Geosciences Journal
Vol. 18, No. 3, p. 307 − 324, September 2014
DOI 10.1007/s12303-014-0008-8

Petrological study of the Kaimur Group sediments, Vindhyan Supergroup, Central India: implications for provenance and tectonics

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ABSTRACT: The Mesoproterozoic Kaimur Group (1.1 Ga) belongs to the upper part of the Vindhyan Supergroup, which overlies the carbonate-rich sequence of the Semri Group (Lower Vindhyan), conformably in the Son Valley, Central India. The Kaimur Group consists predominantly of sandstones. On the basis of the present study they are classified as subarkose, sublitharenite, and quartz arenite in the Quartz (Q)-Feldspar (F)-Rock fragment (R) triangular diagram. The XRD patterns indicate that illite is the most prominent clay mineral. The Kaimur sequence can be divided into the Lower and Upper Kaimur Groups. The modal analyses data and the mineralogical ratios [Quartz/Feldspar (Q/F), Quartz/Lithic fragments (Q/L), Monocrystalline Quartz/Polycrystalline Quartz (Qm/Qp), Quartz/(Feldspar + Rock fragment) (Q/(F + R))] suggest that the Lower Kaimur Group has a fining upward sequence characterized by a decrease in textural and compositional maturity. In contrast, the Upper Kaimur terrigenous rocks have a coarsening upwards sequence with an increase in compositional and textural maturity. Monocrystalline Quartz-Feldspars and granite fragments-Lithics plus quartzose varieties (Qm-F-Lt) and total Quartz-Feldspar-Lithics (Qt-F-L) ternary plots, Polycrystalline Quartz-Non-undulose Quartz-Polycrystalline Quartz- Undulose Quartz ((Qp)-Q(nu)-(Qp)-Q(u)) diamond diagram and the types of lithic fragments suggest that the Lower Kaimur was derived mainly from a craton interior plutonic provenance (uplifted Bundelkhand craton that lies to the north of the basin). The Upper Kaimur terrigenous rocks are dominantly product of a recycled orogen composed of medium- to high-grade metamorphic rocks from the south (Mahakoshal metasediments and Chhotanagpur Gneissic Complex (CGC) of the Central Indian Tectonic Zone (CITZ)). The Polycrystalline Quartz/(Feldspar + Lithics) (Qp/(F + L)) vs. Quartz total/(Feldspar + Lithics) (Qt/(F + L)) ratios represent the deposition of Kaimur sandstones in the warm humid climate.

Key words: Kaimur Group, provenance, quartz arenite, Bundelkhand, Chhotanagpur gneisses

1. INTRODUCTION

The Kaimur Group, of the Vindhyan Supergroup, is part of the largest and best preserved intracratonic, Proterozoic sedimentary sequence in the world (Chakraborty, 2006; Chakraborty et al., 2010). On the basis of the lithological heterogeneity, the Supergroup has been separated into a carbonate-rich Lower Vindhyan succession (Semri Group) and siliciclastic-rich Upper Vindhyan succession (Kaimur, Rewa and Bhander Groups). The Kaimur Group, the lowermost unit of the Upper Vindhyan succession is a 400-m-thick, sandstone-dominated unit which gradationally overlies the Semri carbonates. The depositional environments of the Kaimur Group varied from shallow coastal fluvial and eolian environment to shoreface environment. Shoaling-up tidal-bars represent the shore face environment whereas the braid plain delta or eolian sandsheet represents the shallow coast where wind and water sculptured the topography (Singh, 1980; Chakraborty and Bose, 1992; Bhattacharya and Morad, 1993; Chakraborty, 1993, 1996; Chakraborty, 1995; Chakraborty, 1999; Bose et al., 2001; Sen, 2010). The Kaimur Group provides evidence regarding the changing environments of deposition, climatic conditions, tectonics and weathering conditions during the Mesoproterozoic (Mishra and Sen, 2010). The age of the Kaimur Group is about 1.1 Ga (Gregory et al., 2006; Malone et al., 2008).

The composition of sandstone is strongly controlled by the parent rock composition in the source region from which the sediments are derived. The term provenance encompasses all the processes related to sediment production, viz. parent rock composition, topography, and climate of the source area from which sediment is derived (Pettijohn et al., 1987). The detrital composition of terrigenous sediments has been thus correlated with specific plate-tectonic settings based on the mineralogical composition of sands and sandstones (Dickinson and Suczek, 1979; Dickinson et al., 1983). Modifications occurring during weathering, sediment transport, deposition, and diagenesis have been studied to determine the plate-tectonic setting of an ancient terrigenous successions (Zuffa, 1985; Johnsson and Basu, 1993). The palaeoclimate of the sandstones has been inferred by various workers (Basu, 1976; Suttner et al., 1981; Franzinelli and Potter, 1983).

The present paper aims to present detailed petrologic and mineralogic data from the Kaimur Group siliciclastic rocks. This study, for the first time, reports the compositional and textural distinction between the Lower and Upper Kaimur sequences of the Vindhyan Basin. The rock types present,

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provenance, tectonics, and paleoclimate of the Kaimur sandstones are also interpreted based on petrography, modal analyses, and XRD data.

2. GEOLOGY

The Kaimur Group comprises unmetamorphosed, gently dipping, sub-horizontal beds of sandstones and shales. The samples were obtained from the Son Valley sector, covering parts of the Mirzapur and Sonbhadra districts in Uttar Pradesh, India (Fig. 1a). The Bundelkhand granitic terrain forms the basement of the Son Valley basin and is exposed on the surface to the north. The Central Indian Tectonic Zone (CITZ), composed of the Mahakoshal Group and Chhotanagpur Granite Gneiss, fringes the southern margin of the study area.

The Lower Kaimur Group constitutes the Sasaram Sandstone, Ghurma Shale and Markundi Sandstone in ascending stratigraphic order. The Upper Kaimur comprises, from base to top, the Bijaigarh Shale, Mangesar Formation, and the Dhandraul Sandstone, with gradational contact between them.

The observations for the present study were carried out along five sections; the Ahraura-Markundi Ghat, Churk-Ghurma-Agori, Chirhuli, Patwadh-Mangesar and Chunar-Sakteshgarh (Fig. 1b).

2.1. Lower Kaimur Group

The coarse-grained and massively bedded Sasaram Sandstones rest conformably on the Rohtas limestone of the Semri Group. The Ghurma Shale, overlying the Sasaram Sandstone, is composed of a medium to fine-grained, thinly bedded sandstone. This is followed by the medium to fine grained Markundi Sandstone. The grain size and bed thickness both decrease upwards.

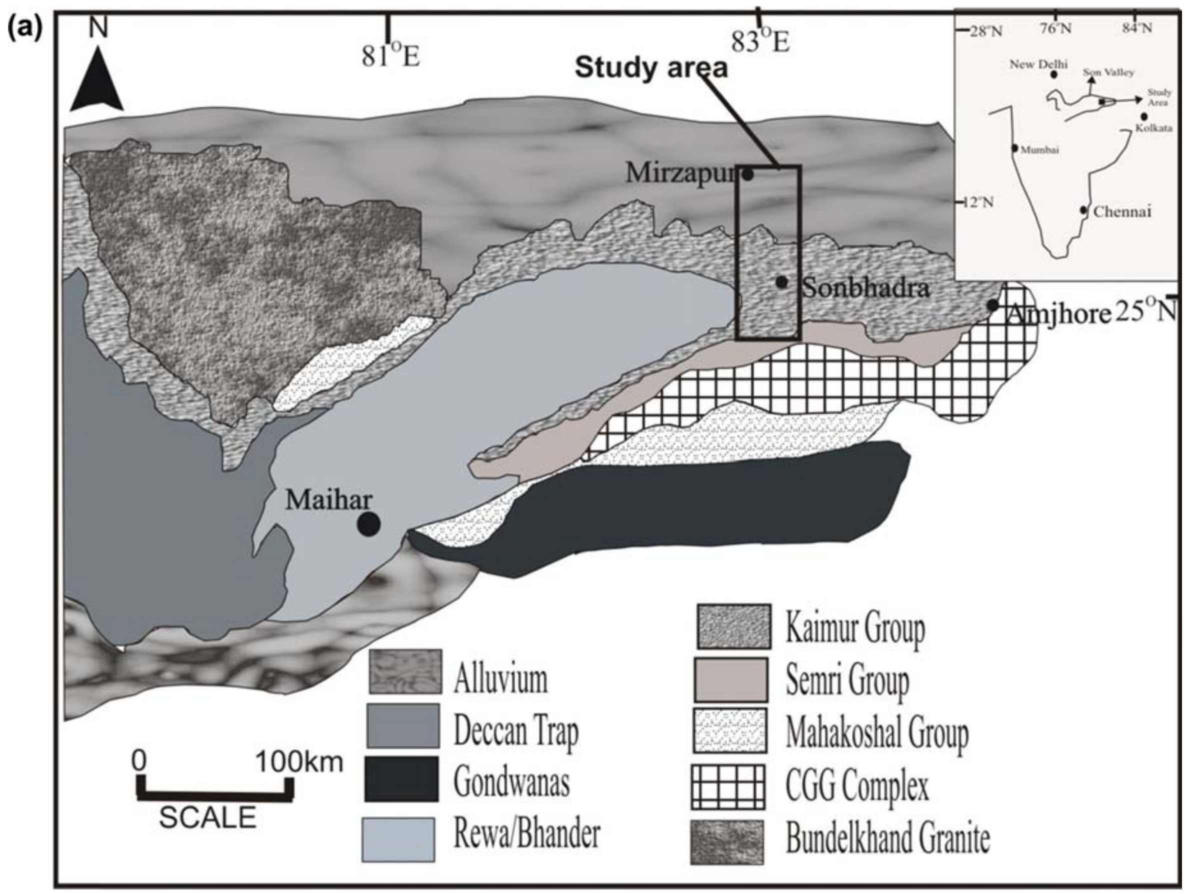

Fig. 1. (a) Geological map of the Son Valley sector of the Vindhyan basin. Inset shows the position of the Vindhyan basin, Son Valley and the study area in the map of India. The location of the study area is shown by the box and arrow. The age of the important lithologic units are as follows: Bundelkhand granite ~2.2 Ga (Sarkar et al., 1995); Chhotanagpur Gneissic Complex (CGC) ~2 Ga (Mukherjee and Ghose, 1999; Ghose and Mukherjee, 2000); Mahakoshal Group ~1.8 Ga (Sarkar et al., 1998); Semri Group ~1.6 Ga (Ray et al., 2002; Rasmussen et al., 2002; Ray et al., 2003; Sarangi, 2004; Ray, 2006); Rewa/Bhander Group ~1.0 Ga (Malone et al., 2008) and Kaimur Group ~ 1.1Ga (Gregory et al., 2006; Malone et al., 2008). (b) Geological map of the study area in the Mirzapur and Sonbhadra districts (Son Valley). The sections studied have been marked by A – Ahraura-Markundi Ghat, B – Chunar-Sakteshgarh, C – Chirhuli, D – Patwadh-Mangesar and E – Churk-Ghurma-Agori.

