11	200
S-35	518	72	15	9	4	145
S-37	495	46	17	37	0	191
G-3	438	46	14	40	0	195
G-4	390	41	10	46	1	213
S-40	350	56	15	24	5	179
S-50	330	28	5	64	4	244
S-51	280 (6.95 Ma)	37	10	51	3	220
Avg.		46	11	39	4	201
Std. dev.		12	6	17	3	29

Rm1: metamorphic rank 1, Rm2: metamorphic rank 2, Rm3: metamorphic rank 3, Rm4: metamorphic rank 4, and MI: metamorphic index.

be attempted. The test indicates (table 4) that except Rm4 (the rest Rm1, Rm2, Rm3), MI values are not overlapping. It is interesting to note that Rm1 and Rm2 inputs were high and on the contrary, Rm3 was less in the post ~5.90 Ma part.

6. Discussion

The Himalayan orogen, a type example of continental collision, in response to its uplift and erosion supplied variedly consequent detritals to the Himalayan Foreland Basin. The variation in the distribution of the detrital grains of sandstones is used to constrain the thrusting episodes of MCT and MBT (DeCelles 1998; Kumar *et al* 1999; Ghosh and Kumar 2000; Ghosh *et al* 2009) and infer the exhumation history (DeCelles 1998, 2001). The studied Ramganga sub-basin detrital grains of varied metamorphic ranks are contributed by the hinterland thrust system, namely the Main Boundary Thrust (MBT), Ramgarh Thrust (RT) and further north Almora Thrust (AT). The detrital rock fragments of this sandstone suggests a varied suit

of metamorphic and granitic rocks of the Lesser Himalaya as the source area lithology (Misra and Valdiya 1961; Tiwari and Yadav 1993; Bora and Shukla 2005). The textural and compositional variability of the sandstone suggests a mixed provenance comprising of abundant low- to medium-grade metamorphic and subordinate sedimentary and igneous lithology (Jalal *et al* 2011). In addition, the study also indicates existence of crystalline bodies of the Ramgarh and Almora prior to 7 Ma and continued detritus supply till 5 Ma (Jalal *et al* 2011).

Absence of Rm0 signifies deficiency of the unmetamorphosed rock fragments input from the source. The sequential presence of the rock fragments as Rm1 (50%) > Rm3 (25%) > Rm2 (20%) > Rm4 (5%) in the sandstone shows a higher contribution from the very low- to low-grade metamorphic (meta-sedimentary) and minor from medium- to high-grade metamorphic source. The MI values (118–224) also support the aforesaid inferences. Taking into account the source area lithology (figure 2), Rm1 and Rm2 representing the low grade metamorphic rocks are commonly associated with Jaunsar and Ramgarh groups

(figure 2) and their uninterrupted presence noticed from ~ 5.05 to ~ 4.75 Ma. Similarly, Rm3 and particularly, the coarser nature of Rm4 detritus suggest derivation from the nearby situated Lesser Himalayan Crystalline (LHC) of Ramgarh and or Almora Group (figure 2) and not from the far-situated Higher Himalayan Crystalline (HHC) (figure 1a). In this context, the adjoining Nepal Siwalik succession shows detritus contribution from the Greater or Higher Himalayan zone (DeCelles *et al* 1998) which in the present case does not seem to be tenable, owing to the coarser and lithic arenite composition of the sandstone. Compositionally, the sandstones of the BGR sections are mostly lithic to sublithic arenite and thus implying relatively short distance of transport (Franzinelli and Potter 1983), rapid erosion and high-relief source area (Basu 1985; Pettijohn *et al* 1987). Higher proportions of soft pelitic rock fragments in the sandstones indicate derivation from the nearby Lesser Himalayan source area. Polycrystalline quartz grains with sutured boundaries are common in these sandstones. This is an additional indicator of metamorphic source and polycrystalline quartz grains with straight inter-crystal boundaries indicating a plutonic source (Young 1976; Scholle 1978; Blatt *et al* 1980).

