

Depositional environment and tectono-provenance of Upper Kaimur Group sandstones, Son Valley, Central India

M. A. Quasim¹ · A. H. M. Ahmad¹ · Sumit K. Ghosh²

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Abstract The Mesoproterozoic Upper Kaimur Group consists of Bijaigarh Shale, Scarp Sandstone, and Dhandraul Sandstone. Based on the lithofacies data set, two major facies associations were identified, namely—tidal sand flat/sand bar facies association (TSFA) and tidally influenced fluvial channel facies/tidal channel facies association (TIFCFA). The Dhandraul Sandstone has been interpreted as a product of TIFCFA and the underlying Scarp Sandstone in TSFA which endorses a tidal dominated estuarine setting. Detrital modes of the Dhandraul and Scarp Sandstones fall in the quartz arenite to sub-litharenite types. Petrographical data suggest that the deposition of the Upper Kaimur Group sandstones took place in humid climate and was derived from mixed provenances. The sandstone composition suggests detritus from igneous rocks, metamorphic rocks, and recycled sedimentary rocks. The sandstone tectonic discrimination diagrams suggest that the provenances of the Upper Kaimur Group sandstones were continental block, recycled orogen, rifted continental margin to quartzose recycled tectonic regimes. It is envisaged that the Paleo- and Mesoproterozoic granite, granodiorite, gneiss, and metasedimentary rocks of Mahakoshal Group and Chotanagpur granite–gneiss present in the western and northwestern direction are the possible source rocks for the Upper Kaimur Group in the Son Valley.

Keywords Mesoproterozoic · Upper Kaimur Group · Son Valley · Lithofacies · Petrography · Depositional environment · Tectono-provenance

Introduction

Sediment characteristics in any depositional environment are determined by the physical, chemical, and biological processes that occur during denudation, transport, and deposition. A facies is produced by one or several processes operating in a particular depositional environment, although the appearance of the facies can be considerably modified by post-depositional processes (Tucker 1998). The facies succession is a facies association in which the sediments occur in a particular order (Reading and Levell 1996).

Provenance studies of the clastic sedimentary rocks have been carried out using a number of analytical techniques such as petrographic modal analysis of sandstones and dense minerals (Dickinson 1985; Akhtar and Ahmad 1991; Ghosh 1991; Akhtar et al. 1994; Singh 1996, 2013; Singh et al. 2000; Ghosh and Kumar 2000; Singh et al. 2004; Ahmad and Bhat 2006; Ahmad et al. 2009; Srivastava and Pandey 2011; Jalal and Ghosh 2012; Patra et al. 2014). The aim of the provenance study is to deduce the characteristics of the source areas from the compositional and textural properties of the detrital modes. Dense mineral interpretation may be an effective tool for reconstruction of sediment provenance (Singh et al. 2004; Mange and Otvos 2005).

The Mesoproterozoic sandstones of the Upper Kaimur Group of the Vindhyan Supergroup are exposed in Son Valley (around Sonbhadra and Mirzapur districts), Central India. The Upper Kaimur Group in this area offers an excellent opportunity to perform sedimentological and provenance analyses due to good outcrop conditions (near horizontal

✉ M. A. Quasim
adnanquasim@gmail.com

¹ Department of Geology, Aligarh Muslim University, Aligarh 202002, India

² Formerly Wadia Institute of Himalayan Geology (WIHG), 7 Kalimandir Enclave, G M S Road, Dehradun 248001, India

disposition in a vast area), un-metamorphosed lithology, and well-preserved sedimentary structures (Chakraborty and Bhattacharya 1996).

This sedimentary package is studied keeping in view to bridge the gap in the Vindhyan sedimentation history existing mainly due to the isolated nature of outcrops in the study area as compared to other areas of the Son Valley. As yet, no detailed facies analysis has been attempted in the Mesoproterozoic strata of the Upper Kaimur Group of studied lithosection. Thus, this study aims to use facies analysis, detrital modes for reconstructing sediment provenance of the Mesoproterozoic Upper Kaimur Group in Sonbhadra and Mirzapur districts, to ascertain the depositional environments and prevailing, tectono-climatic conditions.

Geological background

The Vindhyan Basin is the largest (exposed area 104,000 km²) of the Precambrian intracratonic sedimentary basins in India. This basin comprises of nearly 4-km-thick sequence of largely undeformed rock-shales, sandstones, limestones, and dolostones with subordinate felsic volcanics, lying on top of the deformed metasediments of either Bijawar/Mahakoshal Group or Archaean gneissic basement (Sastry and Moitra 1984; Bhattacharya 1996; Chaudhuri et al. 1999; Bose et al. 2001; Ray and Chakraborty 2006) (Fig. 1). The Vindhyan Supergroup is divided into two sequences separated by an unconformity and a laterally correlatable conformity (Bose

et al. 2001). The Lower Vindhyan (Semri Group) is formed by the dominant carbonate deposit and the overlying Kaimur Group by siliciclastic deposit. This sharp upward transition from carbonates to siliciclastics reflects a basin-wide regression (Bose et al. 2001).

The Vindhyan Supergroup is broadly separated from base to top into four groups—Semri, Kaimur, Rewa, and Bhandar. The Kaimur Group (400 m) lies unconformably over a tilted, somewhat deformed and partially eroded Rohtasgarh Limestone of the Semri Group. The outcrops of the Semri and Kaimur Groups of the Son Valley are bounded by Bundelkhand Gneissic Complex (BGC) in the north and Mahakoshal Group and Chotanagpur Gneissic Complex (CGC) in the south. The Kaimur Group has been divided into Lower Kaimur Group and Upper Kaimur Group. The Lower Kaimur Group is further divided into the Sasaram Formation, the Ghurma Shale, and the Markundi Sandstone. The Upper Kaimur Group comprises three lithostratigraphic units (Fig. 2): Bijaugarh Shale, Scarp Sandstone, and Dhandraul Sandstone (Auden 1933; Prakash and Dalela 1982).

The Vindhyan Basin of north India lies on the stable Bundelkhand craton of Archaean-Early Proterozoic age, which is bounded by Middle Proterozoic Satpura-Bijawar fold belt in the south and Delhi-Aravalli fold belt to the west. The tectonic evolution and age of these fold belts are suggested to have a significant bearing on the origin of the Vindhyan Basin. The cluster of metamorphic ages in both the Delhi and the Satpura belts at about 1500 Ma (Chaudhuri et al. 1984; Sarkar et al. 1990) suggests this as the time of the terminal collision of the

Fig. 1 A part of the regional geological map of the Vindhyan basin, Son Valley (modified after Soni et al. 1987)

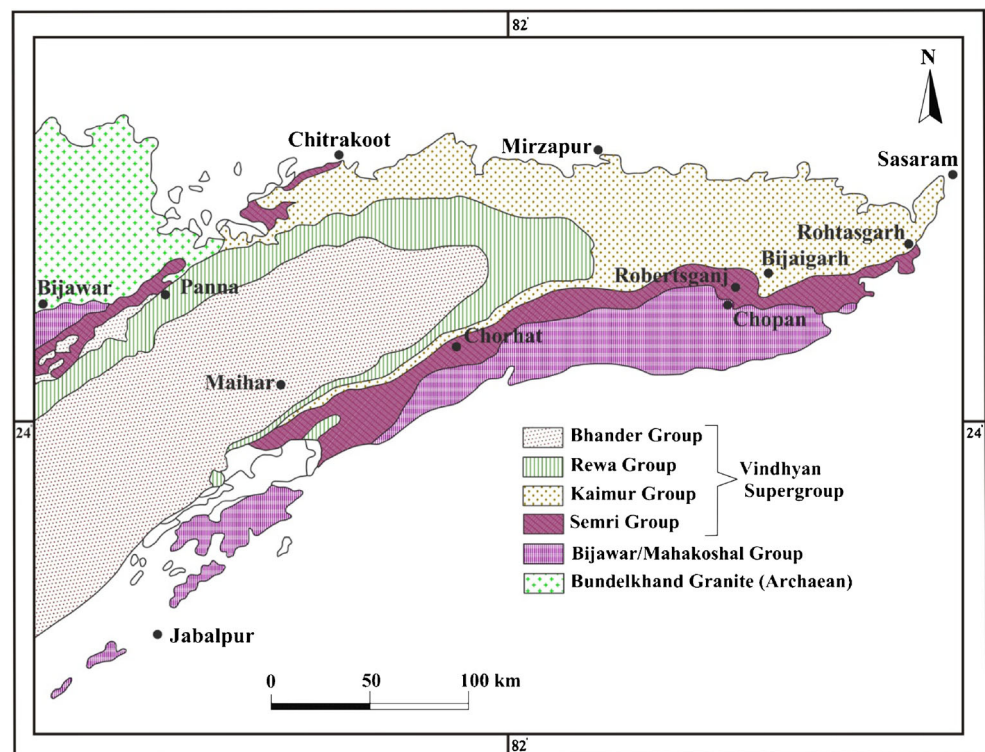
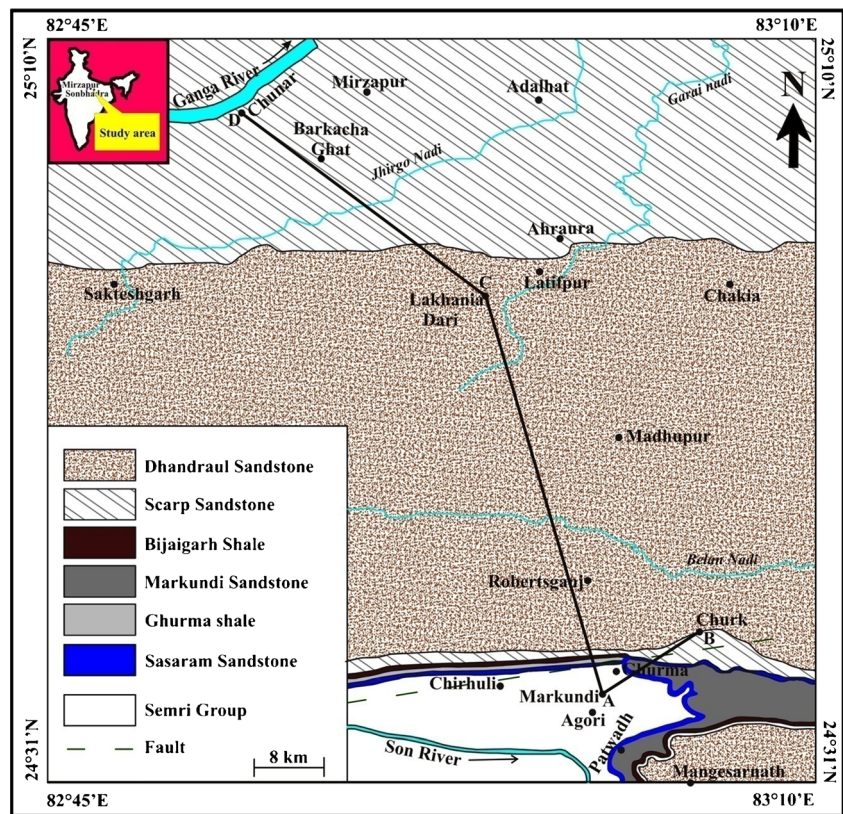


Fig. 2 Geological map of the study area in the Sonbhadra and Mirzapur districts (Son Valley). The studied sections are marked by A Markundi Ghat section, AB Churk Markundi road section, AC Lakhania Dari section, and CD Barkachha Ghat section



two protocontinents of northern Indian shield (Sudgen et al. 1990; Raza et al. 1993) and also the time when the Satpura and the Delhi-Aravalli mobile belts were folded, thrust, and uplifted. The Vindhyan Basin is most likely to have formed after this major Delhi-Satpura orogeny, in as much as the sedimentary fill of the Vindhyan Basin is widely believed to be of Middle and Late Proterozoic age (Radhakrishna 1987). The geological and geochronological data suggest that sedimentation in the Vindhyan Basin started at about 1400 Ma and continued till about Vendian (ca. 600 Ma). The basin was initiated as a linear graben system, expanding into the continental margin sag through time and space accumulating thick pile of sediments of various facies through a long span of some 800 Ma. It is argued that the Middle Proterozoic Vindhyan Basin developed at the end of Delhi-Satpura orogeny as a post-orogenic (post-collision) peripheral basin on the subducted Bundelkhand craton, receiving sediments from the uplifted fold belts to the south and west.