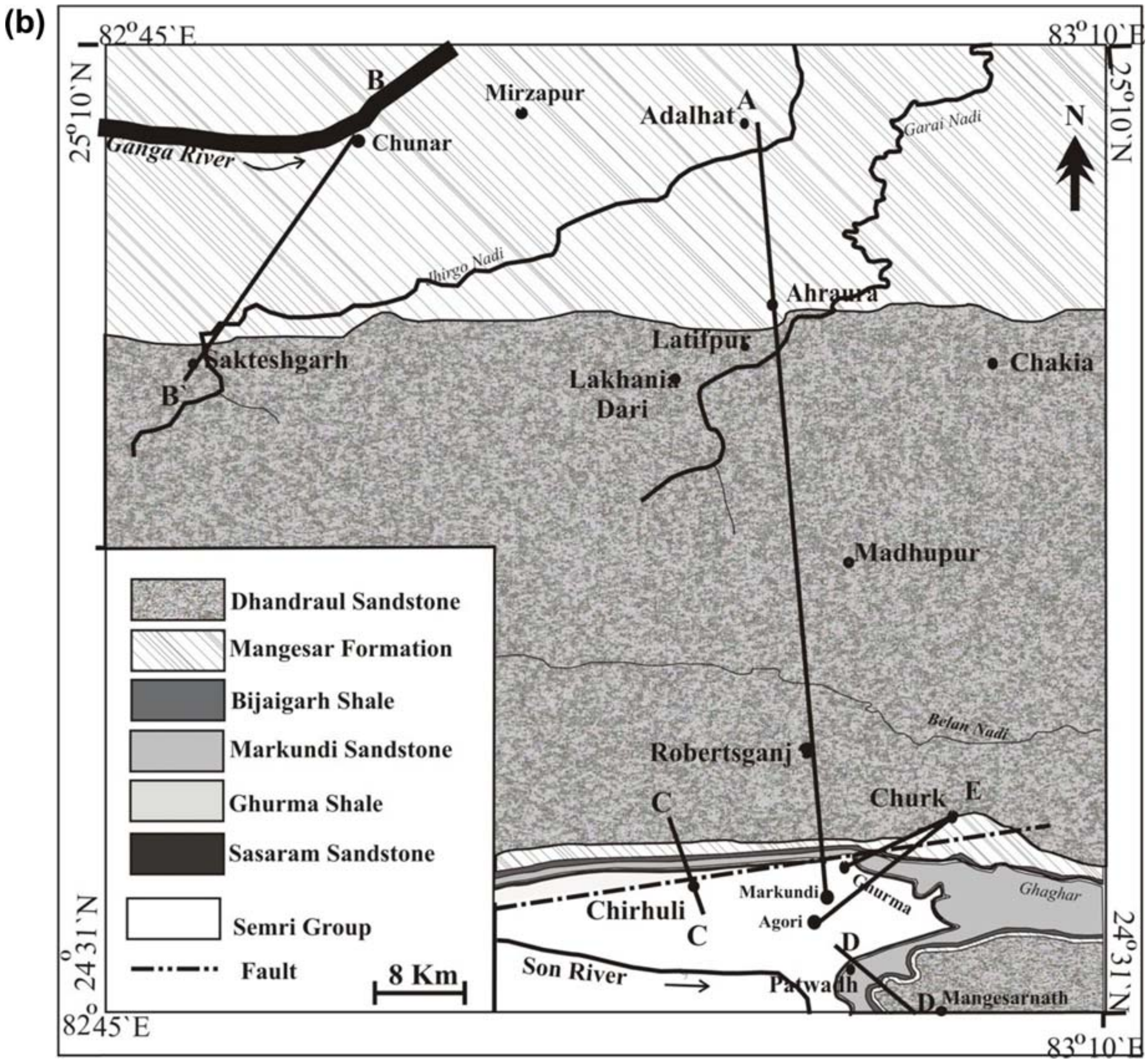

Fig. 1. (continued).

2.2. Upper Kaimur Group

The lowermost unit of the Upper Kaimur is the Bijaigarh Shale. This shale is lithologically heterogeneous with a wide grain size variation from medium sand to clay. The Mangesar Formation is composed of medium to fine grained sandstones of variegated colours. Interestingly, the Mangesar sandstones exhibit rhythmic internal cyclicity of coarse and finer sediments, overall coarsening upwards. The Dhandraul sandstones are massive, coarse grained and thickly bedded. The contact between the Mangesar and Dhandraul sandstones is gradational, and the coarseness increases upwards to off-white, supermature sandstones.

3. METHODOLOGY

Detailed petrographic study of about 50 thin sections of the Kaimur sandstones was carried out under a high resolution Leica DMRX microscope. The photographs were taken with an Olympus BX51 microscope. Modal analysis was carried out using a Leitz SM-LUX-POL microscope. The back-scattered electron probe images of polished thin sections were obtained using a CAMECA SX 100.

The X-ray powder Diffraction (XRD) pattern of the Bijaigarh Shale sample was determined using a Rigaku DMAX III diffractometer. The whole rock powders were scanned from 9 to 76 degrees 2θ with a scanning speed of .05 degrees/sec. Minerals were identified by using JCPDS data file of 1987.

For modal analysis twenty-five representative and clear thin sections were selected. About 500 grains were counted per thin section using the Gazzi-Dickinson point-counting method. There are six samples from the Sasaram Sandstone, two from the Ghurma Shale, three from the Markundi Sandstone of the Lower Kaimur Group. Six samples from the Mangesar Formation and eight from the Dhandraul Sandstone were counted from the Upper Kaimur Group. The modal data for

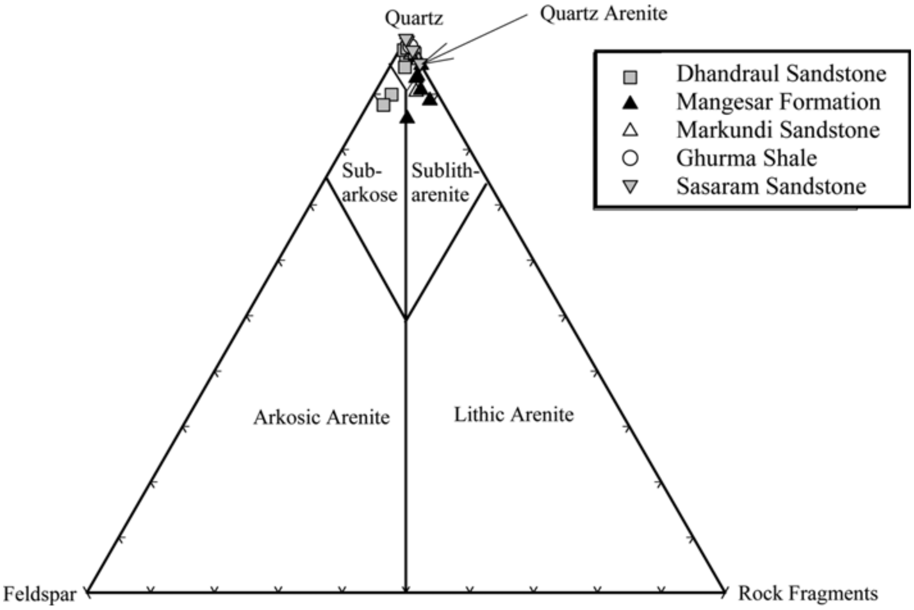

Fig. 2. QFL-triangular plot for the classification of sandstone samples from the Kaimur Group (Folk, 1980).

Table 1. Modal compositions of sandstones of the Kaimur Group obtained from 500 grain counts

