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Integrated Petrographic, Mineralogical, and Geochemical Study of the Upper Kaimur Group of Rocks, Son Valley, India: Implications for Provenance, Source Area Weathering and Tectonic Setting

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ABSTRACT

The upper Kaimur Group (UKG) of the Vindhyan Supergroup in central India, primarily consists of three rock types-Dhandraul sandstone, Scarp sandstone and Bijaigarh shale. The present study aims to reconstruct the parent rock assemblages, their tectonic provenance, mineralogy, weathering intensity, hydraulic sorting and depositional tectonic setting. Samples from the UKG rocks representing the Dhandraul sandstone, Scarp sandstone and Bijaigarh shale were studied using a combination of petrographic, mineralogical, and geochemical techniques. Texturally, medium to coarse grained UKG sandstones are mature and moderate to well sorted. Deficiency of feldspars in these sandstones indicates that the rocks are extensively recycled from distant sources. Their average modal composition for Scarp (avg. Qt_{99} $F_{0\cdot2}L_{0.8}$) and Dhandraul (avg. Qt_{99} $F_{0.1}L_{0.8}$) sandstones, classifies them as quartz arenite to sub-litharenite types, which is consistent with geochemical study. Major element concentrations revealed that sandstones have high SiO_2, K_2O > Na_2O, and low Fe_2O_3, which are supported by the modal data. On the other hand, sandstone samples are enriched in most trace elements such as Ce, Sr, V, Sc and Zr and depleted in U and Th. The CIA values (43.17-76.48) of the UKG rocks indicate low to moderate weathering, either of the original source or during transport before deposition, which may have related to low-relief and humid climatic conditions in the source area. Further, petrographic and geochemical interpretations indicate that they are derived from craton interior to quartzose recycled sedimentary rocks and deposited in a passive continental margin. Therefore, granitic and low grade metamorphic rocks of Mahakoshal Group and Chotanagpur granite-gneiss, situated on the southern and south-eastern side of the Vindhyan basin are suggested as possible provenance for the UKG rocks.

INTRODUCTION

The Vindhyan Supergroup is the largest intracratonic Proterozoic sedimentary basin (Purana basins) in the Indian subcontinent (Soni et al. 1987; Kale and Phansalkar, 1991). Although, an enormous volume of this Supergroup is concealed below the Deccan traps and the Ganga alluvium, it is exposed over an area of more than ~104,000 km^2 in Central India, comprising about ~4000 m of unmetamorphosed and undeformed sediments (Sastry and Moitra, 1984; Venkatachala et al. 1996; Deb et al. 2002; Ray, 2006; Malone et al. 2008; Gopalan et al. 2013). This sedimentary basin, predominantly developed in marine setting, in particular, have an excellent archives of paleo-environmental conditions with decent time resolution (~1800-900 Ma) of the Proterozoic eon (Bhatia, 1983; Valloni and Mezzardi, 1984; Bhatia and Crook, 1986; Roser and Korsch, 1988; McLennan et al. 1993; Armstrong-Altrin et al. 2004; Ghosh et al. 2012; Gopalan et al. 2013). For the last couple of decades this basin has become famous following the discovery of "Cambrian-like" small shelly fossils in the Lower Vindhyan sequences of Paleoproterozoic age (Azmi, 1998; Seilacher et al. 1998; Kumar et al. 2001; Rasmussen et al. 2002; Ray et al. 2003; Bengston et al. 2009). In contrast, previous studies on these sandstones have suggested that the mineralogical and chemical compositions of these kind of clastic sediments are indicative of several complex variables such as the source rock composition, the extent of weathering, transport mechanism, diagenesis, climatic conditions and tectonic settings (Suttner et al. 1981; Bhatia, 1983; Dickinson et al. 1983; Taylor and McLennan, 1985; Bhatia and Crook, 1986; Roser and Korsch, 1986, 1988; Suttner and Dutta, 1986; Pettijohn et al. 1987; Kroonenberg, 1994; Weltje et al. 1998).