On the basis of K-Ar age data of the Vindhyan rocks, Tugarinov et al. (1965) proposed a 1400 Ma age for the Lower Semri and 910 Ma for the Kaimur. The kimberlite pipes intruding the Upper Kaimur sandstone give Rb-Sr age of 1140 Ma (Crawford and Compston 1970) and 1067 Ma (Kumar et al. 1993) and K-Ar age of 1130 Ma (Paul et al. 1975). These ages suggest the initiation of the Vindhyan sedimentation before 1150 Ma (Crawford and Compston 1970). Based on the available chronological data, Misra (1969) suggested the age of the Vindhyan sedimentation at about

1400 Ma, whereas Raha and Sastry (1982) assigned a Middle Rhiphaean age (1650–1000 Ma) for the Lower Vindhyan and Middle to Late Rhiphaean (younger than 940–910 Ma) to the Upper Vindhyan sediments. Crawford and Compston (1970) assigned an upper age limit of the Vindhyan at 550 Ma. Although the age of various formations of the Vindhyan Supergroup varies significantly, an age of 1400 Ma is generally accepted for the beginning of the Vindhyan sedimentation (Misra 1969; Crawford and Compston 1970; Naqvi and Rogers 1987; Hari Narain 1987; Maithy 1981); the sedimentation continued till Vendian (–600 Ma; Maithy and Babu 1993) or at most up to 550 Ma (Crawford and Compston 1970).

In a major turmoil in the Vindhyan chronostratigraphy and paleobiology, two startling fossil discoveries were published: firstly the trace fossils of “triploblastic animals” (Seilacher et al. 1998) from the Chorhat Sandstone of the Lower Vindhyan with assigned age of more than 1.1 billion year and secondly the small shelly fossils of earliest Cambrian age (Precambrian–Cambrian boundary markers ~542 Ma; Azmi 1998a) from the Rohtasgarh Limestone that conformably lay little above the trace fossil-bearing Chorhat strata, suggesting far younger age than the traditional age of the Vindhyan Supergroup. But the record of the earliest Cambrian small shelly fossils indicating a major upward age revision of the Vindhyan Supergroup made a claim of “deep” metazoan origin in the Vindhyan succession a hot debatable issue (Azmi 1998a b; Brasier 1998; Kerr 1998a).

An evaluation between conflicting radiometric dates and evolutionary consistency in the Vindhyan fossil records, latter indicating Vendian–Early Cambrian age for the Vindhyan Supergroup (Azmi et al. 2007), is shown in (Fig. 3). However, the age constraints of the Kaimur Group, derived from the Rb/Sr dating of a kimberlite pipe that intrudes the Kaimur Group at Majhgawan are as follows: Crawford and Compston (1970) reported 1140 + 247 Ma, Kumar et al. (1993) reported 1067 + 31 Ma, and Gregory et al. (2006) reported 1073.5 + 13.7 Ma from the ⁴⁰Ar/³⁹Ar from the phlogopite in the kimberlite pipe.

Methods

The traverses were taken along Markundi-Ghat, Churk-Markundi road, Barkachha Ghat, and Lakhania dari sections in Sonbhadra and Mirzapur districts (Fig. 2). This study is based mainly on regional field works augmented by laboratory techniques. The field works include lithosection measurement, lithologic description, and collection of representative samples of the measured sections of the Upper Kaimur Group sandstones in the Son Valley. In this section, the Upper Kaimur Group (Dhandraul Sandstone, Scarp Sandstone, and Bijaigarh Shale) is exposed and Lower Kaimur Group dislocated by the Markundi-Jamwal Fault (Prakash and Dalela 1982). Thus, Bijaigarh Formation directly rests over the Semri Group. The relevant details pertaining to the stratigraphy, lithology, and structure of the Upper Kaimur Group

are summarized in (Table 1). Brief description of the major lithounits is mentioned below.

Dhandraul Sandstone is characterized by mostly tabular and laterally persistent (for tens to hundreds of meters), white, coarse-grained quartzose sandstone beds with sharp boundaries and exhibits sedimentary structures like large-scale cross-bedding with long, low-angle foresets alternate with co-sets of parallel laminated sandstone, trough bedding, and ripple marks.

Scarp Sandstone is characterized by trough and planar cross-stratified variegated medium-grained sandstone. It shows planar, laterally impersistent erosional surfaces invariably carpeted by lensoid bodies of conglomerates, consisting of flattened and angular red shale pebbles of intraformational origin.

Bijaigarh Shale consists of 55–60-m-thick black splintery carbonaceous shale with millimeter thick lamination and a meter to centimeter thick bands (locally) of pyrite. It is intercalated with thin beds of fine- to very fine-grained sandstones with cross-strata, wave ripples, parallel bedding, wrinkle marks, rill marks, and mud cracks, at places capped by volcanoclastics (Chakraborty et al. 1996).

Laboratory studies also include documentation of the stratigraphic sections and construction of depositional models of the Upper Kaimur Group sandstones. The other related studies include mega- and microscopic (petrographic) descriptions of the collected samples. For petrographic study, a total of 46 indurated sandstone samples selected and 300 points were counted following Gazzi-Dickinson point-counting method

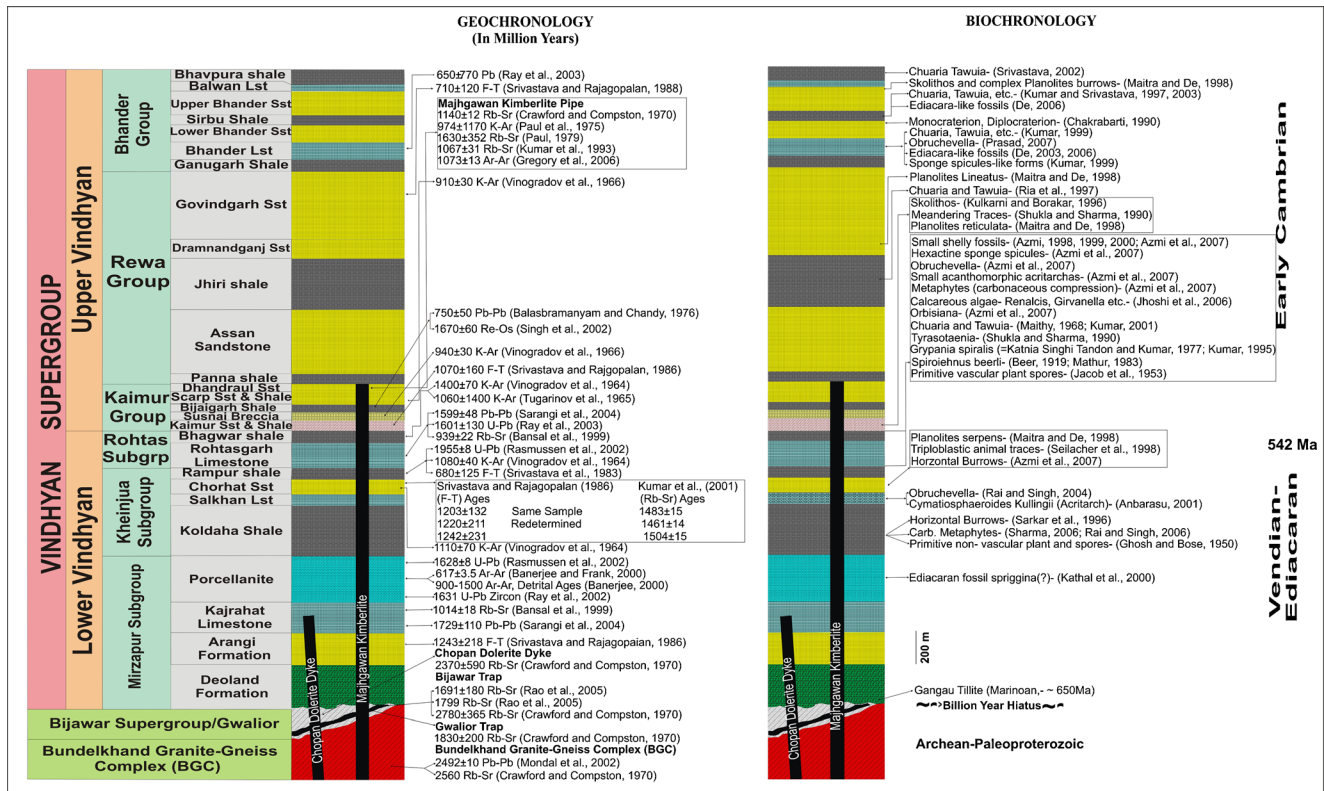


Fig. 3 Conflicting radiometric dates and evolutionary consistency in the Vindhyan fossil records (modified after Azmi et al. 2007)

Table 1 Stratigraphy of Vindhyan Supergroup showing details of Upper Kaimur Group (after Prakash and Dalela 1982) with special reference to lithology and sedimentary structures

Group	Formation	Lithology	Structures			
Upper Vindhyan	Upper Kaimur	Bhandar (139-580m)	Dhandraul Sandstone (120m)	Dominantly arenaceous (medium- to coarse-grained) texturally coarsening upward sequence, milky white and compact	Large scale cross bedding, through bedding ripple marks, tabular and lenticular beds	
		Rewa (360-3000m)	Scarp Sandstone (150m)	Medium- grained multicolored sandstone (pink to gray) sublitharenite, micaceous siltstone and sandstone	Cross bedding, fault gouge and breccia, water seepages, drag fold, ripple marks, clay galls	
		Lower Kaimur	Bijaigarh Shale (25m)	Kaimur (8-400m)	Heterogeneous lithology, reddish brown to buff color shale ranging from siltstone to mudstone Carbonaceous shales	Wavy laminations, Wavy pyritiferous laminae, microbial mats, mud cracks, ripple and wrinkle marks, flute casts, rain prints, adhesion marks
	Markundi Sandstone					Lower Kaimur formations are dislocated by Markundi-Jamwal fault (Prakash and Dalela, 1982)
	Sasaram Sandstone					
..... Faulted/Normal contact						
Lower Vindhyan/ Semri Group (760-3055m)						

(Ingersoll et al. 1984). The objective of point-counting is to identify grain types (framework), cement, matrix, and their proportion. To identify clay minerals, selected samples were studied and examined by scanning electron microscope (SEM) equipped with an energy-dispersive x-ray analyzer.

Lithofacies analysis

Seven lithofacies were identified in the Upper Kaimur Group, based on primary sedimentary structures, geometry of lithounits, grain size, and their temporal changes of the studied sections (Fig. 4). The lithofacies are as follows:

1. Inter-bedded shale within the thinly bedded sandstone facies (Fi-S)

2. Parallel laminated sandstone facies (Si)
3. Herringbone cross-bedded facies (S-hb)
4. Massive sandstone facies (Sm)
5. Rippled bedded sandstone facies (Sr)
6. Trough cross-bedded facies (St)
7. Planar cross-bedded facies (Sp)

The detailed account of the lithosections is abridged in Table 2.