Mineral constituents	Quartz					Feldspar				Rock fragments		
Sample No.	Qm (nu)	Qm (u)	Qp (2-3)	Qp (>3)	Total	Plg.	Mcl.	Otclase	Total	Lithics	Chert	Total
Dhandraul Sandstone												
AH-3b	39.67	43.67	5.33	6.67	95.33	0.00	0.00	1.67	1.67	1.00	0.67	1.67
LT-3	36.33	35.33	7.00	7.33	86.00	0.33	2.67	4.00	7.00	2.00	0.67	2.67
SD-1	39.00	34.67	3.00	6.67	83.33	2.33	2.00	4.67	9.00	2.00	0.33	2.33
SD-4	35.00	44.67	3.33	8.67	91.67	0.67	0.67	1.33	2.67	2.00	0.33	2.33
MAR-3	44.00	40.33	3.00	7.67	95.00	0.00	0.00	1.33	1.33	0.33	0.33	0.67
MAR-19	47.67	43.33	2.67	2.00	95.67	0.00	0.00	0.33	0.33	0.67	0.33	1.00
SPC-12	50.33	41.33	0.33	3.67	95.67	0.00	0.00	0.00	0.00	2.33	0.33	2.67
SPC-13	48.33	37.33	1.33	9.33	96.33	0.33	0.00	0.33	0.67	0.67	0.33	1.00
Mangesar Formation												
MAR-13	65.00	11.67	0.33	1.00	78.00	0.00	0.00	1.33	1.33	3.67	0.67	4.33
MAR-14	45.00	30.00	3.33	8.00	86.33	0.00	0.00	0.00	0.00	3.33	1.00	4.33
SPC-3	42.00	29.67	3.67	4.00	79.33	0.33	0.67	0.67	1.67	7.67	0.67	8.33
SPC-4	48.00	26.00	2.33	1.67	78.00	0.67	0.00	1.00	1.67	3.33	1.00	4.33
AD-15	46.33	25.00	4.00	3.00	78.33	0.00	0.00	2.00	6.00	5.00	1.00	6.00
CHR-4	48.67	21.67	1.00	5.67	77.00	1.00	1.33	4.00	6.33	6.00	0.67	6.67
Markundi Sandstone												
CLI-1	73.33	10.67	0.00	0.67	84.67	1.67	1.33	0.00	3.00	6.00	0.00	6.00
CLI-3	76.33	13.00	0.00	0.00	89.33	0.00	0.67	0.00	0.67	2.00	0.00	2.00
CLI-7	79.67	10.33	0.00	0.00	90.00	0.00	0.00	0.00	0.00	3.67	0.00	3.67
Ghurma Shale												
MAR-31	83.67	11.67	0.00	0.00	95.33	0.00	0.00	0.00	0.00	1.33	0.00	1.33
MAR-36	84.57	10.47	0.00	0.00	95.04	0.00	0.00	0.00	0.00	1.93	0.00	1.93
Sasaram Sandstone												
PWK-4	70.00	26.00	0.67	0.33	97.00	0.00	0.00	0.00	0.00	0.33	0.00	0.33
AGR-3A	61.00	23.00	4.67	4.33	93.00	0.00	0.00	0.00	0.00	4.33	0.00	4.33
GHR-1	71.67	16.33	5.00	4.67	97.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00
AGR-1	70.67	17.33	3.67	2.33	94.00	0.00	0.00	0.00	0.00	2.00	0.00	2.00
PWK-3A	77.67	14.33	3.33	3.33	98.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PWK-1B	87.33	9.33	0.67	1.33	98.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 1. (continued)

Cement				Matrix				Mica			Others
Silica	Ferru.	Calc.	Total	Clayey	Silty	Sandy	Total	Musc.	Biotite	Total	
0.67	0.33	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33
1.33	0.00	0.00	1.33	2.00	0.00	0.00	2.00	0.67	0.00	0.67	0.33
2.67	0.00	0.00	2.67	1.00	0.33	0.00	1.33	0.67	0.00	0.67	0.67
2.33	0.00	0.00	2.33	0.00	0.33	0.00	0.33	0.00	0.00	0.00	0.67
2.00	0.00	0.00	2.00	0.33	0.00	0.00	0.33	0.33	0.00	0.33	0.33
1.33	0.00	0.00	1.33	0.67	0.00	0.00	0.67	0.67	0.00	0.67	0.33
0.33	0.00	0.00	0.33	0.67	0.00	0.00	0.67	0.33	0.00	0.33	0.33
0.67	0.33	0.00	1.00	0.33	0.00	0.00	0.33	0.33	0.00	0.33	0.33
0.00	12.33	0.00	12.33	3.00	0.67	0.00	3.67	0.00	0.00	0.00	0.33
1.33	4.00	0.00	5.33	3.67	0.00	0.00	3.67	0.00	0.00	0.00	0.33
0.00	1.00	0.00	1.00	6.33	2.67	0.00	9.00	0.67	0.00	0.67	0.00
0.00	8.33	0.00	8.33	3.67	3.33	0.00	7.00	0.67	0.00	0.67	0.00
0.33	6.00	0.00	6.33	3.00	0.67	0.00	3.67	0.00	0.00	0.00	0.00
0.33	2.00	0.00	2.33	3.00	4.00	0.00	7.00	0.33	0.00	0.33	0.33
0.00	1.00	0.00	1.00	5.00	0.00	0.00	5.00	0.33	0.00	0.33	0.00
0.00	6.00	0.00	6.00	2.00	0.00	0.00	2.00	0.00	0.00	0.00	0.00
0.00	2.00	0.00	2.00	2.33	0.00	0.00	2.33	1.33	0.00	1.33	0.67
1.00	0.00	0.00	1.00	1.33	0.00	0.00	1.33	0.00	0.00	0.00	1.00
1.60	0.00	0.00	1.60	1.42	0.00	0.00	1.42	0.00	0.00	0.00	0.00
2.33	0.00	0.00	2.33	0.00	0.33	0.00	0.33	0.00	0.00	0.00	0.00
1.00	0.33	0.00	1.33	0.33	1.00	0.00	1.33	0.00	0.00	0.00	0.00
2.33	0.00	0.00	2.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.00	0.00	0.00	3.00	0.67	0.00	0.00	0.67	0.33	0.00	0.33	0.00
1.33	0.00	0.00	1.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.33	0.00	0.00	1.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Abbreviation used: Qm (nu) – monocrystalline non-undulose quartz; Qm (u) – monocrystalline undulose quartz; Qp (2-3) – polycrystalline quartz 2-3 subgrains; Qp (>3) – polycrystalline quartz >3 subgrains, Plg. – plagioclase, Mcl. – Microcline, Otclase – Orthoclase, Ferru. – Ferruginous, Calc. – Calcareous, Musc. – Muscovite.

these sandstones are given in Tables 1 and 2.

The modal data were recalculated on a matrix-free basis to plot on a QFL diagram. The polycrystalline quartz was placed at the Q-pole to obviate the problems of distinction between plutonic polycrystalline quartz and metaquartzite fragments. In the ternary diagram, constructed for delineating the tectonic setting of the provenance by Dickinson et al. (1983), the polycrystalline quartz was placed at the Lt pole in the QmFLt plot and at Qt pole in the QtFL diagram. Cherts are of sedimentary origin and therefore placed at the rock fragment pole of the plots. The F pole comprises all types of feldspar grains including those from a granitic source.

The source rock composition, provenance, tectonic setting, and paleoclimate of the Kaimur sandstones were deduced using the modal analysis data. The modal data were plotted in the diagrams suggested by Basu et al. (1975), Basu (1985) Dickinson et al. (1983), and Suttner and Dutta (1986). Folk's (1980) classification was used for characterizing the sandstones.

4. PETROGRAPHY & XRD

4.1. Lower Kaimur Group

The Sasaram Sandstones are quartz arenites (Fig. 2) with rounded to sub-rounded detrital grains and bimodal grain size distribution (Fig. 3a). The framework grains constitute 94–98.6% of detrital quartz. Non-undulatory, monocrystalline quartz [Qm(nu)] is the most common while polycrystalline quartz (Qp) and undulatory, monocrystalline quartz [Qm(u)] occur in subordinate amounts (Tables 1 and 2). The sub-grains of Qp have straight and sutured contacts (Fig. 4b). The etched surfaces of quartz grains point to the effect of pressure solution activity. Feldspars are absent. Lithic fragments comprise about 0.3–4.3% of the total grains and include clasts from mostly sedimentary (Fig. 3c) and plutonic sources. Zircon and tourmaline are the most common heavy minerals. Siliceous cement is the dominant binding material (1.33–2.33%) and occurs as an overgrowth, rendering a sub-angular shape,

Table 2. Quartz (Q), Feldspar (F) and Lithic Fragment (L) proportions in sandstones

							Recalculated to 100			
Sample No.	Qm	Qp	Qt	F + Rgr	L	Total	Q	F	L	Total
Dhandraul Sandstone										
AH-3b	83.33	12.00	95.33	1.67	1.67	98.67	96.62	1.69	1.69	100
LT-3	71.67	14.33	86.00	7.00	2.67	95.67	89.90	7.32	2.79	100
SD-1	73.67	9.67	83.33	9.00	2.33	94.67	88.03	9.51	2.46	100
SD-4	79.67	12.00	91.67	2.67	2.33	96.67	94.83	2.76	2.41	100
MAR-3	84.33	10.67	95.00	1.33	0.67	97.00	97.94	1.37	0.69	100
MAR-19	91.00	4.67	95.67	0.33	1.00	97.00	98.63	0.34	1.03	100
SPC-12	91.67	4.00	95.67	0.00	2.67	98.33	97.29	0.00	2.71	100
SPC-13	85.67	10.67	96.33	0.67	1.00	98.00	98.30	0.68	1.02	100
Mangesar Formation										
MAR-13	76.67	1.33	78.00	1.33	4.33	83.67	93.23	1.59	5.18	100
MAR-14	75.00	11.33	86.33	0.00	4.33	90.67	95.22	0.00	4.78	100
SPC-3	71.67	7.67	79.33	1.67	8.33	89.33	88.81	1.87	9.33	100
SPC-4	74.00	4.00	78.00	1.67	4.33	84.00	92.86	1.98	5.16	100
AD-15	71.33	7.00	78.33	2.00	6.00	86.33	90.73	2.32	6.95	100
CHR-4	70.33	6.67	77.00	6.33	6.67	90.00	85.56	7.04	7.41	100
Markundi Sandstone										
CLI-1	84.00	0.67	84.67	3.00	6.00	93.67	90.39	3.20	6.41	100
CLI-3	89.33	0.00	89.33	0.67	2.00	92.00	97.10	0.72	2.17	100
CLI-7	90.00	0.00	90.00	0.00	3.67	93.67	96.09	0.00	3.91	100
Ghurma Shale										
MAR-31	95.33	0.00	95.33	0.00	1.33	96.67	98.62	0.00	1.38	100
MAR-36	95.04	0.00	95.04	0.00	1.93	96.97	98.01	0.00	1.99	100
Sasaram Sandstone										
PWK-4	96.00	1.00	97.00	0.00	0.33	97.33	99.66	0.00	0.34	100
AGR-3A	84.00	9.00	93.00	0.00	4.33	97.33	95.55	0.00	4.45	100
GHR-1	88.00	9.67	97.67	0.00	0.00	97.67	100.0	0.00	0.00	100
AGR-1	88.00	6.00	94.00	0.00	2.00	96.00	97.92	0.00	2.08	100
PWK-3A	92.00	6.67	98.67	0.00	0.00	98.67	100.0	0.00	0.00	100
PWK-1B	96.67	2.00	98.67	0.00	0.00	98.67	100.0	0.00	0.00	100

Abbreviations used: Qm – monocrystalline; Qp – polycrystalline quartz; Qt – Total quartz; F –Feldspar; Rgr – Granite fragment; L – Lithic fragment.

like the crystal faces of the undisturbed quartz grain.