However, significant contributions have been made by several studies in relation to the regional geology, stratigraphy and/or sedimentology of the UKG sandstones exposed in Son Valley, India. (e.g., Dickinson and Suczek, 1979; Bhatia, 1983; Valloni and Mezzardi, 1984; Bhatia and Crook, 1986; Roser and Korsch, 1988; McLennan et al. 1993; Armstrong-Altrin et al. 2004; Ghosh et al. 2012). Additionally, it provides the excellent opportunity for young researchers to understand the evolutionary history of complex life on the earth by petrography and geochemical analysis of these sedimentary rocks. The UKG of rocks from two exposed sections – Churk Markundi road and Markundi Ghat – in Son Valley are investigated. Further, these data sets will help us for a better understanding of the paleo-climatic reconstruction and more comprehensive models for the evolution of Vindhyan Supergroup in Central India. The main objectives of this study are (a) infer possible provenance and tectonic setting of UKG sandstone, (b) determination of the possible weathering conditions at the source area based on the petrography and major and trace elements geochemistry, and (c) integration of all data set to infer paleo-environmental conditions of the Proterozoic time in central India.

GEOLOGICAL BACKGROUND

Proterozoic Vindhyan Supergroup of rocks is exposed in the Son valley of central India (Fig. 1) are considered to be the largest sedimentary basin exposing about ~6000 m thick succession of undeformed – shales, sandstones, limestones, dolostones with subordinate felsic volcanics and lies on the top of the deformed metasediments of either Bijawar/Mahakoshal Group or Archaean gneissic basement. Developed in an intracratonic and dominantly marine setting, the Vindhyan Supergroup is divided into two sequences

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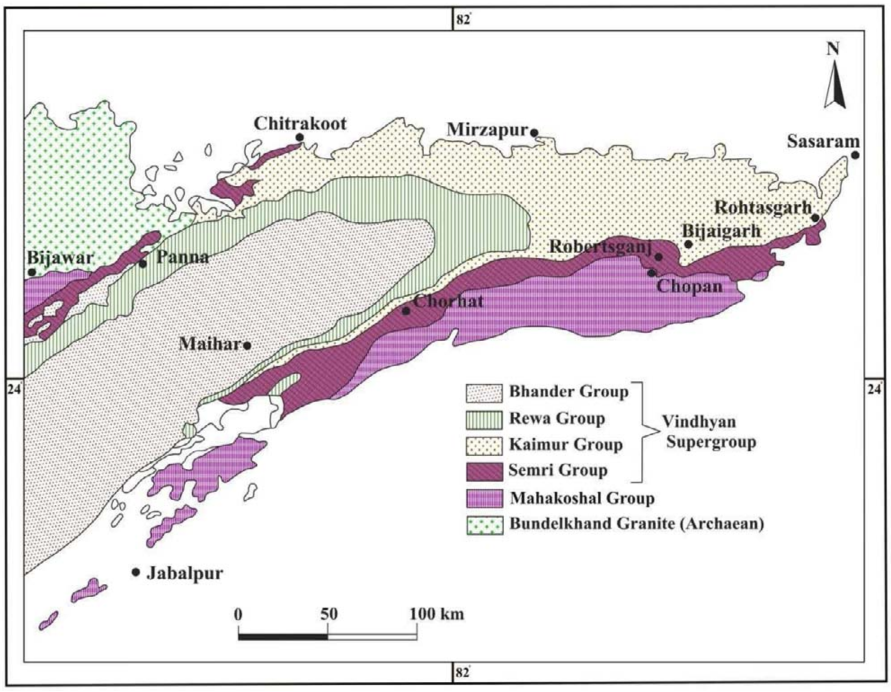


Fig. 1. Geological map of the Vindhyan basin, Son Valley, India showing various lithological units (modified after Soni et al. 1987).

separated by an unconformity with a laterally correlatable conformity (Bose et al. 2001). A sharp upward transition from carbonates to siliciclastics across this surface reflects a basin-wide regression of the sea (Bose et al. 2001). The lower Vindhyan (Semri Group) constitutes dominant carbonate deposit and the overlying Kaimur Group by siliciclastic deposit.