Facies association

A wide range of lithofacies that occur in combination is known as facies assemblages and are helpful in the interpretation of

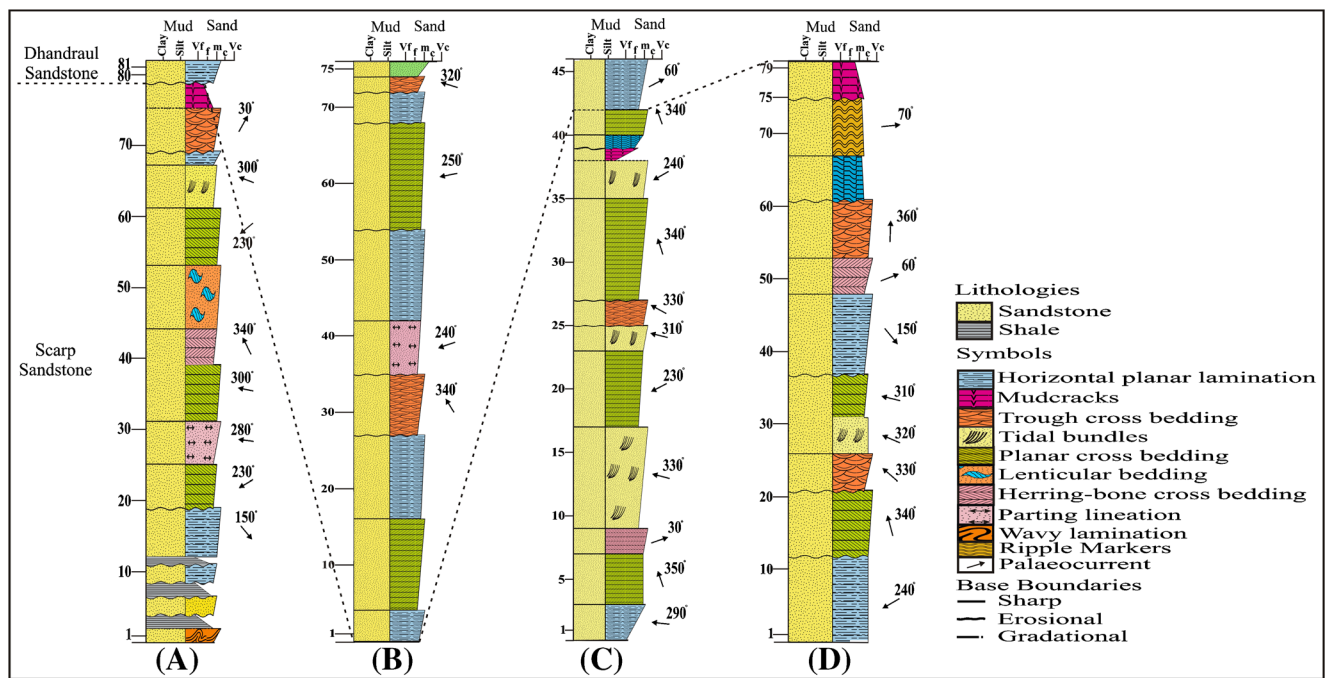


Fig. 4 Lithologs of the studied sections showing distribution of primary sedimentary structures in Scarp and Dhandraul Sandstones. Sections representing (A) Markundi Ghat section, (B) Churk-Markundi road section, (C) Barkachha Ghat section, and (D) Lakhania Dari section

depositional setup. The abovementioned lithofacies are grouped into two distinct facies associations (Fig. 5).

Tidally influenced fluvial channel facies/tidal channel facies association (TIFCFA)

This facies association is represented by coarsening-upward trend, with a maximum thickness of 21 m, comprising of Sp, Si, and St facies of Dhandraul Sandstone in the Markundi Ghat and Churk-Markundi road sections. The maximum thickness of the TIFCFA is 76 m in Churk-Markundi road section. In Markundi Ghat section, massive sandstone facies is absent. However, in the Churk-Markundi road sections, Si-facies form the base of TIFCFA, overlain by Sp facies. Whereas, in the Markundi Ghat section, sandstone with mud cracks forms the basement for the Si facies. It occurs as horizontal, laterally continuous tabular bodies traced for a distance up to hundreds of meters. At some places, these beds are inclined, having an inclination 2° to 5° in the Churk-Markundi road section. The horizontal bedded sandstone has individual beds with thickness of 0.5–4 m. Si facies shows thin laminations (7 mm–1 cm) forming 3–15-cm-thick coset. The upper surface of the Si facies is marked by well-developed parting lineations (Fig. 6E) with a consistent trend for a larger extent in the Churk-Markundi road section. In Markundi Ghat section, 12-m-thick thinly bedded sandstone with interbedded shale facies (Fi-S) is also marked at the base (Fig. 6A). This thinly bedded sandstone interbedded with shale shows wave ripples and wavy laminations. The Sp facies is characterized by the presence of thick cross bed sets with

low angle of inclination of the foreset (Fig. 6D). The thickness of the individual cross bed set is 1–2 m and is separated from the planar erosional surface. The thickness of the foreset is 20–25 cm with similar grain size grading and the length of the foresets traced up to hundreds of meters. The bed orientation is consistent towards N/NW direction, with few exceptions of S/SW. St facies is also measured in Churk-Markundi road section at two stratigraphic levels. The St facies in this section is characterized by closely interlocked small scale trough sets. The width of small trough that varies between 12 and 20 cm are bounded by the planar erosional surface. Mud drapes are common in the cross-bedded Dhandraul Sandstone.

Interpretation

The TIFCFA facies association comprises of large-scale trough cross-bedded sandstone, large-scale planar cross-bedded sandstones, parallel-laminated sandstones, and massive sandstone. Large-scale trough cross-bedded sandstones are interpreted as lateral migration of sand dunes of the tidal channel bars. The trough cross-bedded sandstones were thought to be deposited in tidal dominated nearshore coastal environment. Reactivation surfaces are formed as the subordinate current erodes the lee face of the dune formed by the preceding dominating current (e.g., Dalrymple et al. 1992). Thinly bedded nature of sandstones indicates tidally influenced environment (Casshyap et al. 2001). The upward fining large-scale cross-bed sets are interpreted to represent bars in the tidal channel (e.g., Sultan and Bjorklund, 2006). Presence of small-scale planar cross-bedding in the assemblage with

Table 2 Description of facies and facies associations of the Upper Kaimur Group sandstones in Sonbhadra and Mirzapur districts

Facies association	Facies	Description	Interpretation
Tidally influenced fluvial channel facies/tidal channel facies association A (TIFCFA)	Parallel laminated sandstone facies (St)	Laminated sandstone; medium- to fine-grained with coarsening upward sequence; pure white to brown in color; occurs as horizontal and tabular bodies traced about 100 of meters in continuation; dips at low angle 2° to 5°; bed thickness 3 m, on the bedding plane of laminated sandstone parting lineation is best developed having trend 150–180°, traced for a long distance; these sandstones sometimes show purple staining; this sandstone has the sharp contact with the overlying cross-bedded sandstone	In essence, the coarsening upward sequence, sand body geometry, the type, the scale, and the direction of the sedimentary structures infer that the facies association A is a product of tidally influenced fluvial channel facies/tidal channel facies association (TIFCFA)
	Planar cross-bedded facies (Sp)	This planar cross-bedded sandstone dips at low angle; coSETS are horizontal or dips at 15–18° bed thickness 12 m; mean azimuth of this cross-bedded sandstone in between 65° and 270°; cross-bed thickness 20–160 cm; each is separated by sharp contact	
	Trough cross-bedded facies (St)	Small-scale trough; medium- to coarse-grained, small-scale troughs are interlocked; the width of each small-scale trough varies between 10 and 25 cm; azimuth 0–350°	
	Massive sandstone facies (Sm)	Pink, light pink, white-colored compact sandstone; this sandstone is medium to coarse grained; these massive sandstones are forming an escarpment	
Upper flow regime tidal sand flat/sand bar facies association B (TSFA)	Inter-bedded shale within the thinly bedded sandstone facies (Fi-S)	Thinning upward sandstone interval separated by a thin mud parting overlain by shale units; bedded sandstone facies (Fi-S); the color of this shale is grayish black; three shale units are identified; upper and lower units are sandy in nature; middle layer is black shale occasionally pyritiferous; parallel laminations are found in these shale units with low angle; some minor undulations are also observed in this shale	Facies association B is attributed to the processes operative close to the shoreline as elongate sand bars associated with upper flow regime sand flats are typical of the seaward settings in the tide-dominated estuaries (Dalrymple et al. 1992)
	Herringbone cross-bedded facies (S-hb)	Fine- to medium-grained sandstone with 180° reversal of the palaeoflow direction; color of the sandstone is brown; thickness of the bed is 2–3 m; mean palaeoflow direction for both the direction in the thickness is 60–340°	
	Rippled bedded sandstone facies (Sr)	White to gray; fine-grained rippled laminated sandstone; ripples are found on the top surface of this sandstone body; at many places, laminations are noted to show reverse palaeoflow direction	
	Trough cross-bedded facies (St)	5-m-thick iron red-pigmented sandstone with large-scale trough bedding; large-scale trough cross-sets in thickness 0.8–1.2 m; occurs above the large-scale cross-bedded sandstone and have erosional contact with the overlying cross-bedded sandstone with tidal bundles; mean azimuth of the tidal bundles is 210–300°; on the top surface of trough cross-bedded sandstone, some cracks are observed; these cracks are filled with secondary materials	
	Parallel laminated sandstone facies (St)	12 m-thick horizontal bedded sandstone; medium- to coarse-grained yellowish brown-colored sandstone; parting lineations are visible on the top surface of the horizontal bedded surface individual beds are 1.2–2-m thick and traced for a long distance; every so often, laminations are observed in this horizontal bedded sandstone dipping at low angle	