Ghurma Shales are mostly quartz arenites (Fig. 2). They are characterized by medium grained, moderately sorted sandstones and a bimodal grain size distribution (Fig. 3d). The framework grains consist mainly of monocrystalline quartz with minor feldspar and muscovite (Fig. 3d). The lithic fragments, mostly of plutonic origin, constitute about 1.33% of the total framework grains. Mudstone detrital grains are also present (Fig. 3e). The Markundi Sandstone are sublitharenites to quartz arenites and are characterized by a lesser maturity than the underlying sandstones (Fig. 3f). The framework grains of the Markundi Sandstone are subangular to angular in shape, where Qm(nu) is dominant (~76.4%) in comparison to Qm(u) which is ~11.3% with occasional polycrystalline quartz. The samples in contact with the Ghurma Shale show bimodality in grain size. Microcline and plagioclase (0.67–3%), are present among the feldspars. Lithic fragments (2–6%) are mostly of metamorphic origin. The brown tourmaline is abundant (Fig. 3g), whereas, zoned zircon grains are present in minor amounts. Cement is predominantly ferruginous (1–6%) that occurs in isolated patches within the clayey matrix.

4.2. Upper Kaimur Group

In the Upper Kaimur Group, the Bijaigarh Shale consists of quartz and feldspars as the dominant detrital minerals. Muscovite exhibits kinking due to compaction and alignment parallel to the laminations. The binding materials comprise clay minerals and ferruginous cements of hematite. X-ray

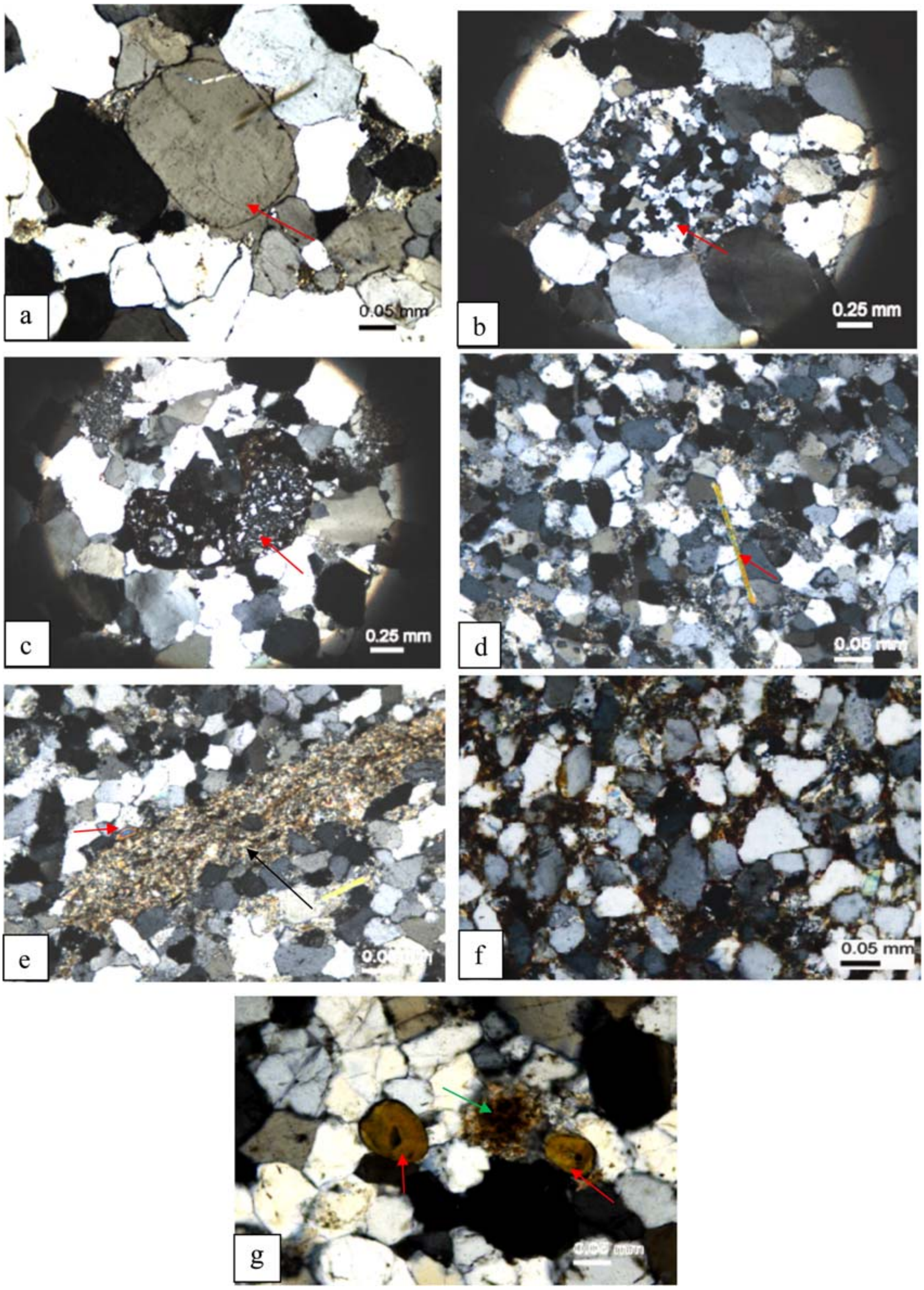

Fig. 3. Microphotographs of the Lower Kaimur sandstones (a) A bimodal grain size distribution in the Sasaram sandstone. An arrow shows rounded coarse grain of quartz with silica overgrowths (b) Coarse polycrystalline quartz with sutured contact, shown by an arrow in the Sasaram sandstone (c) Detrital subrounded sedimentary rock fragment (shown by an arrow) in the Sasaram sandstone, (d) Medium to fine grained sandstone from the Ghurma Shale, (e) Mud intraclast (black arrow) in the sandstones of the Ghurma Shale with a zoned zircon grain (red arrow). (f) Markundi sandstone photomicrograph shows medium grained, subangular quartz grains with a slight bimodal grain size distribution and ferruginous (hematitic) cement along with the clayey matrix (g) Rounded brown tourmaline (red arrow) present in an abundance in the Markundi Sandstone. The green arrow shows clayey matrix with ferruginous cement patches in the Markundi sandstone.

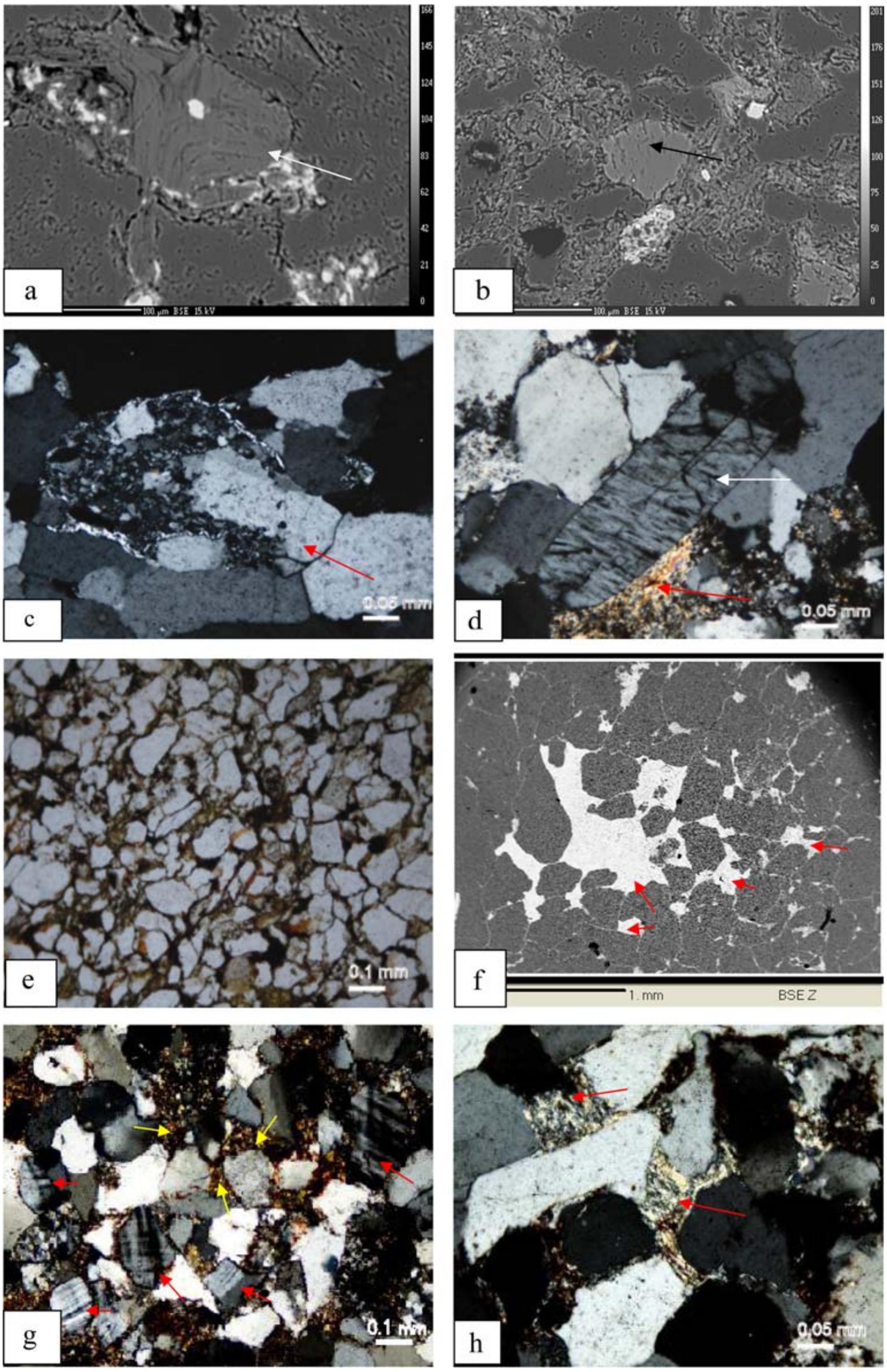

Fig. 4. (a) Backscattered image of a muscovite in the Mangesar sandstone, shown by an arrow (b) Backscattered image of orthoclase in the Mangesar sandstone. The arrow shows the cleavage planes. (c) Rock fragment of possibly gneissic origin (shown by an arrow) present in the Mangesar sandstone. (d) Perthitic texture is an intergrowth texture found in plutonic rocks like granites and a clast of perthite (shown by an arrow) is present in the Mangesar sandstone. (e) Ferruginous (Hematite) cement is the most important binding material in the red coloured Mangesar sandstone with subangular quartz. (f) Backscattered image of the hematite in the Mangesar sandstone, shown by the arrows (g) The abundance of the feldspars of three types – orthoclase, microcline and plagioclase (red arrows),with ferruginous cement (yellow arrows) present in the Mangesar sandstone. (h) The feldspar grains probably have altered after deposition to form the pseudo-matrix in the Mangesar sandstone, shown by the arrows.