Sedimentation in the Vindhyan started before 1.7 Ga until shortly after 1 Ga (Sarangi et al. 2004; Gregory et al. 2006; Chakraborty, 2006; Malone et al. 2008). Kajrahat limestone and Deonar/Porcellanite Formation yielded a Pb–Pb age of 1721±90 Ma and U–Pb ages of 1630-1631 Ma, respectively (Sarangi et al. 2004, Rasmussen et al. 2002, Ray et al. 2002). Thus the sedimentation in the basin, in particular Son valley, started sometime prior to 1721 Ma and continued till ~650 Ma. However, the upper limit of Vindhyan sedimentation has been bracketed down to 1Ma (Malone et al. 2008). 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 ~542Ma; Azmi, 1998a) from the Rohtasgarh Limestone that conformably lay little above the trace fossils-bearing Chorhat strata, suggesting far younger than the traditional age to the Vindhyan Supergroup. But the record of the earliest Cambrian small shelly fossils indicating a major upward age revision of the Vindhyan Supergroup made 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 (updated from Azmi et al. 2007). However, the age constraints for the Kaimur Group derive from the Rb/Sr dating of a kimberlite pipe that intrudes the Kaimur Group at Majhgawan. 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 $^{40}Ar/^{39}Ar$ of the phologopite in the kimberlite pipe.

Furthermore, the Vindhyan Supergroup is broadly divided from base to top into four groups-Semri, Kaimur, Rewa and Bhander. The Semri Group, also called lower Vindhyan Group, is gently deformed and mildly metamorphosed and consists of carbonate-rich sediments.

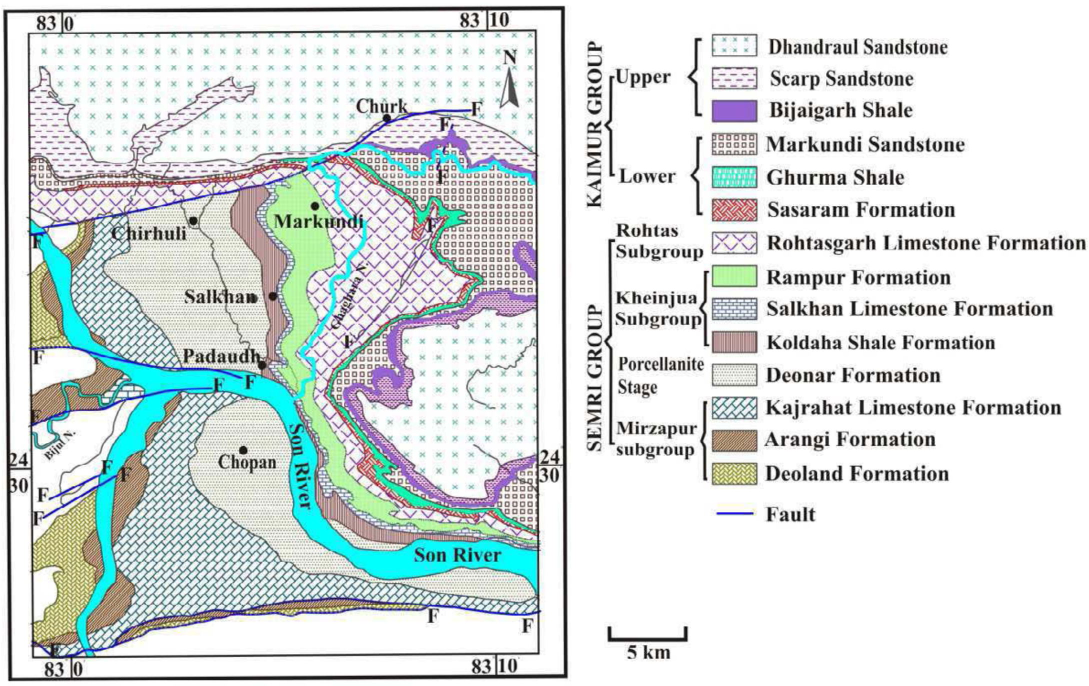


Fig.2. Detailed geological map of Vindhyan Supergroup in and around Sonbhadra and Mirzapur district, UP, India (modified after Auden, 1933; Sastry and Moitra, 1984).