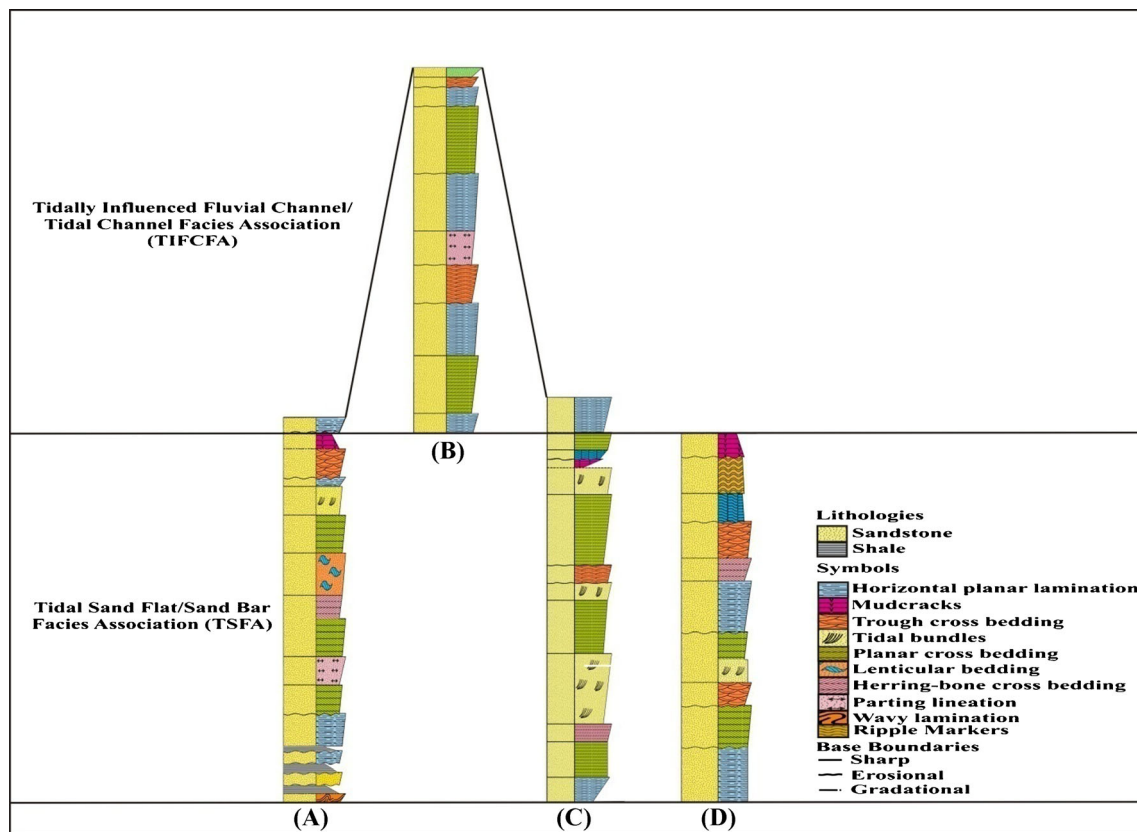


Fig. 5 Correlation of the lithostratigraphic units into facies association I and II (I TIFCFA and II TSFA) of Upper Kaimur Group in Son Valley. A Markundi Ghat Section, B Churk Markundi road section, C Barkachha Ghat Section, D Lakhania Dari Section

lamination, ripple marks, etc. suggests mixed tidal flat depositional environment (e.g., Reineck and Singh 1980). The planar cross-bedding is formed by the migration of 2-D bedforms (Breda and Preto 2011). The migration of one large-scale bedform over another bedform indicates high-energy and large sediment influx (Allen 1980; Reineck and Singh 1980). Mud drapes present within cross-sets indicate episodic migration of dunes that remained stable over multiple depositional events under the tidal setting (Willis et al. 1999). The parallel laminated sandstone facies represents occasional storm events during the intervening periods of low sediment influx in the inter-tidal environment (Dalrymple et al. 1992; Bjorklund 2005). Cross-bedsets associated with laminated bedsets suggest their deposition on the beach-face environment under the influence of strong tidal and longshore intertidal environment (e.g., Khalifa et al. 2006). Massive sandstone facies or thickly bedded sandstone facies occur in the tidally dominated and river-dominated estuaries (Singh and Singh 1995).

Tidal sand flat/sand bar facies association (TSFA)

The TSFA comprises of Sp, St, S-hb, Si, and Sr facies. This facies association is well developed in the Lakhania Dari, Barkachha Ghat, and Markundi Ghat sections, where

it attains a maximum thickness of 46 and 82 m, respectively. TSFA forms a stacked package of 1–2-m-thick Sp facies with wide lateral extent in Lakhania Dari, Barkachha Ghat, and Markundi Ghat sections, characterized by 2–2.5-m-thick, cross-bedded medium-grained sandstone with low angle (10–15°) foreset. Tidal bundles (Fig. 6B) are associated with Sp facies. The bundles formed during neap cycle condition are small and vice versa in the spring condition. The thicknesses of neap cycle bundles are 20–45 cm and average 1 m for the spring cycle bundles. S-hb facies are characterized by 180° palaeoflow reversal. Developed in all the studied sections, the St facies (Fig. 6F) is characterized by large and small trough sets having a thickness of 1.5–2 m. Sr facies (Fig. 6C), noticed only in Lakhania Dari section, is represented by 2-m-thick white to gray fine-grained sandstone. Si facies is also noticed in all studied sections, characterized by flat, plane bedding, varying in thickness from 2 to 2.5 m. Some of these packages occur as lenticular bodies of 0.4 m thick and 6 m long with fining and thickening upward trends. The undulating laminae display internal truncations which form broad scours or swales in the Lakhania Dari section. The collected NW and SW palaeoflow pattern on wave ripple crests in the Sr-facies in the Lakhania Dari section indicates NE–SW orientation of palaeo-shoreline of the Vindhyan Sea.

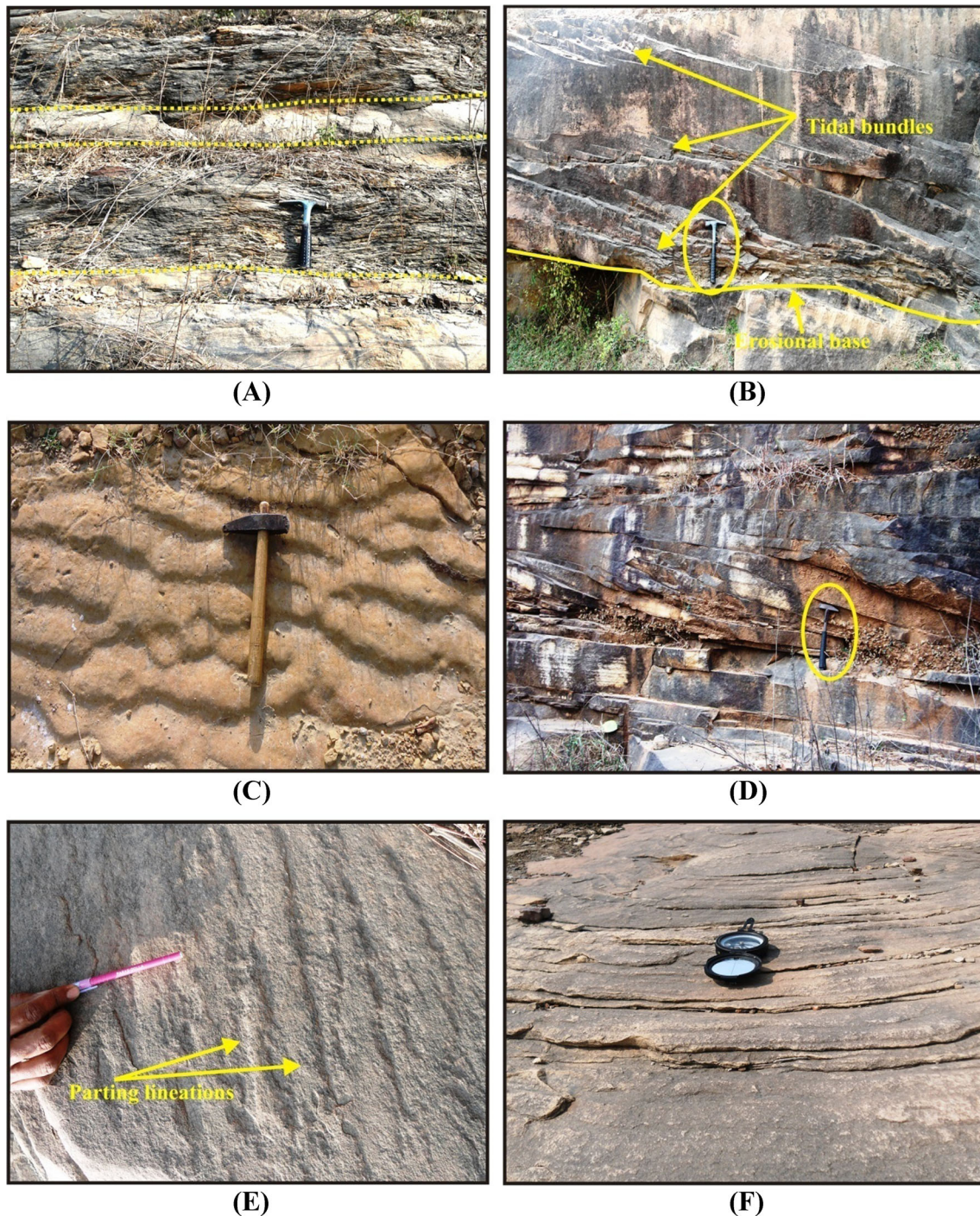


Fig. 6 Field photograph showing **a** alternate beds of sandstone and shale, **b** tidal bundles in Scarp Sandstone, **c** ripple marks in Scarp Sandstone, **d** large-scale cross-bedding in Dhandraul Sandstone, **e** parting lineations in Dhandraul Sandstone, and **f** large-scale trough in Scarp Sandstone

Interpretation

TSFA is interpreted as a tidal sand bar/sand flat deposit, evident from the dispersion of tabular sandstones and low angle planar cross-bedding. The planar cross-beds are formed by the migration of 2-D bed form (Breda and Preto 2011). The migration of large-scale bedform reflects a condition of high-energy and large

sediment influx (Allen 1980; Reineck and Singh 1980). The plane laminated facies with parting lineation closely substantiate a high energy beach environment (Reineck and Singh 1980; Dalrymple et al. 1992; Bose and Chakraborty 1994). This lithofacies also show an excellent development of parting lineation which belongs to the upper flow regime (Harms et al. 1982). Trough cross-beds are formed by the migration of 3-D bed forms

in a shallow water condition (Harms et al. 1982; Breda and Preto 2011). Trough cross-bed developed in fine-grained sandstone is indicative of deposition under subtidal environment (Reineck and Singh 1980; Mowbray and Visser 1984). Boothroyd (1985) described that herringbone cross-bedding is an excellent indicator of reversing or bidirectional flow in estuaries environment. The tidal bundles are formed as a result of fluctuation in tidal current strength, direction, and water depth (Boersma and Terwindt 1981; Basilici et al. 2012). Presence of modified ripples and interference ripples is the sign of shallow water condition and discrete exposures under intertidal setting. Modified ripples and mud cracks point to discontinuous subaerial exposure of the saturated deposition interface (Shukla and Pant 1996). The scours are common in nearshore areas, suggestive of periods of higher energy flow by storm wave reworking (Bourgeois 1980; Klein 1967; Cheel and Leckie 1993; Hori et al. 2001; Bjorklund 2005). The similar facies architecture and evidences have been related to the upper flow regime of the tidal sand flats (Klein 1967; Bjorklund 2005). The palaeoflow recorded within this facies association is either perpendicular or oblique to the inferred NW–SE-oriented palaeo-shoreline (Fig. 7).

Petrographic attributes

The Scarp Sandstones are medium- to fine-grained and moderately to poorly sorted. The Dhandraul Sandstones are medium- to coarse-grained moderately to well sorted. Major detrital framework components of the sandstones are quartz, feldspar, lithic fragments, mica, and heavies. The Qt-F-L diagram (Fig. 8) shows that the sandstones of the Scarp (average $Qt_{99}F_{0.2}L_{0.8}$) and Dhandraul (average $Qt_{99}F_{0.1}L_{0.8}$) lithounits fall in the quartzarenite to sub-litharenite types.