Diffraction (XRD) analysis indicates that illite is the common clay mineral in the Bijaigarh shales. This was further corroborated by EPMA (Sen, 2010) and geochemical data (Mishra and Sen, 2012). The Mangesar sandstones have angular to subangular, poorly to moderately sorted grains and are characterized as sublitharenite to quartz arenite. Quartz constitutes about 77–86% of the framework grains. The Qm(nu) grains are dominant and comprise about 42–65% of the total quartz, Qm(u) ranges between 11.6–30%, and Qp occurs in minor amounts (Table 1). Muscovite displays preferred alignment and bending due to compaction (Fig. 4a). Orthoclase is the dominant feldspar (Fig. 4b), whereas, plagioclase and microcline are equally present in minor amounts. Clay minerals have developed along the cleavage, fractures, and twin surfaces of the altered orthoclase. Lithic fragments (4–6%) are mostly of metamorphic (Fig. 4c) and plutonic origin. Perthitic texture (Fig. 4d) implies their derivation from a plutonic source. The distinguishing feature of the sandstones from the Mangesar Formation is the presence of the hematitic cement (Fig. 4e), which consists of micron-size platy hematite crystals (Fig. 4f) apart from the siliceous cement.

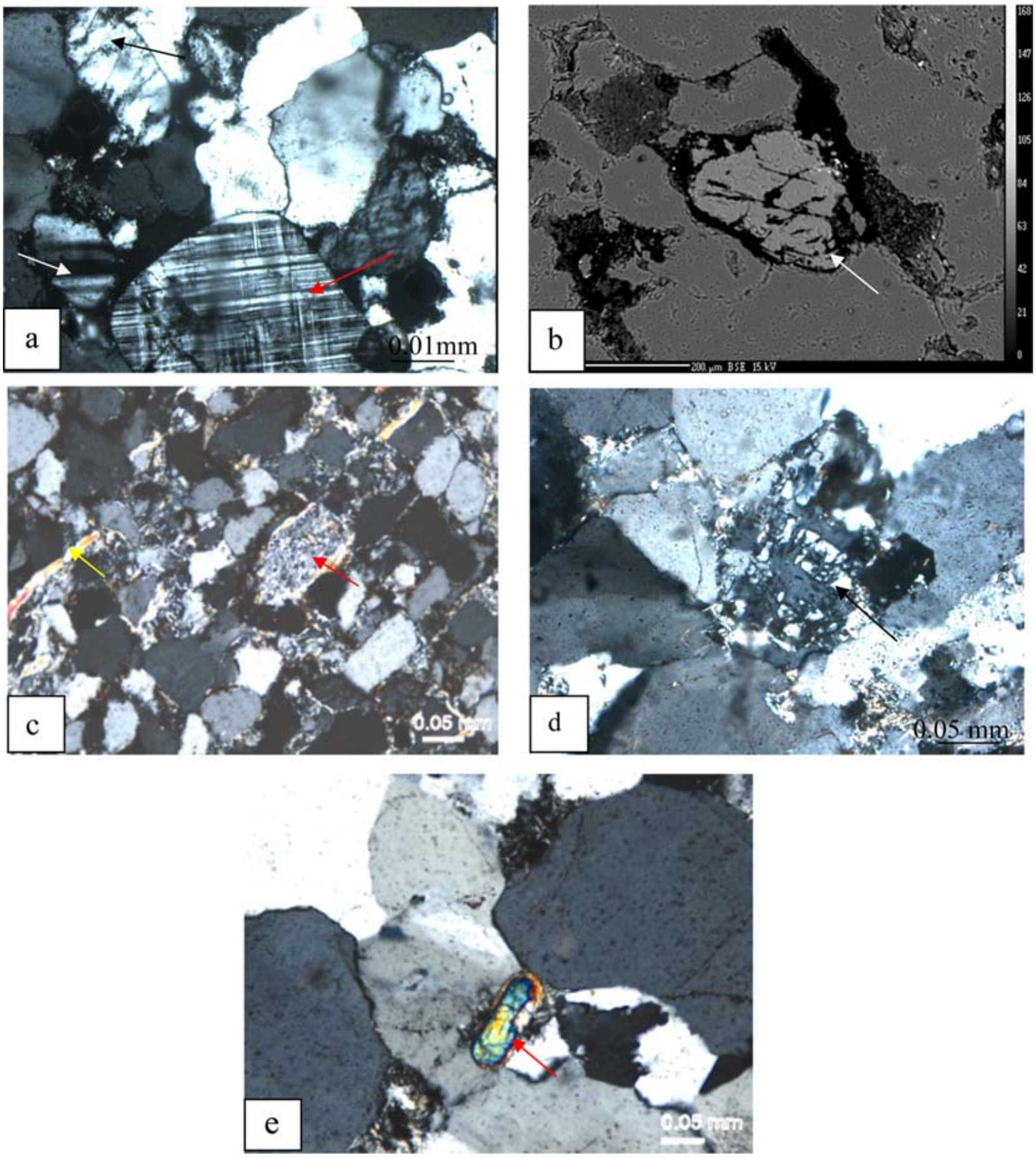

Fig. 5. (a) Rounded orthoclase (black arrow), microcline (red arrow) and plagioclase (white arrow) with subangular quartz grains, present in the Dhandraul sandstones. (b) Back scattered image of a microcline grain in the Dhandraul sandstones depicting two sets cleavage, shown by an arrow. (c) Feldspars (orthoclase) suffering alteration along the cleavage planes possibly to mica (red arrow). Muscovite is shown by a yellow arrow in the Dhandraul sandstone. (d) Detrital granite fragment showing graphic granite texture (shown by an arrow) in the Dhandraul sandstone of the Kaimur Group. (e) Zoned zircon (shown by an arrow) is the most abundant in the Dhandraul sandstone when compared with the other formations of the Kaimur Group.

The Mangesar sandstone, at its contact with the Bijaigarh Shale, contains abundant feldspar (Fig. 4g). The feldspar content decreases stratigraphically upwards where probably the feldspars and mica have altered to form pseudomatrix, and the silica cement becomes dominant (Fig. 4h). Therefore, textural and compositional maturity increases stratigraphically upwards. The Dhandraul Sandstone is sub-arkose at a lower stratigraphic level and grades to quartz arenite with an overall upward increase in the mineralogical and textural maturity.

The framework grains are composed of quartz (83.3–96.3%), feldspars (0.33–9.0%) and lithic fragments (0.6–2.67%) (Table 1). The grains are usually spherical and round. Monocrystalline, non-undulose and undulose quartz are equally abundant, whereas, polycrystalline quartz grains are subordinate, with both straight and sutured contacts. Microcline, plagioclase, and orthoclase (0.33–7%) are present (Figs. 5a and b). The abundance of muscovite and feldspar decreases upwards (Figs. 5a and b). Their grains have altered to form pseudomatrix. The feldspars are altered to muscovite along cleavage planes and cracks by the process of muscovitization (Fig. 5c) (Zuffa, 1985). Clay minerals have also developed along the cleavages, fractures and twin surfaces of the altered feldspar grains. Rock fragments include chert, lithic fragments of metamorphic origin and fragments that display igneous textures viz. granophyric, graphic (Fig. 5d) and perthitic. Zircon (zoned and unzoned) (Fig. 5e), tourmaline, and minor sphene are present. The heavy mineral separation shows the presence of garnet which is also confirmed by an EPMA analysis (Sen, 2010). Silica cement constitutes about 0.33–2.3% as quartz overgrowths.

5. DISCUSSION

5.1. Classification

According to Folk's sandstone classification diagram (Fig. 2), the Lower Kaimur Group is composed of sub-litharenites to quartz arenites while the Upper Kaimur Group is composed of shales, sub-litharenites, sub-arkose, and quartz arenites. Most of the Kaimur siliciclastic rocks are quartz arenites.

5.2. Stratigraphic Variation in Framework Composition and Textural Attributes

The vertical stratigraphic succession of the Kaimur Group is characterized by the variations in compositional and textural maturity. The deposition of the Kaimur siliciclastics took place in two phases (Fig. 6). The siliciclastics in the Lower Kaimur Group represent the first phase of deposition in a fining upward sequence. In this, the quartz grain percentage, silica cement, and the grain size gradually decrease upward. Simultaneously, the kinds of framework grains (feldspar, mica, lithic fragments), their angularity, and matrix concentration increase upward. Thus, the observations suggest a decrease in the textural and mineralogical maturity stratigraphically upwards during the deposition of the Lower Kaimur siliciclastic rocks. The Upper Kaimur Group is, however, a coarsening upward succession that represents the second phase of deposition. The base of the second phase contains fine grains with the most abundant feldspar and muscovite in the Bijaigarh Shale. The quartz grain percentage, grain size, and the silica cement concentration increases. The mica, rock fragments, matrix concentration, and angularity of grains decreases upwards to Mangesar sandstone that are sublitharenite to quartz arenite (Fig. 2). The uppermost Dhandraul sandstones are subarkose, having feldspars in the lower horizon that grades to texturally and mineralogically mature quartz arenites in the upper horizon. Therefore, in the second phase there is broadly an increase in the textural as well as mineralogical maturity of the sediments.