They are overlain by siliciclastics of later three Groups, i.e., the upper Vindhyans Group. The Kaimur Group (400 m) lies unconformably over a tilted, somewhat deformed and partially eroded Rohtasgarh limestone of the Semri Group (Misra, 1969). The rocks of the Kaimur Group are largely of fluvial origin (Auden, 1933; Bhattacharya et al. 1986; Morad et al. 1991; Bhattacharya and Morad, 1993; Bose et al. 2001; Mishra and Sen, 2008a, b), whereas some workers have interpreted their depositional environment varying from beach to barrier bar or shoal to tidal flat and lagoon (Misra, 1969; Banerjee, 1974; Singh, 1980; Quasim et al. 2017). Additionally, the Kaimur Group has been divided into lower Kaimur Group (LKG) and upper Kaimur Group (UKG). The LKG is further divided into the Sasaram Formation, the Ghurma shale and the Markundi sandstone and UKG comprises three lithounits namely Bijaigarh shale being the lowermost followed by the Scarp sandstone and the Dhandraul sandstone (Auden, 1933; Prakash and Dalela, 1982), (Fig. 2).

STUDY AREA

For this study, two traverses were taken along Churk-Markundi road and Markundi-Ghat sections in Sonbhadra and Mirzapur districts, respectively (Fig. 3). In these sections the UKG (Dhandraul sandstone, Scarp sandstone and Bijaigarh shale) is broadly exposed whereas LKG dislocated by the Markundi-Jamwal fault (Prakash and Dalela, 1982). Consequently, Bijaigarh Formation directly rests over the Semri Group. The relevant details pertaining the stratigraphy, lithology and structure of the UKG are summarized in (Table 1). Brief description of the these major lithounits are as follows.

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. It also exhibits sedimentary structures such as 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 trough and planar cross bedded variegated medium-grained sandstone. It shows characteristic planar, laterally impersistent erosion 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 having millimeter thick lamination and meter to centimeter thick bands (locally) of pyrite. Further it is intercalated with thin beds of fine to very fine grained sandstones with cross-bedding, wave ripples, parallel bedding, wrinkle marks, rill marks mud cracks. Locally at some places it is capped by volcaniclastics (Chakraborty et al. 1996).

MATERIALS AND METHODS

In this study, two stratigraphic sections representing UKG, exposed in Son Valley (Fig. 1 and 2) were thoroughly studied in the field and detailed lithologs (Fig. 3) were prepared for systematic lithofacies analysis. Further, fresh sandstone samples were collected from outcrops of Churk Markundi Road and Markundi Ghat from bottom, middle and top levels of these roadside exposed sections. Forty-six, thin sections were prepared and detailed petrographic investigations were carried out. Modal mineralogical determinations were made by counting ~300 grains per thin section. The point counts were done using standard Gazzi-Dickinson methods (Gazzi, 1966; Dickinson, 1970) and the relative proportions of quartz, feldspar and rock fragments were determined and plotted on QFL triangular diagram to delineate the lithology and tectonic setting. Framework parameters and detrital modes of sandstones from the UKG are listed in (Table 2 and 3). The identification of bulk mineralogy and their abundance were identified by X-ray diffraction (XRD) analyses using the available facility at the Advanced Center for Materials Sciences (ACMS), Indian Institute of Technology Kanpur (IITK). The powder samples were run on Rigaku Mini Flex 600. Whereas Cu-Kα (λ=1.54Å) source at scan speed 1°/min, step size of 0.05°, and 2θ in the range 5° to 70° were chosen for all XRD analysis.