A prominent line cannot be drawn between the contributions of Ramgarh or Almora Crystalline bodies owing to their similar metamorphic grade. Ideally due to the activity of Almora Thrust we may expect abundance of Rm3 due to the contribution from the hanging wall (Almora Group) and footwall (Ramgarh Group) of this thrust. The resulting sediments (sandstone) are likely to be composed of a higher proportion of Rm4 and lower percentage of Rm1, Rm2 and Rm0 fragments. On the other hand, activity of the Ramgarh thrust would lead to abundant Rm2 > Rm3, Rm1 contributed partly from the footwall (Jaunsar Group) and major fraction from the hanging wall (Ramgarh Group). Grain size of the detritus shed would be relatively larger from the Almora Group owing to its proximity to the basin. However, the activity of MBT would release a greater proportion of Rm1 and Rm2 detrital grains and the grain-size should be larger being nearest to the basin. However, the increasing trend of Rm1 and Rm2 (table 4) clearly hint towards the unroofing of hanging wall due to the activity along MBT. The increment in the percentage of Rm2, Rm3 and Rm4 indicates higher contribution from the Lesser Himalayan Crystallines (Ramgarh and Almora groups) between 825 and 885 m (~ 5.37 to ~ 5.15 Ma). However, the Higher Himalayan Crystalline contribution is uncertain because of the complementing medium-grained nature of the detritals.

7. Conclusions

The detrital rock fragments of ~ 7.7 – 4.5 Ma sandstones of the Baliagad–Gaula river section, Ramganga sub-basin show variability in terms of types and concentration of metamorphic rank (Rm). The textural and compositional variability of the rock fragments collectively suggests a larger contribution from metamorphic provenance. Rm factor suggests contribution of varied metamorphic sources from very low- to high-grade. However, the contribution from very low-grade metamorphic rock is pronounced. The detritus sediment supply is primarily controlled by the differential uplift of the various thrust planes. The subordinate medium- to high-grade metamorphic detritals is contributed from the Lesser Himalayan Crystalline bodies. The detrital mode of the ~ 7.7 – 4.5 Ma sandstone succession of the Ramganga sub-basin suggests the exhumation of Lesser Himalayan Crystalline bodies of the Ramgarh and Almora prior to 7 Ma. This has resulted in abundance of Rm2 and Rm3 fragments. However, after ~ 5.90 Ma, the source area shifted and resulted in supply of abundant detritals from the Jaunsar Group due to activity along the MBT around ~ 5.55 Ma.

Acknowledgements

The first author is thankful to University Grant Commission for sponsoring the study under RFSMS scheme. The Director, Wadia Institute of Himalayan Geology and Prof. Y P Sundriyal, Department of Geology, H.N.B Garhwal University are thanked for the necessary facilities provided. The authors are thankful to Dr A K Dubey, WIHG for the fruitful discussion and review of the paper. They are also thankful for the comments of Prof Abhijit Basu, Indiana University and the anonymous reviewer.

References

- Basu A *et al* 1975 Re-evaluation of the use of undulatory extinction and polycrystallinity in detrital quartz for provenance interpretation; *J. Sedim. Petrol.* **45** 873–882.
- Basu A 1985 Influence of climate and relief on compositions of sands released at source areas; In: *Provenance of Arenites* (ed.) Zuffa G G (Dordrecht: Reidel), pp. 1–18.
- Blatt H *et al* 1980 *Origin of Sedimentary rocks*; 2nd edn, Englewood Cliffs, New Jersey: Prentice-Hall; 782p.
- Bora D S and Shukla U K 2005 Petrofacies implication for the Lower Siwalik Foreland Basin evolution, Kumaun Himalaya, India; *Paleontol. Soc. India Spec. Publ.* **2** 163–179.
- Burbank D W and Reynolds R G H 1988 Stratigraphic keys to the timing of thrusting in terrestrial foreland basins:

- Applications to the northwestern Himalaya; In: *New Perspective in Basin Analysis* (eds) Kleinspehn K L and Paola C (New York: Springer Verlag), pp. 331–351.
- Buslov M M 2004 Cenozoic tectonics of central Asia: Basement control; *Him. J. Sci.* **2**(4) 1–104.
- DeCelles P G *et al* 1998 Eocene early Miocene foreland basin development and the history of Himalayan thrusting, western and central Nepal; *Tectonics* **17** 741–765.
- DeCelles P G *et al* 2001 Stratigraphy, structure tectonic evolution of the Himalayan fold-thrust belt in western Nepal; *Tectonics* **21**(6) 487–509.
- Dickinson W R 1970 Interpreting detrital modes of graywacke and arkose; *J. Sedim. Petrol.* **40** 695–707.
- Dickinson W R *et al* 1983 Provenance of North American Phanerozoic sandstones in relation to tectonic setting; *Geol. Soc. Am. Bull.* **94** 222–235.
- Dickinson W R 1985 Interpreting provenance relations from detrital modes of sandstones, In: *Provenance of Arenites* (ed.) Zuffa G G (Dordrecht–Boston: D. Reidel Publishing Company), pp. 333–361.
- Dickinson W R 1988 Provenance and sediment dispersal in relation to paleotectonics and paleogeography of sedimentary basins, In: *New Perspectives in Basin Analysis* (eds) Kleinspehn K L and Paola C (New York: Springer), pp. 3–25.
- Dubey A K *et al* 2001 Erratic shortening from balanced cross sections of the western Himalayan foreland basin causes and implications for basin evolution; *J. Asian Earth Sci.* **19** 765–777.
- Franzinelli E and Potter P E 1983 Petrology, chemistry and texture of modern river sands, Amazon River system; *J. Geol.* **91** 23–40.
- Garzanti E and Vezzoli G 2003 A classification of metamorphic grains in sandstones based on their composition and grade; *J. Sedim. Res.* **73** 830–837.
- Garzanti E *et al* 2004 Collision-Orogen Provenance (Western Alps): Detrital signatures and unroofing trends; *J. Geol.* **112** 145–164.
- Garzanti E *et al* 2007 Quantifying sand provenance and erosion (Marsyandi River, Nepal Himalaya); *Earth Planet. Sci. Lett.* **258** 500–515.
- Ghosh S K and Kumar R 2000 Petrography of the Neogene Siwalik sandstone of the Himalayan foreland basin, Garhwal Himalaya: Implications for source area tectonics and climate; *J. Geol. Soc. India* **55** 1–15.
- Ghosh S K *et al* 2009 Response of 10 Ma thrusting event in the Himalayan Foreland sediments, Kangra sub-basin, Himachal Pradesh, India; *Him. Geol.* **30**(1) 1–15.
- Hisatomi K 1990 The sandstone petrography of the Churia (Siwalik) Group in the Arung Khola–Binai Khola Area, west central Nepal; *Bull. Fac. Edu. Wakayama Univ. Nat. Sci. Lett.* **39** 5–29.
- Hodges K V *et al* 1996 Tectonic evolution of the central Annapurna Range, Nepalese Himalayas; *Tectonics* **15** 1264–1291.
- Hubbard M S and Harrison T M 1989 $^{40}\text{Ar}/^{39}\text{Ar}$ constraints on deformation and metamorphism in the Main Central Thrust Zone and Tibetan Slab, eastern Nepal Himalaya; *Tectonics* **8** 865–880.
- Ingersoll R V 1990 Actualistic sandstone petrofacies: Discriminating modern and ancient source rocks; *Geology* **18** 733–736.
- Jalal P *et al* 2011 Detrital modes of Late Neogene Siwalik Sandstone of the Ramganga Sub-basin, Kumaun Sub-Himalaya: Implication for the source area tectonic history; *Him. Geol.* **32**(2) 123–135.
- Joshi M and Tiwari A N 2004 Quartz C-axes and metastable phases in the metamorphic rocks of Almora Nappe: Evidence of pre-Himalayan signatures; *Curr. Sci.* **87**(7) 995–999.
- Kotlia B S *et al* 2001 Lithology and magnetic stratigraphy of the Lower–Middle Siwalik succession between Kathgodam and Ranibagh, Kumaun Himalaya; *J. Geol. Soc. India* **58** 411–423.
- Kumar R *et al* 1999 Evolution of a Neogene fluvial system in a Himalayan foreland basin, India; In: *Himalaya and Tibet: Mountain Roots to Mountain Tops* (eds) Macfarlane A, Sorkhabi R B and Quade (Colorado: Boulder), *J. Geol. Soc. Am. Spec. Paper*, pp. 239–256.
- Kumar *et al* 2011 Sedimentary Architecture of Late Cenozoic Himalayan Foreland Basin Fill: An overview; In: *Facets of Phanerozoic* (ed.) Bhargava O N, *Geol. Soc. India Memoir* **78** 245–280.
- Kurhl J H 1996 Prism and basal plane parallel subgrain boundary in quartz: A microstructural geothermobarometer; *J. Met. Geol.* **14**(5) 581–589.
- Macfarlane A M 1992 A structural analysis of the Main Central thrust zone, Langtang National Park, central Nepal Himalaya; *Geol. Soc. Am. Bull.* **104** 1389–1402.
- Mack G H and Suttner L J 1977 Paleoclimate interpretation from petrographic comparison of Holocene sands and the Fountain Formation (Pennsylvanian) in the Colorado Front Range; *J. Sedim. Petrol.* **47** 89–100.
- Meigs A J *et al* 1995 Middle–late Miocene (N10 Ma) formation of the Main Boundary Thrust in the western Himalaya; *Geology* **23** 423–426.
- Misra R C and Valdiya K S 1961 Petrology and sedimentation of the Siwaliks of the Tanakpur area, district Nainital, U.P.; *Indian Mineral.* **2**(1) 7–35.
- Pandey P *et al* 2005 Structural state transformation in alkali feldspar: Evidence for post-crystallization deformation from Proterozoic granite, Kumaun Himalaya (India); *J. Asian Earth Sci.* **25** 611–620.
- Pearson O F and DeCelles P G 2005 Structural geology and regional tectonic significance of the Ramgarh thrust, Himalayan fold-thrust belt of Nepal; *Tectonics* **24**(4) TC4008, doi: 10.1029/2003TC001617.
- Pettijohn F J *et al* 1987 Sand and Sandstone; 2nd edn, (New York: Springer), 553p.
- Raiverman V 1997 On dating of the Himalayan thrusts; *Him. Geol.* **18** 63–79.
- Raiverman V *et al* 1983 Basin geometry, cenozoic sedimentation and hydrocarbon prospects in north western Himalaya and Indo-Gangetic plains; *Petrol. Asia J.* **1** 67–92.
- Raiverman V 2002 Foreland sedimentation; In: *Himalayan tectonic regime. A relook at the orogenic process* (ed.) Bisen Singh Mahendra Pal Singh, Dehradun, 371p.
- Sangode S J *et al* 1999 Paleomagnetic and rock magnetic perspectives on the post-collision continental sediments of the Himalaya, India; *Geol. Soc. India Memoir* **44** 221–248.
- Scholle P A 1978 A colour illustrated guide to carbonate rock constituents, textures, cement and porosity; *Am. Assoc. Petrol. Geol. Memoir* **27** 241p.
- Shrestha S B 1987 Geological map of far western Nepal, scale 1/250,000. Department of Mines and Geology–Ministry of Industry, His Majesty's Government of Nepal, Kathmandu.
- Sinha S *et al* 2008 Role of tectono-climatic factors in the Neogene Himalayan Foreland sediments: Petrology and geochemical approach, Kangra Sub-basin; *J. Geol. Soc. India* **71** 787–807.
- Stipp M *et al* 2002 The eastern Tonale fault zone: A 'natural laboratory' for crystal plastic deformation of quartz over a temperature range from 250 to 700°C; *J. Struct. Geol.* **24** 1861–1884.
- Tandon S K 1976 Siwalik sedimentation in a part of Kumaun Himalaya; *Sedim. Geol.* **16** 131–154.
- Thakur V C 1992 *Geology of Western Himalaya* (Oxford: Pergamon Press), 363p.