5.3. Effect of Diagenesis

The effect of diagenesis is observed in the Mangesar and Dhandraul sandstones of the Upper Kaimur Group. The feldspars and muscovite present in the Mangesar sandstone when in contact with the Bijaigarh Shale becomes visibly less common in the upper horizons. This is possible either by the change in source or due to the process of diagenesis. The presence of pseudomatrix evisages diagenetic alteration in these sandstones. Similarly Dhandraul sandstones also have experienced diagenesis with the alteration of feldspars by the process of muscovitization and the presence of pseudomatrix (Fig. 5c).

Diagenesis may involve the destruction of unstable grains like the feldspars and the lithic fragments with increasing depth. In the Kaimur Group the abundance of these detrital grains follows an overall cyclic trend with no apparent diagenetic destruction of the unstable framework grains with depth. Therefore, it is likely that the diagenetic processes may not have changed the original composition of Kaimur sandstones.

5.4. Source Rock Composition

The occurrence of the feldspars, lithic fragments, and the detrital quartz grains are used to deduce the provenance of the sandstones. Due to the scarcity of feldspars and rock fragments in the Kaimur sediments the detrital quartz grains are used to define the provenance of these Kaimur sandstones. The dominance of the monocrystalline quartz that are slightly undulose suggests a plutonic source while the presence of moderate to strongly undulose, monocrystalline quartz grains suggests a metamorphic source (Basu et al., 1975; Basu, 1985).

The degree of undulosity in the monocrystalline quartz grains and the number of subgrains within the polycrystalline quartz grains are used in a diamond diagram as the dis-

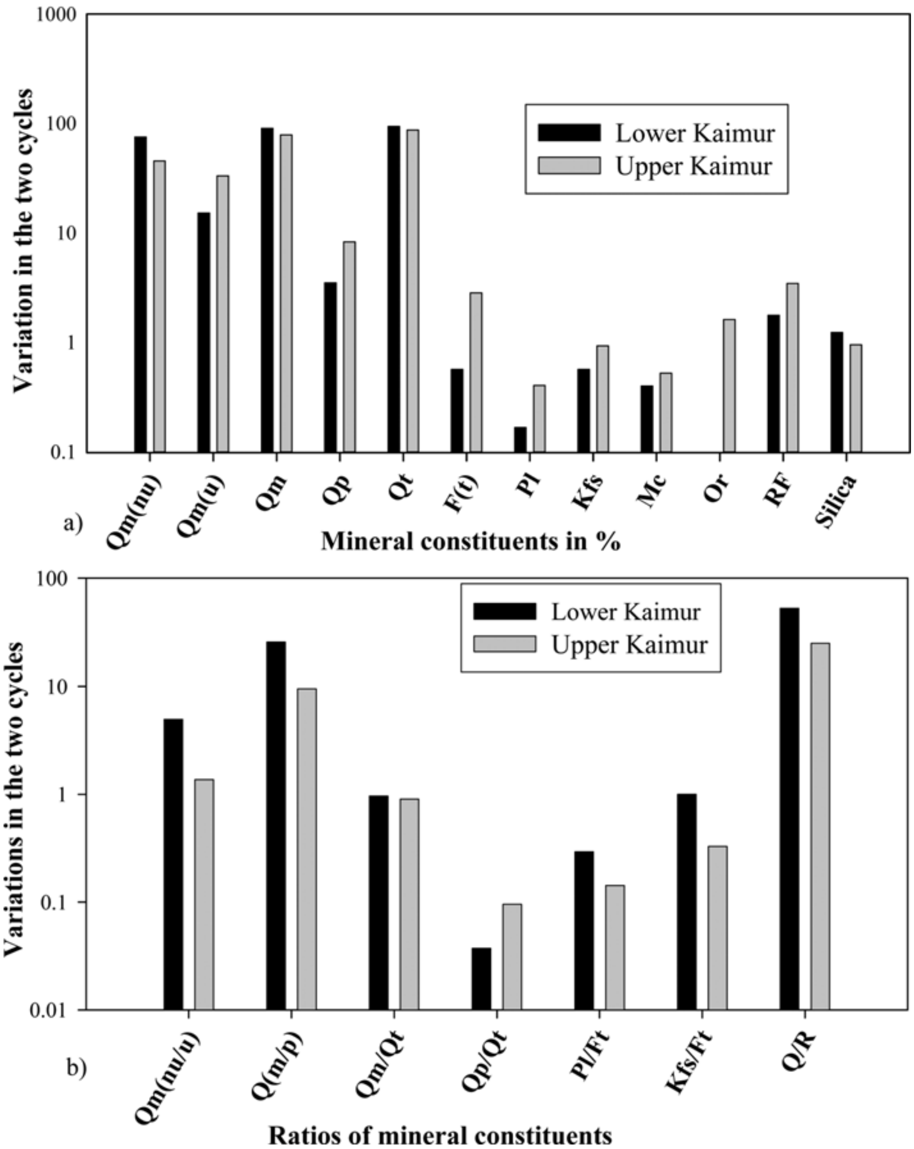

Fig. 6. Graphical representation of (a) compositional variation of mineral constituents and (b) their ratios. Abbreviations used: Pl – Plagioclase, Kfs – K-feldspar, F(t) – total feldspars, RF – rock fragment, Silica – siliceous cement and the rest are mentioned in Tables 1 and 2.

criminants for different source rocks (Fig. 7). According to Basu et al. (1975), if >25% of all the polycrystalline quartz grains consist of >4 subgrains each, then the lower triangle of the diamond diagram is used; otherwise the counts are plotted in the upper triangle. The Kaimur sandstones have the polycrystalline grains with 4 subgrains that contribute more than 25% of total polycrystalline grains, therefore, the samples plot in the lower triangle (Fig. 7). However, there is a limitation to this diagram since it should only be applied to the medium sand-size fraction of first cycle sandstones (Basu et al., 1975; Basu, 1976, 1985). The Sasaram sandstones are coarse-grained quartz arenites, therefore, they could be of multicyclic origin. The characteristics of these sandstones do not change stratigraphically upward to the Ghurma Shale. Probably the provenance for both sandstone types could have been similar, therefore, they have also been included in the diamond diagram, considering them as single phase sandstones and the changes otherwise observed may be due to the action of the environment of deposition (Pettijohn et al., 1987).

In the diamond diagram, the sandstones of the Lower Kaimur Group show a plutonic igneous source (Fig. 7). The plutonic igneous source implies a granitic provenance. This can be corroborated by the presence of lithics of the plutonic igneous rocks. However, the presences of the lithics of metamorphic and sedimentary origin in these sandstones imply that they are an additional source to the main plutonic provenance.

In the fourier diagram (Fig. 7) the sandstones for the Upper Kaimur siliciclastics show a medium- to high-grade metamorphic rock source. This metamorphic source indicates they were derived from a garnet through sillimanite metamorphic rock. This can be also be associated with the presence of their lithics. However in the Upper Kaimur Group there are cherts

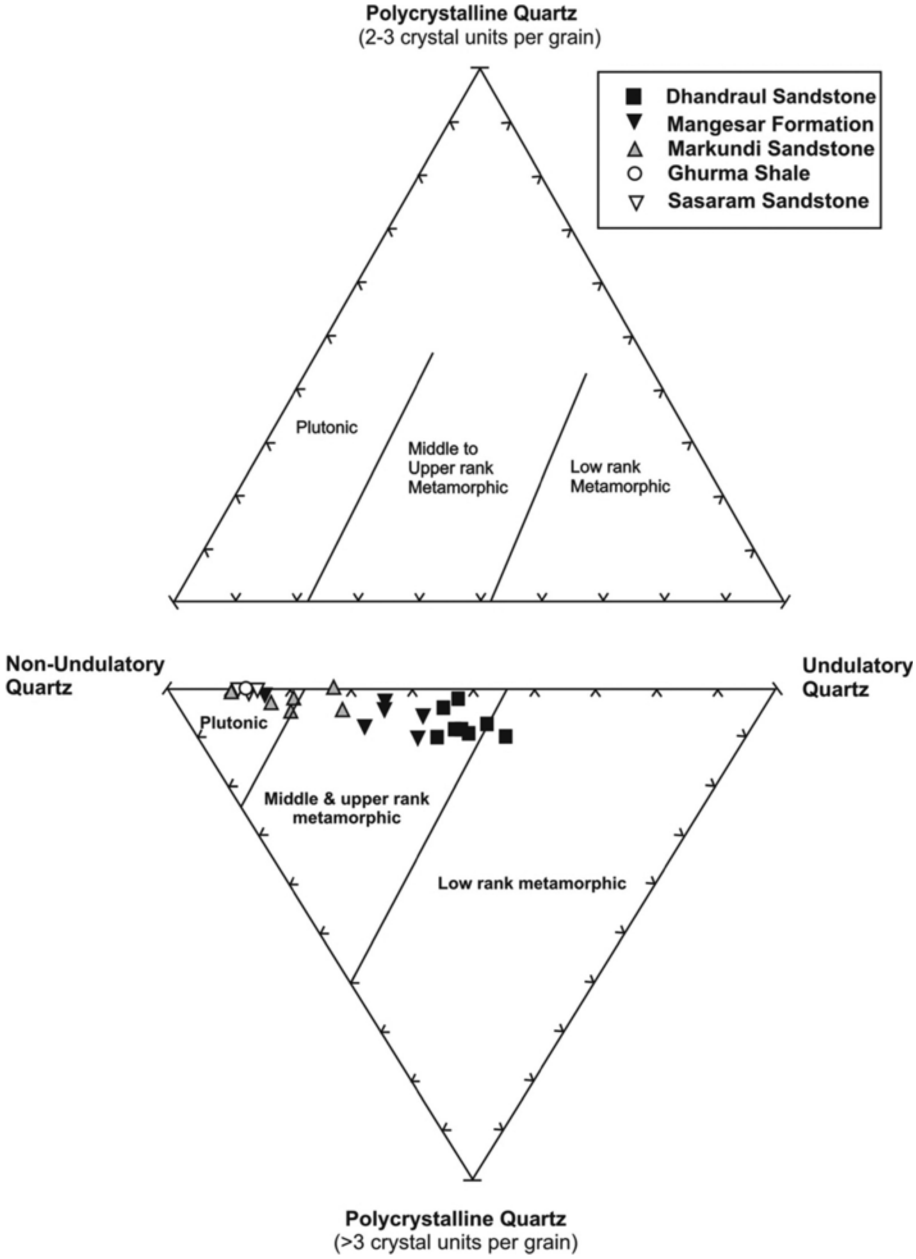

Fig. 7. Diamond diagram (Basu et al., 1975) to determine the provenance for the Kaimur Group sediments.

and rock fragments of granite parentage that also suggest their sedimentary and plutonic source respectively.