Further, fifteen representative sandstone and shale samples were chosen for geochemical analysis. The major oxides and the trace elements were analyzed using Rigaku ZSX primus II wave-length dispersive X-ray fluorescence spectrometer (WD-XRF), at ACMS, IIT Kanpur. SCo-1 (Cody Shale, Natrona County, Wyoming, US) and LKSD-2 (Lake Sediments, Ontario, Canada) standards were also run along with the samples to determine accuracy of measure-ments. Moreover, the total iron is expressed as Fe_2O_3. Major oxide data were recalculated to an anhydrous (LOI-free) basis and adjusted to 100% before using them in various diagrams.

RESULTS

Petrographic Analysis of the Dhandraul Sandstone

Dhandraul sandstone units of the UKG are classified as upper sandstone member which have medium to coarse grained texture and

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

	Group		Formation	Lithology	Structures
Upper Vindhyan	Bhander (139-580 m)	Upper Kaimur	Dhandraul Sandstone (120 m)	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 (360-3000 m)		Scarp Sandstone (150 m)	Medium grained multicolored sandstone (pink to gray) sublitharenite, micaceous siltstone and sandstone	Cross bedding, fault gouge and breccia, water seepages, seepages, drag fold, ripple marks, clay galls
	Kaimur (8-400 m)		Bijaigarh Shale (25 m)	Heterogeneous lithology, reddish brown to buff colour 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
		Lower Kaimur	Markundi Sandstone	Lower Kaimur formations are omitted by Markundi-Jamwal fault (Prakash and Dalela, 1982)	
			Ghurma Shale		
			Sasaram Sandstone		
~~ Faulted/Normal contact ~~~					
Lower Vindhyan/Semri Group (760-3055 m)					