Components of sandstone

Quartz (Q) is the most abundant framework grain, comprising 91 %. The average modal composition of the Scarp and Dhandraul Sandstones are mentioned in Table 3. Monocrystalline and polycrystalline quartz are present, though monocrystalline quartz is dominant over the polycrystalline quartz (Table 4). Most of the monocrystalline quartz grains

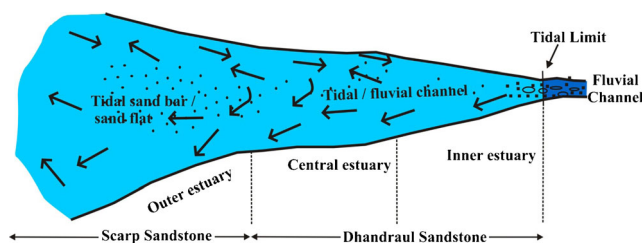


Fig. 7 Schematic depositional modal suggested for the Scarp and Dhandraul Sandstones, depicting the tidal-dominated estuarine setting

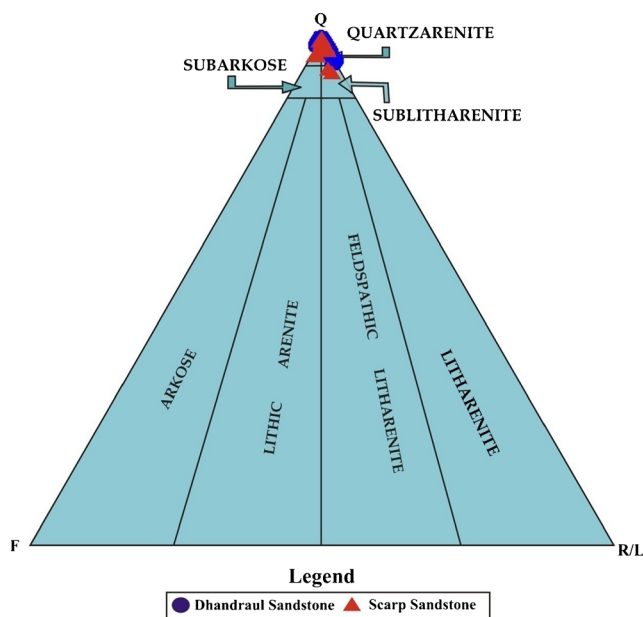


Fig. 8 Classification of the Upper Kaimur Group sandstones, Son Valley, according to Folk (1980)

have undulatory extinction. Polycrystalline quartz varies from 7 and 6 % of the total quartz content in Scarp and Dhandraul Sandstones, respectively (Fig. 9a). Some show a coarse texture of polycrystalline quartz grains containing two or more crystals that have straight, equant to concave–convex boundaries. Coarse to finer texture polycrystalline quartz grains contain numerous elongate crystals that exhibit smooth, crenulated, and/or sutured boundaries. Some of quartz grains contain inclusions of rutile, zircon, and tourmaline (Fig. 9e).

Feldspar (F) content is low with average 0.1 and 0.2 % in the Dhandraul and Scarp Sandstones, respectively. Both potash and plagioclase feldspars are less common. Microcline with cross-hatched pattern is common among the total feldspar (Fig. 9b). The majority of the feldspar grains are altered, which implies a high degree of chemical weathering.

Lithic fragments (L) occur as clusters of multiple grains that are represented by metamorphic, volcanic, clastic, and non-clastic fragments. Mostly chert, siltstone, phyllite, schist, and graphic quartz detrital are observed (Fig. 10a). Lithic fragments constitute a very small component in Dhandraul Sandstone nil to 2.7 % (average 0.3 %) and in Scarp Sandstone 0 to 0.6 % (average 0.05 %).

Micaceous minerals (M) in the sandstones are represented mainly by muscovite and biotite, which occurs as tiny to large elongate flakes with frayed ends. The average occurrences of mica in Dhandraul Sandstone are 1.4 and 1.3 % in Scarp Sandstone. Detrital mica grains usually show the effect of compaction, as bending and kinking around detrital grains (Figs. 9f and 10d).

Table 3 Range and average of mineralogical composition of sandstones of the Upper Kaimur Group, Son Valley

	Monocrystalline quartz	Polycrystalline quartz		Feldspar		Mica		Chert	Lithic fragments	Dense minerals
	Common quartz	Recrystallized metamorphic quartz	Stretched metamorphic quartz	Plagioclase	Microcline	Muscovite	Biotite			
Dhandraul Sandstone										
Range	83–97.5	0.0–4.2	0.9–13.3	0.0–0.4	0.0–1.1	0.0–10.5	0.0–0.9	0.0–1.5	0.0–2.8	0.0–1.1
Average	91.5	1.2	4.9	0.02	0.1	1.4	0.1	0.3	0.4	0.2
Scarp Sandstone										
Range	82.2–96.7	0.0–2.8	1.3–17.0	0.0–0.35	0.0–1.9	0.0–2.6	0.0–0.6	0.0–1.7	0.0–0.6	0.0–0.5
Average	90.8	0.6	6.1	0.03	0.1	0.08	1.2	0.7	0.05	0.09

In addition, suits of *dense minerals (D)* form a minor constituent (0.2 and 0.1 % in Dhandraul and Scarp Sandstones). Dense minerals include rounded to well-rounded zircon, rutile, tourmaline, garnet, and opaque (Fig. 9d, e) minerals limonite, magnetite, and hematite. Grains of dense minerals show moderate abrasion.

Cementation

The Upper Kaimur Sandstones (Dhandraul and Scarp Sandstones) consist of siliceous, ferruginous, calcareous, and clay cements (Table 5). The occurrence of these cements in Upper Kaimur sandstone is described below:

Siliceous cements range from an average 6.3 and 2.8 % in Dhandraul and Scarp Sandstones, respectively (Table 5). In most of the samples, silica cement occurs as syntaxial overgrowth with an optical continuity with quartz grains (Fig. 11a). Quartz is the principal cement lining and filling fractures.

Ferruginous cement in the Upper Kaimur sandstones varies from 2.8 to 9.0 % and 1.2 to 3.8 % (average 5.5 and 2.4 %) in Dhandraul and Scarp Sandstones. It occurs in the form of black coating around detrital quartz and

feldspar grains as well as isolated patches and pervasive pore fillings (Fig. 11b), completely filled most of the pore spaces and resulted in reduction in sandstone porosity. Similar coatings also occur around altered and leached feldspar grains.

Calcareous cement occurs as a coarse crystalline (<200 μm) poikilotopic, pore filling blocky, or mosaic aggregates. Some of the quartz and feldspar grains have been corroded and replaced by this cement in the Upper Kaimur sandstones. It ranges from nil to 1.4 % and 0.4 to 2.6 % in Dhandraul and Scarp Sandstones, respectively (Fig. 11c).

Clayey cement is present in a very little amount. The observed clayey cements are as follows: *Illite* is the abundant clay mineral, exhibiting delicate fibrous lathe-like shapes and pore bridges, mostly noticed within the matrix and partly in pore spaces. Secondary pores, formed due to the dissolution of feldspar grains, are usually filled with the pore-lining illite.

Kaolinite is the most widespread authigenic clay mineral noticed in the sandstones. Based on SEM investigation, the kaolinite occurs as intergranular pore occluding clusters with pseudo-hexagonal forms commonly arranged as face-to-face

Table 4 Percentage of framework mode of sandstones of the Upper Kaimur Group, Son Valley

	Qt	F	L	Qm	F	Lt	Qp	Lv	LS	Qm	P	K
Dhandraul Sandstone												
Range	98.2–100	0.00–1	0.00–4.2	71.4–98.2	0.0–1	1.7–28.5	72.2–100	0.0–56	0.0–17.2	99.1–100	0.0–0.4	0.0–1.2
Average	99.0	0.1	0.8	92.2	0.1	7.6	89.8	5.6	4.4	99.8	0.03	0.1
Scarp Sandstone												
Range	97.1–100	0.0–2.3	0.0–1.5	82.8–96.7	0.0–0.0	3.2–17.1	54.5–100	0.0–8.2	0.0–45.4	97.4–100	0.0–0.3	0.0–2.1
Average	99.0	0.1	0.7	92.3	0.0	7.6	87.7	0.6	11.6	99.8	0.04	0.1

Qt total quartz, F total feldspar, L total lithic fragments, Qm monocrystalline quartz, Lt total lithic grains, Qp polycrystalline quartz, Lv volcanic lithic grains, Ls sedimentary lithic grains, P plagioclase, K orthoclase and microcline

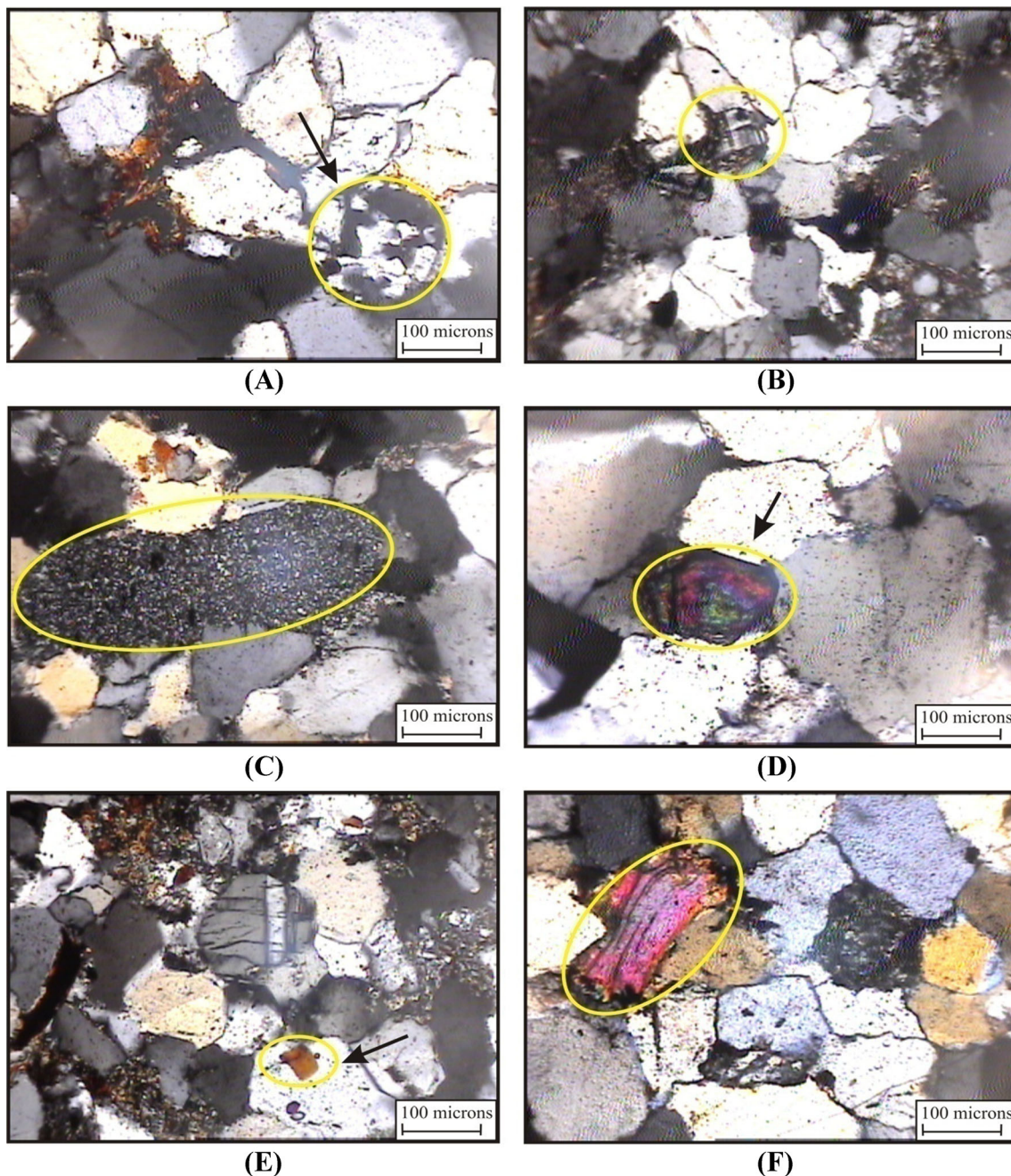


Fig. 9 Photomicrographs showing the types of detrital observed in the Upper Kaimur Group Sandstones of the Son Valley. **a** Polycrystalline quartz grain in Dhandraul Sandstone. **b** Microcline grain in Scarp

Sandstone. **c** Chert grain in Dhandraul Sandstone. **d** Zircon grain in Dhandraul Sandstone. **e** Inclusion of tourmaline grain in Scarp Sandstone. **f** Muscovite flake in Scarp Sandstone

stacking booklets and vermicular aggregates. The SEM images of the kaolinite show pore lining (Fig. 11e). Authigenic kaolinite occurs in filling the pore spaces in two forms: as well-developed euhedral pseudo-hexagonal plates forming booklets and aggregates and secondly as thin skeletal subhedral plates forming vermicules.