Therefore there are multiple sources for the Kaimur sediments, namely, plutonic, sedimentary and metamorphic. In the Lower Kaimur deposition, the plutonic source was dominant with minor contributions from the metamorphic and sedimentary sources. While for the Upper Kaimur sediments the metamorphic source was predominant with plutonic and sedimentary source as minor.

5.5. Tectonic Setting of the Provenance

The tectonic setting of the provenance for the Kaimur sandstones has been determined using the ternary QmFLt and QtFL diagrams (Dickinson and Suezek, 1979; Dickinson et al., 1983). The QtFL plot emphasizes the grain stability and maturity, relief in the provenance, transport mechanism and the source rock composition. The QmFLt diagram deals with the source rock composition and its grain size, as finer grained rocks yield more lithic fragments in the sand-size range (Dickinson and Suezek, 1979; Dickinson et al., 1983; Dickinson, 1985; Dutta, 2005). In the QmFLt plot (Fig. 8a), Qm is the measure of monocrystalline quartz grains; F represents the total feldspars grains (plagioclase, microcline and K-feldspar) and the granite fragments. Lt denotes the total polycrystalline lithic grains including the quartzose varieties. In the QtFL diagram (Fig. 8b), Qt includes total quartzose grains including polycrystalline lithic grains of

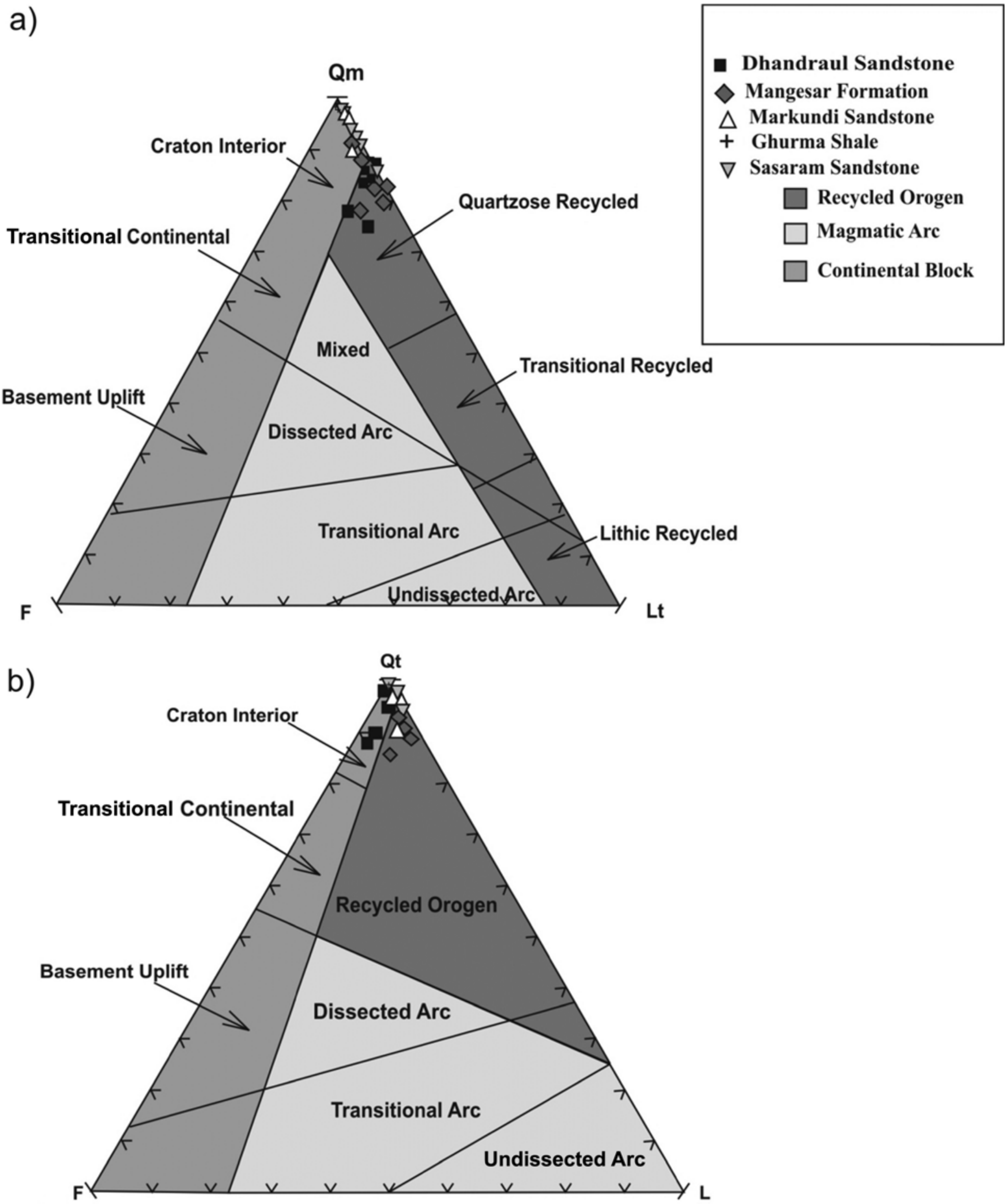

Fig. 8. (a) QmFLt ternary diagram (b) QtFL ternary plot after Dickinson et al. (1983) for the determination of the tectonic setting of the provenance for the Kaimur sandstones**.**

cherts and quartzites; F depicts monocrystalline feldspar grains (plagioclase and K-feldspars) with the granitic lithics; L defines the igneous, metamorphic and sedimentary unstable polycrystalline lithic grains.

Dickinson and Suezek (1979) classified the provenance into 3 main types: continental blocks, magmatic arcs, and recycled orogen. Dickinson et al. (1983) further classified them into their subfields, as described in Figure 8. Dickinson and Suezek (1979) and Dickinson et al. (1983) did not include the Precambrian suites in their provenance analysis because of the uncertainty of the plate tectonics in the Precambrian. In view of the fact that the Indian craton is a collage of several Archean cratonic nuclei and mobile belts (Naqvi and Rogers, 1987; Acharyya, 2003), an attempt has been made here to analyze the tectonic setting of provenance of the Proterozoic Kaimur sandstones.

In the QmFLt diagram the Lower Kaimur Group sandstones fall in the field of the craton interior continental block provenance while the Upper Kaimur Group sandstones suggest a quartzose recycled orogen provenance (Fig. 8a). However it should be considered that in the Mangesar and Dhandraul sandstones of the Upper Kaimur Group, the feldspars and the lithic grains like cherts may have suffered removal by diagenesis. If the feldspar content would have been greater than what is observed, all the samples would have fallen in the craton interior field and not on the recycled orogen field. However like the feldspars, the lithic fragments like cherts, too, must also have suffered dissolution during diagenesis. Therefore, it is really difficult to determine the provenance based on the lithic and feldspar content, using the QmFLt diagram only.

In the QtFL diagram all the Kaimur sandstones except for the Mangesar sandstones show a craton interior continental block provenance. Mangesar sandstones have a recycled orogen provenance (Fig. 8b). Few samples from the Dhandraul sandstones have shifted from the recycled orogen field to the craton interior field. This is so, because, in the Dhandraul sandstones all the lithics of quartzose variety have been added in the Qt pole of the diagram thereby weakening the L pole of the ternary plot and enhancing the F pole.

Therefore, the general petrographic attributes and various diagrams to determine provenance suggest a mixed source for the sandstones of Kaimur Group. In the deposition of the Lower Kaimur, the plutonic craton interior source was dominant with minor contributions from the metamorphic and the sedimentary sources. While for the Upper Kaimur sediments the metamorphic recycled orogen provenance was predominant. The plutonic and the sedimentary rocks acted as a minor source.

5.6. Paleoclimate

Climate affects the parent rock composition of the sand from which it was derived. Basu (1976), Suttner et al. (1981), Franzinelli and Potter (1983) and Van De Kamp (2010) have provided the basis for the role of climate in the composition of sands which have helped to provide signatures from the ancient sandstones. The paleoclimate discriminant plot by Suttner and Dutta (1986) has been used, in which the climate is classified as arid, semi-arid, semi-humid, and humid. The ratio of total quartz to feldspars + rock fragments (Qt/F + L) and polycrystalline quartz to feldspar + rock fragments (Qp/F + L) have been calculated and plotted in the log-log graph paleoclimate diagram. The Lower and Upper Kaimur siliciclastic rocks mostly fall within the range of a humid climate except for a few samples in the semi-humid climate (Fig. 9). The presence of iron oxide as a cement at various stratigraphic levels of the Kaimur Group and iron-oxide impregnated grains supports the idea of humid climate at the time of deposition (Van Houten, 1973; Turner, 1980). According to Van De Kamp (2010), humid tropical climates yield quartz-rich sand and the feldspars are more abundant in arid to semi-arid climates. Kaimur sandstones are also quartz-rich arenites; hence the above idea also supports their deposition in the humid climate. The occurrence of warm humid climate during the formation of the Kaimur Group sedimentary rocks is also evident by the extents of chemical weathering of their source rock (Mishra and Sen, 2010; Sen, 2010).Warm humid climate during the Mesoproterozoic added to the effect of diagenesis in the Mangesar and Dhandraul sandstones that is evident by the presence of the pseudomatrix and feldspar alteration.