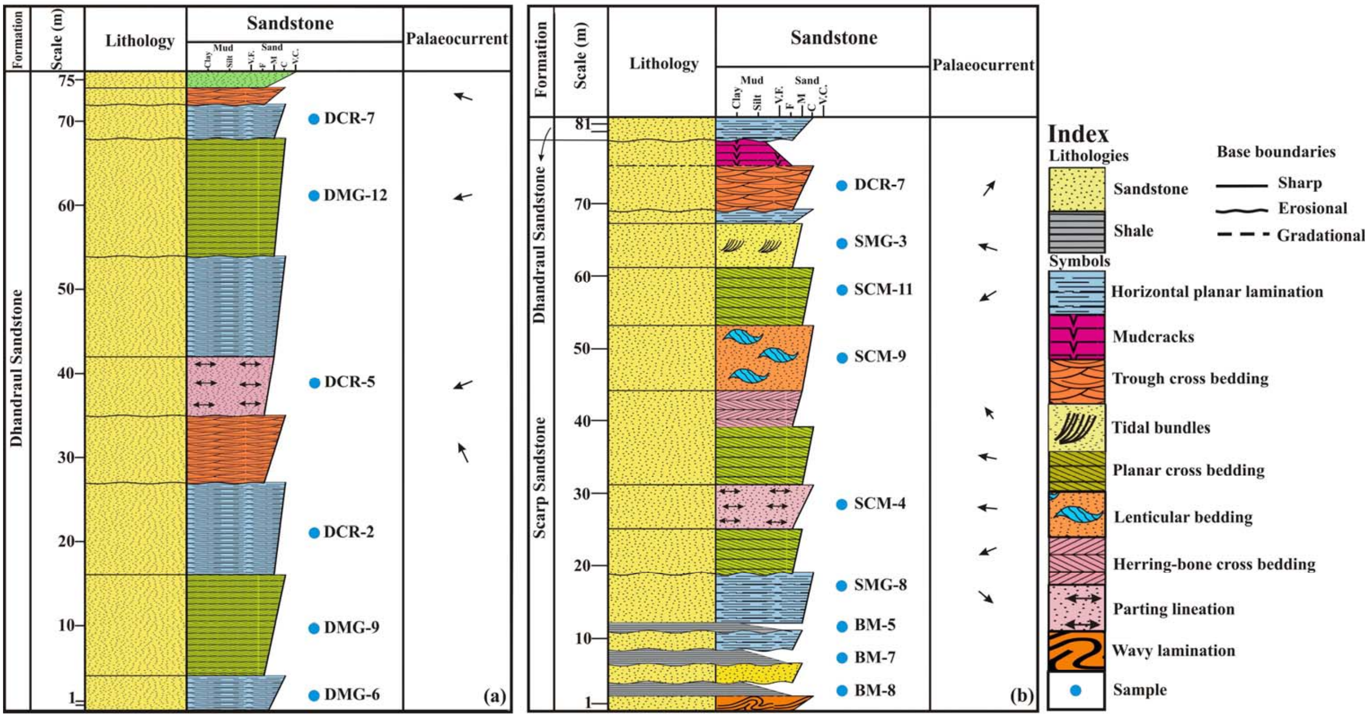


Fig. 3. a b Lithostratigraphic columnar sections of the Dhandraul Sandstone, Scarp Sandstone and Bijaigarh Shale at **(a)** Churk Markundi road section and **(b)** Markundi Ghat section, respectively.

are moderate to poorly sorted. Classification of this sandstone was determined using Folk (1980) methods. Major detrital framework components of the sandstone namely quartz, feldspar and lithic fragments were used to construct a QFL ternary diagram (Fig. 4). The plotted points of the Dhandraul sandstone member of the UKG falls in the field of quartz arenite with an average modal composition of (Qt_{99} $F_{0.1}L_{0.8}$).

Mineralogical Composition

Quartz: Quartz is the most abundant mineral, comprising between 98.20-100% in the modal composition (Table 3). Monocrystalline (Qm)

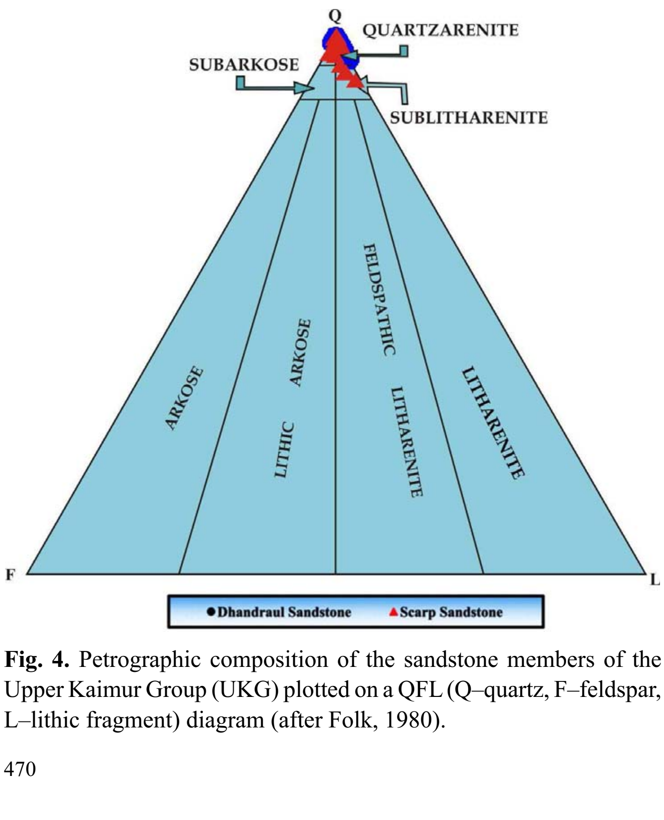


Fig. 4. Petrographic composition of the sandstone members of the Upper Kaimur Group (UKG) plotted on a QFL (Q–quartz, F–feldspar, L–lithic fragment) diagram (after Folk, 1980).

and polycrystalline quartz (Qp) are present in the UKG sandstones (Fig. 5.1a). Some of the quartz grains show multiple deformation fractures. Among quartz grains, Qm (avg. 91.49%) is dominant over Qp (avg. 6.0%). Monocrystalline quartz (Qm) grains exhibit unit extinction and a few of them display undulose extinction. Qp grains are composed mainly of non-oriented crystallites, commonly with two, three, or more crystals per grain with straight to equant to concave-convex boundaries. Inclusions are present both in monocrystalline and polycrystalline grains, but they are more common in Qm. They include zircon, tourmaline, and rutile.