Matrix occurs in all the samples of Upper Kaimur Group sandstone with an average percentage of 1.64 and 3.87 % in Dhandraul and Scarp Sandstones, respectively. It is composed

of less than 63- μm -sized plagioclase, glass, and clay minerals. Both syn- and post-depositional matrix is present (Fig. 11d).

Source rock assessment

The following criteria were used for assessing the characters of source rock for Scarp and Dhandraul Sandstones of Upper Kaimur Group.

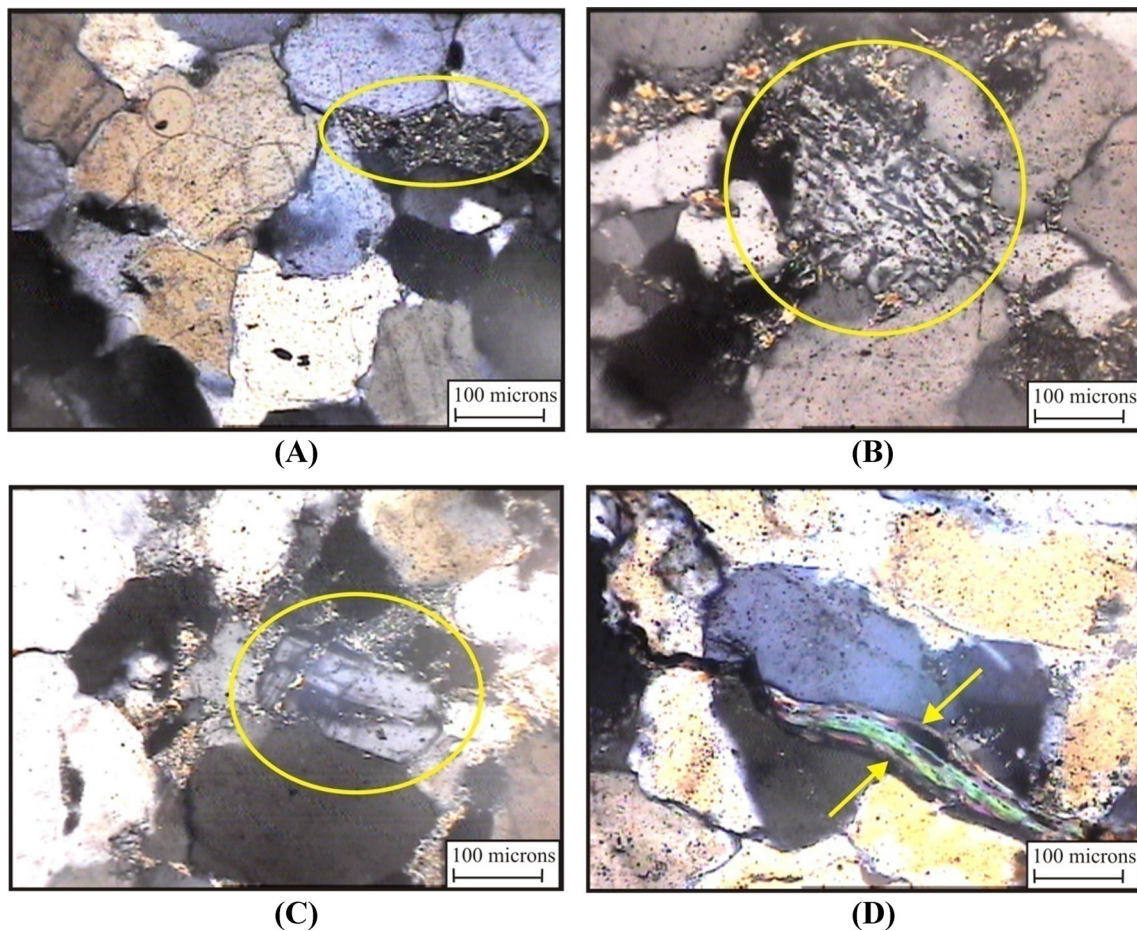


Fig. 10 Photomicrographs showing detrital observed in the Upper Kaimur Sandstones of the Son Valley. **a** Phyllite fragment in Dhandraul Sandstone. **b** Graphic quartz in Dhandraul Sandstone. **c** Altered feldspar grain in Scarp Sandstone. **d** Banded muscovite flake in Scarp Sandstone

Evidence from the framework grains

Detrital quartz In sedimentary rock quartz, detritus is often used as an indicator of provenance. The presence of strain-free quartz grains suggests their source in plutonic rocks also (Basu 1985). The sandstones have considerably high percentages of monocrystalline quartz (91.5 and 90.8 %) as compared to polycrystalline quartz (6.1 and 6.7 %) in Dhandraul and Scarp Sandstones, respectively (Table 3), indicating removal

of polycrystalline quartz by weathering and recycling. The polycrystalline quartz detritals show two distinctly different sizes of crystals within a single grain indicating derivation from metamorphic source. A high ratio of polycrystalline quartz to total quartz also suggests a metamorphic source. The quartz-type data mainly falls in the plutonic and middle to high rank metamorphic fields (Fig. 12). This plot yields consistent results that indicate a source area containing largely of plutonic and upper metamorphic rocks, The Q-F-L ternary

Table 5 Percentage of cements and void spaces in sandstones of the Upper Kaimur Group, Son Valley

Sample	Cements					Total cement	Detrital grain	Optical existing porosity
	Silica	Iron	Carbonate	Clay	Matrix			
Dhandraul Sandstone								
Range	8.0–2.5	13–5	1.5–0.0	1.6–0.0	3.8–0.0	20.9–11.2	87.1–77.1	2.6–0.6
Average	4.6	8.9	0.5	0.5	1.6	16.0	82.3	1.7
Scarp Sandstone								
Range	5.5–1.1	8.7–1.8	2.8–0.4	3.3–0.8	9.2–2.8	22.9–13.4	84.2–75.3	2.4–1.3
Average	3.4	5.6	1.6	2.2	6.1	18.8	79.2	1.9

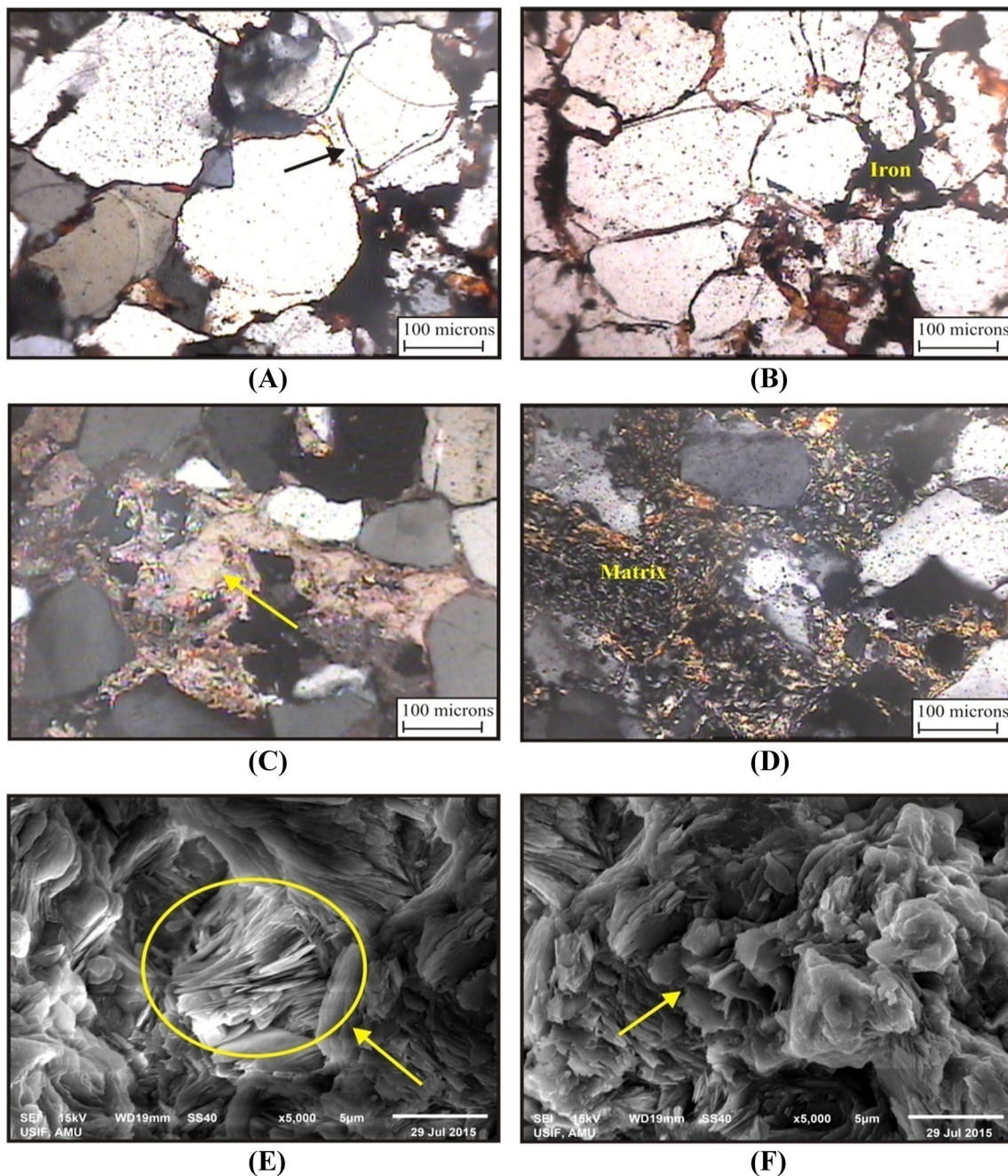


Fig. 11 Photomicrographs showing the nature of cements in the Upper Kaimur Sandstones of the Son Valley. **a** Quartz overgrowth in Dhandraul Sandstone. **b** Iron oxide cements in Dhandraul Sandstone. **c** Carbonate