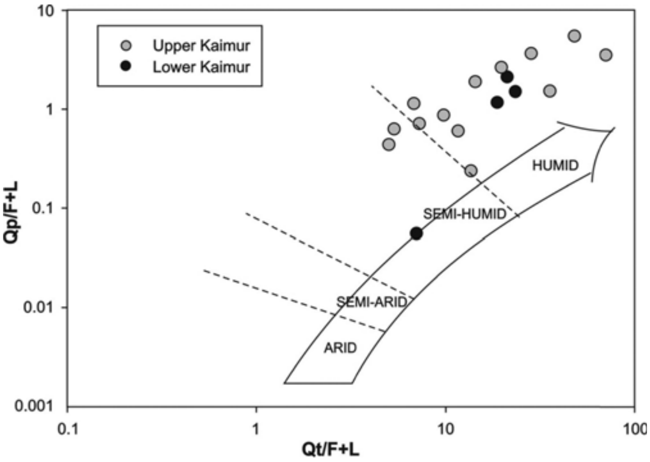

Fig. 9. Paleoclimatic discrimination plot for the Upper and Lower Kaimur sandstones (Suttner and Dutta, 1986).

The Dhandraul Sandstone shows textural inversion where fresh feldspar and quartz grains (orthoclase, microcline, plagioclase) are rounded and are associated with the angular quartz (Fig. 5a). The textural inversions in sandstones are generally considered to be the results of mixing of the sand grains either from different sources or different environments (Pettijohn et al., 1987; Folk, 1964). However, this textural inversion due to mixing of rounded and angular grains in the common area of deposition may be attributed to transportation by two different agencies, one causing high degree of rounding of quartz and feldspar grains, and the other affecting them to a lesser degree (Chaudhuri, 1977). Highly rounded grains of fresh feldspars are a strong indicator of the intense aeolian activity in the dry and arid climate (Chaudhuri, 1977). Chandler (1988) considers the wind as the most effective rounding agent that also causes selective winnowing (Basu, 1976; Suttner and Dutta, 1986). Therefore, mixing of the sand took place from two different agencies, eolian and aqueous, that caused the textural inversion in the Dhandraul sandstones, even though they were derived from the same source. This observation is corroborated by the sedimentological observations of Bhattacharya and Morad (1993) and Chakraborty (1993, 1996) who have suggested the depositional environment of the Dhandraul Sandstone to be a nearshore, braidplain delta aeolian sandsheet. The present petrographic observations support fluvio-aeolian deposition of the Dhandraul Sandstone. Therefore, the climate during the deposition of Kaimur sediments must have been humid with some dry spells or aridity.

6. GEODYNAMIC EVOLUTION OF KAIMUR GROUP SEDIMENTS

The present study revealed that the Kaimur Group sedimentary rocks were derived from plutonic, sedimentary and metamorphic sources. In the Lower Kaimur deposition, granite source was predominant while the Upper Kaimur sediments are mainly the product of the metamorphic source. The warm humid climate and diagenesis have altered the feldspars and lithic fragments in the Mangesar and Dhandraul sandstones. This might have altered the original source rock composition. However, the discrimination diagram where the most stable quartz is used as a component to derive provenance, helped to reach the conclusions. The results of the ternary plots, the nature of the lithic fragments and the occurrence of feldspars with igneous textures have also contributed to understand the source rock composition of the Kaimur Group sediments.

Various workers with the application of the geochemical and sedimentological tools, have studied the source rock composition of the Kaimur sedimentary rocks. Previous sedimentological studies considered the Mahakoshal metasediments and Bundelkhand granite as the source for the Kaimur rocks (Srivastava and Mehrotra, 1981). Based on heavy mineral data the Bundelkhand granite was presumed to be the prime source for Vindhyan sediments (Prasad and Verma, 1991). Paikaray et al. (2008) believed that the provenance was from Mahakoshals and Chhotanagpur Gneissic Complex. On the basis of the geochemical signatures the source was presumed to be the Mahakoshals and Chhotanagpur gneisses (Chakraborti et al., 2007). They commented that the basin was tectonically active during the entire span of the Vindhyan sedimentation. Mishra and Sen (2010, 2012) have suggested the Chhotanagpur Gneissic Complex and Mahakoshal Supracrustal belt as the source for the Upper Kaimur sandstones and shales based on the major oxides and trace element data. Sen (2010), using mixing modeling calculations, considered the Bundelkhand granite as the major source for the Kaimur Group sediments.

Earlier workers have noted the paleocurrent direction for the Lower Kaimur Group as being SSE and SSW (Gupta et al., 2003; Chakraborty, 2006) with the provenance in the Bundelkhand sector. The westerly and northwesterly paleocurrent direction is established for the Upper Kaimur Group, implied by the earlier workers (Jafar et al., 1966; Chakraborty and Bose, 1992; Bhattacharya and Morad, 1993), with the Mahakoshal belt and the Chhotanagpur Gneissic Complex as the most probable source.

The Vindhyan Basin is bounded by the Bundelkhand craton in the north and the Mahakoshal Supracrustal Belt and Chhotanagpur Gneissic Complex, part of the Central Indian Tectonic Zone (CITZ), in the south, in the Son Valley. The Mahakoshal supracrustal belt is composed of quartzites, carbonates, chert, Banded Iron Formations (BIFs), greywacke, argillite, and mafic volcanic rocks (Nair et al., 1995; Acharyya, 2003). The Chhotanagpur Gneissic Complex (CGC) is a high grade gneissic terrain composed of amphibolite to granulite facies rocks (Ghose and Chatterjee, 2008). This complex, records the two tectono-thermal events, the Satpura orogeny I, between 1.6 and 1.7 Ga and the Satpura Orogeny II at 1.1 Ga (Mallik et al., 1991; Ray Barman and Bishui, 1994). The Bundelkhand granitoid complex consists of Na-rich tonalite-trondhjemite-granodiorite (TTG) gneiss and the Proterozoic granite intrusions associated with the BIFs, mafic volcanics, and dykes (Rahman and Zainuddin, 1993; Sharma and Rahman, 1995; Mondal and Ahmad, 2001; Mondal et al., 2002; Rao et al., 2005).

The observations and inferences from the present study and the earlier works on the provenance are consistent with the Lower Kaimur sediments being derived, mostly from the cratonic Bundelkhand granite. The provenance for the Upper Kaimur siliciclastics is also consistent with their derivation from the Mahakoshal supracrustal belt and Chhotanagpur Gneissic Complex. Accordingly, a conceptual model has been proposed.

The Bundelkhand craton was possibly subjected to an intense weathering and denudation under a warm, humid climate. The craton also suffered a periodic domal uplift from time to time which was manifested by the emplacement of the dykes (Malviya et al., 2006). The dyke emplacement at ~1.1 Ga (Kumar et al., 2007; Pradhan et al., 2012) triggered the domal uplift of the hinterland- the Bundelkhand craton. This tectonic activity caused the denuded sediments to be deposited in the Vindhyan Basin (Fig. 10) initially as the Lower Kaimur sediments. Due to tectonism, as the basin experi-

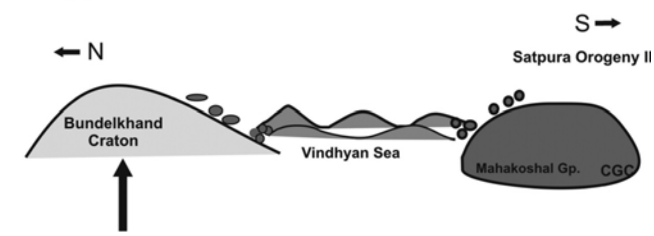

Fig. 10. Proposed model of the Kaimur Group sedimentation along the Sonbhadra and Mirzapur districts, Son Valley, Central India.

enced a change in configuration during the Satpura orogeny–II at ~1.1 Ga, the Central Indian Tectonic Zone (CITZ; Chhotanagpur Gneisses and Mahakoshal belt) was subsequently uplifted and suffered extensive weathering under a hot humid climate. Consequently the tectonism triggered the shedding of the weathered products from CITZ, leading to the deposition of the Upper Kaimur siliciclastics in the Vindhyan basin (Fig. 10). Thus, the tectonism of the hinterland eventually resulted in the fluctuation in provenance which was responsible for the Kaimur sedimentation.

7. CONCLUSIONS

Petrological studies were carried out on the Kaimur Group sediments, and the following are the major conclusions.

1. The deposition of the Kaimur sequence took place in two phases. The Lower Kaimur sediments are the first phase sediments. They were deposited as a fining upward sequence with an increase in angularity of the grains and a decrease in the sorting and mineralogical maturity. The Upper Kaimur Group corresponds to the second phase, and was deposited as a coarsening upward sequence, with an upward decrease in angularity of the grains and an increase in the sorting and mineralogical maturity.
2. The Lower Kaimur Group sedimentary rocks are sublitharenites to quartz arenites, and the Upper Kaimur Group are shales, sub-litharenites, sub-arkoses, and quartz arenites. The Upper Kaimur sandstones have been affected by diagenesis as evident by the presence of the pseudomatrix and feldspar alteration.
3. Kaimur Group sediments are the product of multiple sources–plutonic, sedimentary and metamorphic. The source rock composition for the Lower Kaimur is different from that of Upper Kaimur sedimentary rocks. The former were mainly derived from the granitic crust of the Bundelkhand craton with secondary input from the Mahakoshals and Chhotanagpur gneisses. The latter were mainly derived from a middle to upper grade metamorphic source of the Chhotanagpur gneisses with minor input from the Bundelkhand craton and the Mahakoshals.
4. The uplift of the hinterland-Bundelkhand craton and the subsequent occurrence of the Satpura Orogeny II in the Central Indian Tectonic Zone caused the deposition of the Kaimur sediments in the warm, humid climate of the Mesoproterozoic.

ACKNOWLEGMENTS: The authors deeply thank Profs. Abhijit Basu, Indiana University and Robert Cullers, Kansas State University, Dr. Partha Pratim Chakraborty, University of Delhi and the anonymous reviewer of the journal for their fruitful comments and critical suggestions that improved the quality of the manuscript. SS is thankful to the Head, Department of Geology, University of Delhi, Prof. Dilip Saha, Geological Studies Unit, ISI, Kolkata and Dr. Divya Prakash, Department of Geology, BHU, Varanasi for extending the necessary help in the completion of the present study. SS is also thankful to the University Grants Commission, New Delhi for the financial support rendered to her in the form of Dr. D.S. Kothari Post-doctoral Fellowship (F.13-540/2011).

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Manuscript received September 30, 2013
Manuscript accepted February 19, 2014