Feldspars: Feldspars are the important constituent among the detrital framework grains of Dhandraul sandstone. Point count data indicate that feldspars constitute 0.00-1.07% with an average 0.12% of the total rock components (Table 2). Feldspars are present in the form of potassium and plagioclase feldspar. Potassium feldspar has been found as microcline and orthoclase (Fig. 5.1b). Orthoclase was identified in most cases by its cloudy appearance although a few grains exhibit carlsbad twinning, whereas, microcline was recognized by its typical crosshatch twinning.

Mica: Micas form a minor component in the analyzed samples and are usually muscovites, which are locally kaolinitised and display fish-tail splaying and lattice expansion (Fig. 5.1c). Possible biotite fragments are also recorded.

Lithic fragments: Lithic fragments occur as clusters of multiple grains that are represented by metamorphic, volcanic, clastic and non-clastic lithic fragments. Lithic metamorphic grains are found to be more abundant than the lithic sedimentary grains (Table 2). Very few or traces of lithic volcanic grains are found. Lithic sedimentary grains are dominantly sand/siltstone fragments. Chert fragment (Fig. 5.1d) is next to sand/siltstone rock fragments**.**

Heavy minerals: Heavy minerals form a minor constituent (0.00-1.11%) of the sandstones and include rounded to well-rounded grains of zircon (Fig. 5.1e), tourmaline, epidote and opaque minerals (Table 2). The dominant accessory heavy minerals are composed mainly of opaque minerals (Fig. 5.1f). Grains of heavy minerals are very fine and show moderate abrasion.