- Tiwari R N and Yadav R S N 1993 Significance of heavy minerals: A case study from the Siwalik of Garhwal Himalaya; *J. Indian Acad. Geosci.* **36**(1) 1–10.
- Valdiya K S 1980 *Geology of the Kumaun Lesser Himalaya* (Dehra Dun, India: Wadia Institute of Himalaya), 291p.
- Valdiya K S 1999 Rising Himalaya: Advent and intensification of monsoon; *Curr. Sci.* **76**(4) 514–524.
- Virdi N S 1979 On the geodynamic significance of mega lineaments in the outer and lesser regions of western Himalaya; *Him. Geol.* **9**(1) 79–99.
- Walker J D *et al* 1999 Metamorphism melting and extension: Age constraints from the High Himalayan slab of southeast Zaskar and Northwest Lahaul; *J. Geol.* **107** 473–495.
- Young S W 1976 Petrographic textures of detrital polycrystalline quartz as an aid in interpreting crystalline source rocks; *J. Sedim. Petrol.* **46** 595–603.
- Zuffa G G 1985 Optical analyses of arenites: Influence of methodology on compositional results; In: *Provenance of Arenites* (ed.) Zuffa G G, NATO-ASI Series (Dordrecht: Reidel) **148** 165–189.

MS received 24 May 2011; revised 9 January 2012; accepted 9 January 2012