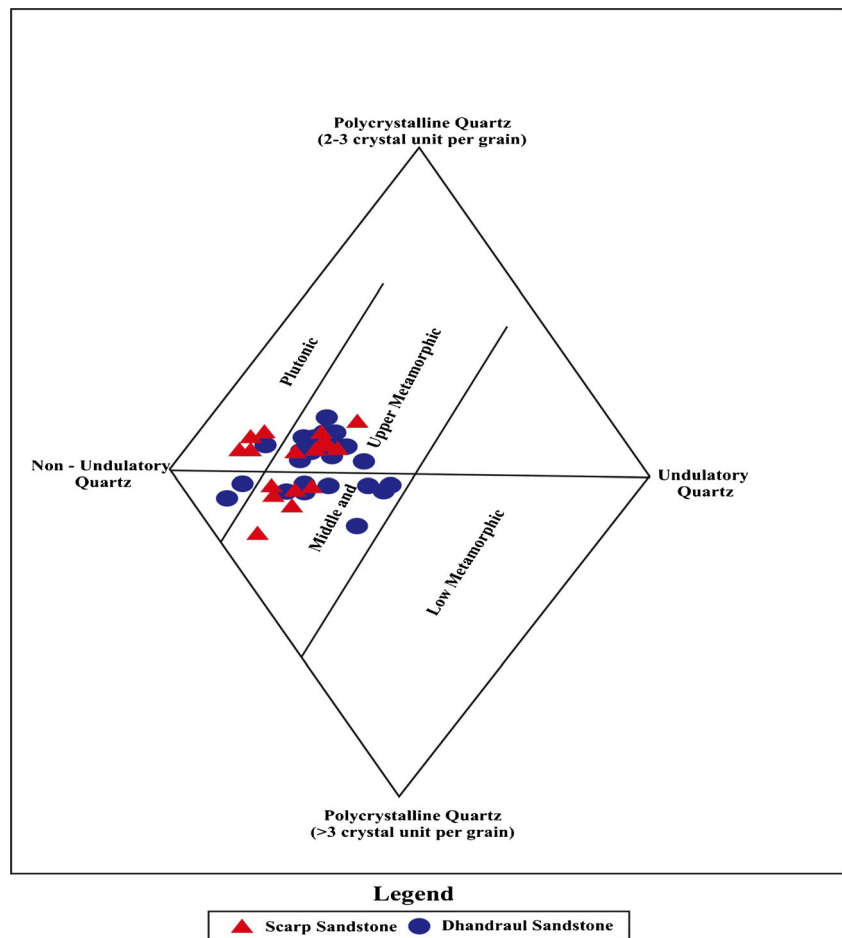
cements in Scarp Sandstone. **d** Matrix in Scarp Sandstone. **e** SEM photograph showing Kaolinite cement in Dhandraul Sandstone. **f** SEM photograph showing smectite in Scarp Sandstone

diagram of Suttner et al. (1981) indicates a metamorphic source rock and humid climate (Fig. 13). However, this particular diagram can discriminate only sources of metamorphic and plutonic rocks (humid or arid conditions), and it does not discriminate between different tectonic settings.

Detrital feldspar The presence of alkali feldspar in these sandstones indicates their plutonic and metamorphic source rocks (Trevena and Nash 1981). The dominant

alkali feldspar in these sandstones indicates a metamorphic source (Palomares and Arribas 1993). The occurrence of the small percentage of feldspar in the studied sandstones may be attributed to the fact that they are lost due to abrasion during transit or lost in solution during diagenesis under prevailing warm and humid climate. However, the presence of weathered and fresh feldspars together may indicate their derivation from two different sources.

Fig. 12 Diamond diagram of Upper Kaimur Group of sandstone (after Basu et al. 1975)



Detrital lithic fragments Lithic fragments are among the most informative of all the detrital components. The Upper Kaimur Group Sandstones commonly contain rock particles of sedimentary (mainly chert) and metamorphic origin (slate, phyllite, schist). Detrital lithic fragments carry their own evidence of provenance (Boggs 1968).

Detrital mica Both muscovite and biotite occur in the studied sandstones. These are derived from metamorphic, plutonic, and rarely from volcanic rocks. The muscovite is chemically more stable than biotite. In general, abundant micas are suggestive of metamorphic provenance (Ghazi and Mountney 2011).

Dense minerals The suite of dense minerals, including biotite, tourmaline, and zircon, indicates an acid igneous source. The mineral assemblage comprises magnetite and rutile points to acid and basic igneous rocks in the provenance. The interpretation is also supported by the presence of abundant opaque mineral grains, including magnetite, hematite, and limonite. It is mainly derived from granitic batholithic or granite gneisses. Presence of garnet reflects a metamorphic source. Well-rounded grains of rutile and zircon are indicative of the reworked source (Blatt and Christie 1963; Blatt 1967).

The above observation suggests that the sediments of the Upper Kaimur Group have been derived from a variety of source rocks. The palaeoflow pattern of the Upper Kaimur succession in the Son Valley indicates detrital derivation from Paleoproterozoic and Mesoproterozoic granite, granodiorite, and gneiss of the Mahakoshal Group and Chotanagpur granite–gneiss (Ghose and Mukherjee 2000) later than Satpura Orogeny in an intracratonic type of tectonic setting.

Tectonic setting

Four triangular diagrams of Dickinson 1985 were used (Table 4) for the present study: Qt-F-L, Qm-F-Lt, Qp-Lv-Ls, and Qm-P-K. The Qt-F-L diagram emphasizes factors controlled by provenance, relief, weathering, and transport mechanism as well as source rock based on total quartzose, feldspathic and lithic modes. In the Qt-F-L diagram, mean detrital modes plot near Qt pole and near Qt-F leg, thereby suggesting a stable, mature craton interior block provenance (Fig. 14a) which suggests their derivation from metasedimentary and sedimentary rocks that were originally deposited along former passive continental margins (Dickinson and Suczek 1979; Dickinson

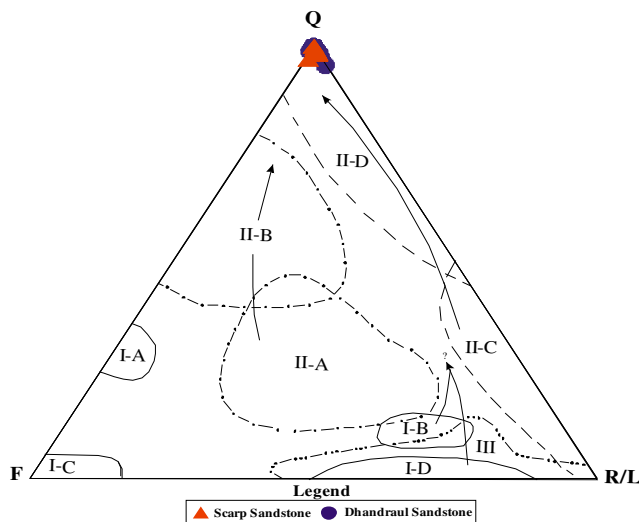


Fig. 13 Postulated idealized evolution model of the Upper Kaimur Group of sandstones with emphasis on source rocks and climate. Expected petrofacies composition from ideal provenances with different climate and their relationship with primary source rocks by Alam (2002). The modal was modified after Cox and Lowe (1995). Fields IA, IB, IC, and ID are of granite, rhyolite, gabbro, and andesite-basalt, respectively, after McBirney (1983). IIA, IIB, IIC, and IID are first cycle of Holocene fluvial sands from granite (arid climate), granite (humid climate), metamorphic (arid climate), and metamorphic (humid climate), respectively, after Suttner et al. (1981). III represents sediments from magmatic arcs after Marsaglia and Ingersoll (1992)

1985). In the Qm-F-Lt diagram, all unstable lithic fragments, including the polycrystalline quartz, are plotted together as Lt, to emphasize the source rocks. Qm-F-Lt diagram shows that the plot of the data falls in continental block provenance with almost equal contribution from recycled orogen provenance (Fig. 14b). The ratio of monocrystalline quartz to that of polycrystalline quartz reflects the maturity of the sediments and sedimentary rocks because the amount of polycrystalline quartz tends to reduce by recycling and weathering (Basu 1985). The Qp-Lv-Ls triangular plot, which is based on rock fragment population reveals the polyminerallic component of the source region and gives a more resolved picture about the tectonic elements and emphasizes the type of the orogenic environment (Dickinson 1985). Graham et al. (1976) and Ingersoll and Suczek (1979) suggest that Qp-Lv-Ls triangular plot is a useful tool to differentiate detrital modes of the suture belts from magmatic arcs and rifted continental margins. The studied data fall in rifted continental margin basin setting and collision suture and fold thrust belt setting (Fig. 14c) reflecting no contribution from the volcanic source. The Qm-P-K plot of the data shows that all the sediment contribution is from the continental block basement uplift provenance (Fig. 14d) and is reflected in the mineralogical maturity of the sediments and stability of the source area.

Discussion

The present study focuses on the processes took place during the deposition of Upper Kaimur Group of sandstones in the Son Valley. The conceptual model (Fig. 7) has been proposed to provide an idea about the environments of deposition of the Scarp and Dhandraul Sandstones based on variability of facies association in space and time and their stacking pattern and palaeo-directional trend.

The TSFA assemblage is internally characterized by small-scale cross-bedding in the assemblage with lamination, ripple marks, etc. suggesting mixed tidal flat depositional environment, (e.g., Reineck and Singh 1980). The sand flats are typical in the tide-dominated estuaries (Dalrymple et al. 1992). The presence of wave generated structures (i.e., symmetrical, asymmetrical ripples and truncating surfaces, low angle dipping cross-lamination, trough cross-bedding, herringbone cross-bedding) in TSFA hints towards the outer estuarine settings (Dalrymple et al. 1992). Ripple bedded sandstone represents shallow water sand flats in a tidal setting. The parallel laminated sandstone represents occasional storm events during the intervening periods of low sediment influx in the intertidal environment (Dalrymple et al. 1992; Bjorklund 2005). Reading (1978) attributed the herringbone type of sedimentary structures in sandstone bodies as a diagnostic feature of tidal currents or excellent indicator of reversing or bidirectional flow in estuaries (Boothroyd 1985). The interbedded fine-grained sandstone and shale facies indicate Lower shoreface transition zone of the inter-tidal environment. The alteration of sandstone and shale with an abundance of small-scale wave and current formed structures suggests their deposition in the low-energy intertidal environment (e.g., Evans 1965; Van Stratten 1954; Corcoran et al. 1998). This is also supported by the palaeoflow patterns, which are multimodal and more divergent (NNE–NW–SW) seawards. The presence of sedimentary structures in the Scarp Sandstone indicates the influence of tidal processes. In addition to facies association consisting of tidal influenced fluvial channel, tidal channel, and tidal sand flat/sand bars, these characteristics support a tidal-dominated estuarine setting.

On the basis of the characteristics of the TIFCFA, the Dhandraul Sandstone evidences a product of TIFCFA. TIFCFA documents evidences of confined tidally influenced fluvial channel facies and consistent unidirectional palaeoflow record. The energy fluctuation of tidal currents results in highly unsteady flows producing frequent reactivation surfaces as observed in this association. The abundance of these surfaces separating foreset packages that are only few centimeter-thick facilitates the differentiation of tidal influence from other disturbances in the fluvial system (Ladipo 1988; Thorez et al. 1988). Sp facies of this facies association shows these evidences suggesting deposition in the inner estuarine settings transitional between fluvial and tidal sedimentation

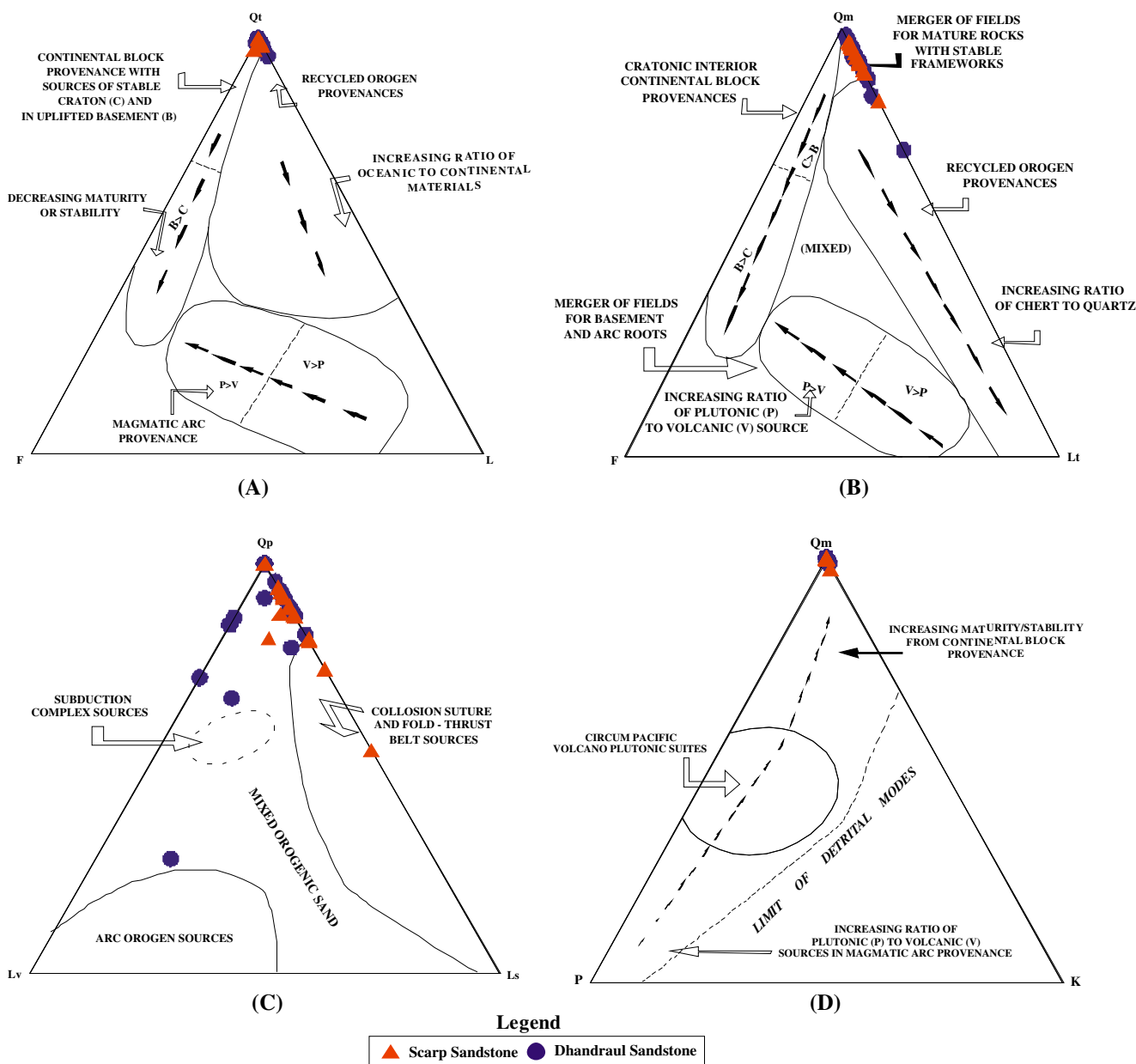


Fig. 14 a–d Plots of the Upper Kaimur Group sandstone in Son Valley, according to Dickinson (1985)

(Dalrymple et al. 1992; Hori et al. 2001; Cooper 2002). The general paleocurrent trend in this facies association (Sp facies) is also consistent in the NNE to NE direction suggesting confined unidirectional estuarine flow regime. Tidal bundles are scarce or even absent from such settings due to the interference of fluvial influx (Leckie and Singh 1991; Hori et al. 2001; Cooper 2002; Heap et al. 2004). The presence of large-scale trough and planar cross-beds with interbeds of pebbles probably produced by the migration of linguoid and lunate megaripples (Clifton et al. 1971; Hunter et al. 1979; Davis 1985; Decelles 1987; Einsele 1992) indicates that St as Sp facies was deposited within the zone of breaking waves or surf zone of nearshore (Einsele 1992). The predominant

distribution in this facies reflects a dominance of landward-driven flood-dominated tidal currents. The parallel laminated sandstone facies with parting lineation closely resembles a high-energy beach environment (Reineck and Singh 1980; Dalrymple et al. 1992; Bose and Chakraborty 1994). This lithofacies show excellent development of parting lineation which belongs to the Upper flow regime (Harms et al. 1982). Solitary cross-beds associated with horizontal laminations suggest latest events of deposition on the beach face under the influence of strong tidal and longshore currents intermittently attacking the sloping beach (Shukla and Pant 1996). Massive sandstone (Sm) sequence represent intertidal environment of deposition (Klein 1985).

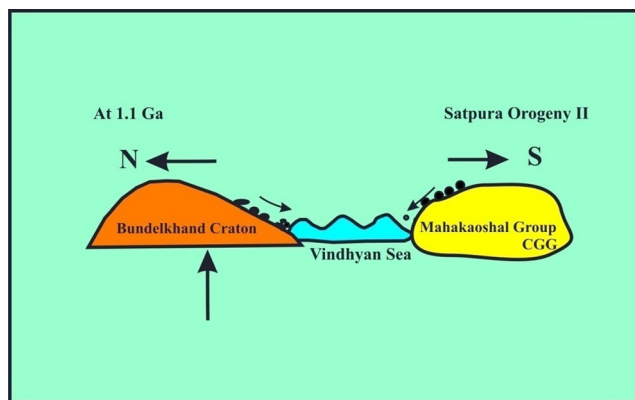


Fig. 15 A schematic model for the Upper Kaimur Group sedimentation in the Sonbhadra and Mirzapur districts Son Valley, India (modified after Sen et al. 2014)

The Vindhyan Basin covers a large part of the northern Indian shield and rests on a wide variety of basement rocks, including the Banded Gneissic Complex in the northern part and the Bijawar Group, the Chotanagpur Granite–Gneiss (CGG), and the Mahakoshal Group in central and western part of India. The palaeoflow directions for the Vindhyan sediments are mostly northerly and northwesterly (Bose et al. 2001). The Vindhyan Basin was formed largely through the rift-controlled subsidence under extensional regime and locally by downward flexuring of the basement near tectonic margins (Ravi Shankar 1993). The original basin possibly extended beyond the existing tectonic boundaries to the south and west. The sediments of the extended basin are no longer exposed/preserved due to subsequent widespread thrusting and erosion with a few exceptions like occurrence of basal Vindhyan rocks of Jungle outlier in the Mahakoshal (Bijawar) Belt of the Son Valley. Observations on tectonics of Son Valley support the condition of possible extension of Vindhyan Basin on the Satpura–Bijawar basement beyond the existing boundary in the south (Ravi Shankar 1993).

The compositional study facilitates that the Upper Kaimur Group sandstones were derived from nearby mixed provenance. Presence of graphic quartz (Fig. 10b) in the Dhandraul Sandstone of the Upper Kaimur Group reveals that it is of granitic source. Upper Kaimur Group sandstone also contains some metamorphic lithic fragments (Fig. 10a) which indicate that these are the product of metamorphic rocks. Rarity of feldspar and lithic fragments in the Dhandraul and Scarp Sandstones suggests that the climate was humid (Fig. 13) during the deposition. Different workers have pondered the source rock composition of the Upper Kaimur Group of sedimentary rocks by using sedimentological and geochemical proxy. Prior sedimentological studies contemplated the source of the Upper Kaimur Group of rocks shall be Mahakoshal metasediments and Bundelkhand granite (Srivastava and Mehrotra 1981). However, on the basis of dense mineral characterization, the prime source of

Vindhyan sediments is inferred from Bundelkhand granite (Prasad and Verma 1991). However, Paikaray et al. (2008) indicated provenance was from Mahakoshaland Chotanagpur Gneissic Complex. On the basis of the geochemical signatures, Chakrabarti et al. 2007 proposed Mahakoshal and Chotanagpur gneisses as a source. They remarked that the basin was tectonically dynamic during the entire duration of the Vindhyan sedimentation. Mishra and Sen (2010, 2012) based on geochemical proxy (major and trace element data) have indicated the source for the Upper Kaimur sandstones and shales as Chotanagpur Gneissic Complex and Mahakoshal Supracrustal belt. Sen (2010) indicated Bundelkhand granite as the source these sediments using mixing modeling calculations. Former workers have noted the palaeoflow direction for the Lower Kaimur Group as being SSE and SSW (Gupta et al. 2003; Chakraborty 2006) with the provenance in the Bundelkhand sector. On the basis of W and NW palaeoflow direction, earlier workers recognized the source for the Upper Kaimur Group as Mahakoshal belt and the Chotanagpur Gneissic Complex (Jafar et al. 1966; Chakraborty and Bose 1992; Bhattacharya and Morad 1993).

An intangible model has been proposed that the Bundelkhand craton was probably subjected to an intense weathering and denudation under a warm, humid climate as indicated by the quartzarenite composition of the studied sandstones. The craton also suffered a periodic domal uplift from time to time due to the emplacement of the dikes (Malviya et al. 2006). The domal uplift of the Bundelkhand craton was triggered by the dike emplacement at ~1.1 Ga (Kumar et al. 2007; Pradhan et al. 2012). Due to tectonism basin experienced a change in configuration during the Satpura orogeny II at ~1.1 Ga, the Central Indian Tectonic Zone (CITZ; Chotanagpur Gneisses and Mahakoshal belt) was subsequently uplifted and suffered extensive weathering under a hot humid climate. With that result, the tectonism commenced the shedding of the weathered product from CITZ, leading to the deposition of the Upper Kaimur Group of Vindhyan Basin (Fig. 15) in the Son Valley. Thus, the tectonism in the hinterland eventually resulted in the versatility in the provenance which was liable for the Upper Kaimur Group sedimentation.

Conclusions

1. The lateral and vertical facies distributions reflect tidal influenced estuarine settings for the Scarp and Dhandraul Sandstones of the Upper Kaimur Group in the Son Valley. The overall vertical gradation from tide-influenced fluvial channel/tidal channel to tidal sand bar/sand flat deposit records upward increasing tidal influence. Evidence of the genetic association of tidal-influenced fluvial channel/tidal channels and tidal sand

bar/tidal sandy flat deposits is typical of a tidal-dominated estuarine system (Woodroffe et al. 1989; Leckie and Singh 1991; Dalrymple et al. 1992; Chappell and Woodroffe 1994; Mulrennan and Woodroffe 1998; Hori et al. 2001; Heap et al. 2004; Bjorklund 2005). The presence of sedimentary structures attributed to tidal processes suggests that the Scarp and Dhandraul Sandstones were formed dominantly under the influence of tidal processes. In addition to facies association consisting of tidal influenced fluvial channel/tidal channel and tidal sand flat/sand bars, these characteristics support a tidal-dominated estuarine setting.

2. Petrographically, the Dhandraul and Scarp Sandstone classification of the Upper Kaimur Group in the Son Valley varies from quartzarenite to sub-litharenite. The modal sandstone composition consists of rounded to subangular grains, monocrystalline and polycrystalline quartz grains, potassium, and plagioclase feldspars, mainly sedimentary and metamorphic lithic fragments, mica, and heavies. The sandstone composition suggests a mixed provenance of metamorphic, plutonic, and recycled sedimentary sources. Likewise, the plots of the Qt-F-L and the Qm-F-Lt ternary diagrams suggest that the Upper Kaimur Group sandstones may be derived mostly from mixed provenances which are the cratonic interiors and recycled orogenic (based on the Dickinson 1985). This Paleoproterozoic and Mesoproterozoic granite, granodiorite, and gneiss of the Mahakoshal Group and Chotanagpur granite–gneiss dominantly contributed to the sediments of the Upper Kaimur Group later than Satpura Orogeny in an intracratonic type of tectonic setting. The sediments were deposited in rifted basin condition as is evidenced by plot on Qp-Lv-Ls diagram. The Qm-P-K diagram suggests the maturity and stability of the source area. The QFL also suggests humid climatic conditions for the Upper Kaimur Group sediments using the model proposed by Suttner et al. (1981).

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