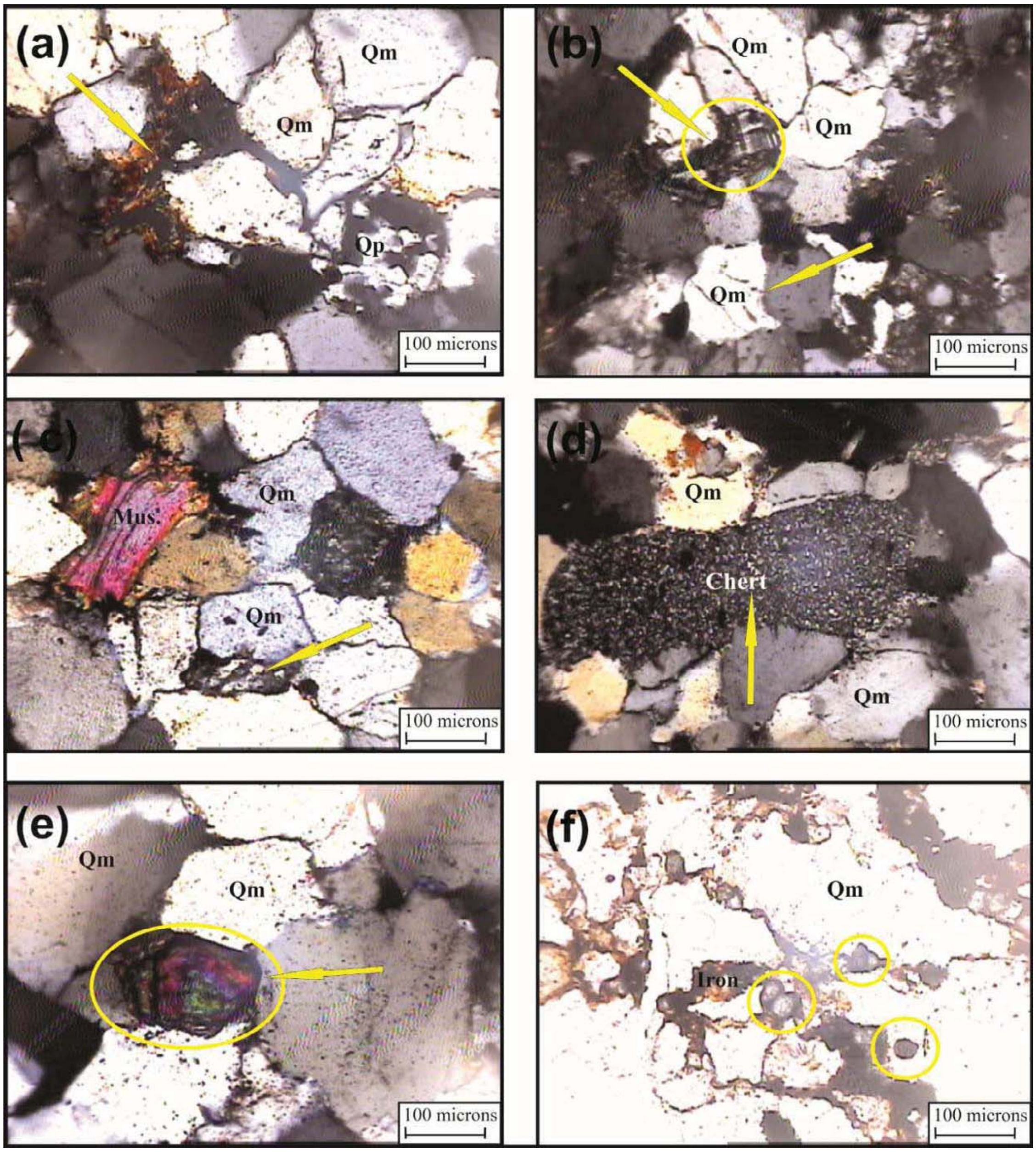


Fig. 5.1. Representative photomicrographs of Dhandraul Sandstone from UKG showing (a) pore-filling iron oxide cement engulfed and stained quartz, monocrystalline quartz grains (Qm) are subangular to subrounded (b) Optical micrograph showing microcline grain (circle) and Qm fractured quartz due to mechanical compaction (c) Detrital muscovite grain has higher interference colour and partially altered along their margin (d) Lithic chert grain (e) Rounded grain of zircon as indicator of recycling (f) Optical micrograph of opaque minerals (circle), Plane polarized light.

Petrographic Analysis of the Scarp Sandstone

Results obtained from plots on the QFL diagram shows that the Scarp sandstone are quartz arenites and sub-litharenites (Folk, 1980) with an average modal composition of ($Qt_{99}\,F_{0\cdot2}L_{0.8}$).

Mineralogical Composition

Quartz: Quartz is the dominant detrital constituent in all samples. The main quartz type is monocrystalline quartz (Qm), and the amount of polycrystalline quartz (Qp) ranges widely, from 1.35-19.84%. Qm is mostly sub-angular with minor angular and sub-rounded grains, ranging from 82.22-96.71% and showing undulose to blocky extinction (Fig. 5.2a). Some of the Qm grains are pitted along their margins. The quartz grains contain inclusions of zircon, tourmaline or microlites (Fig. 5.2b). Some grains are fractured and cloudy in appearance.

Feldspar: The occurrence of feldspar in the Scarp sandstone is comparatively higher to Dhandraul sandstone, units of the UKG. Feldspars are short column-shaped and sub-rounded, consisting of potash feldspar (0-2.28%). As potash feldspars are readily altered, their surfaces are not always clear. Some potash feldspar grains are altered to clay minerals (Fig. 5.2c). The plagioclase grains are mainly tabular, showing polysynthetic twinning. Some of the plagioclase grains are altered to sericite. The microcline grains are 0.3–0.6 mm and sub-angular to sub-rounded, showing crosshatch twinning. The low occurrence of feldspars may be due to the unstable nature of the mineral, because feldspar easily alters to clay minerals during weathering, abrasion and prolonged transportation. The absence of feldspars may suggest that the sediments are derived from a recycled source.

Mica: Muscovite and biotite are present in the studied sandstones as detrital grains. Both muscovite and biotite occur as tiny to large elongate flakes with frayed ends. The percentage of mica in Scarp sandstone ranges from 0 to 3.25% with an average 1.34%. Detrital

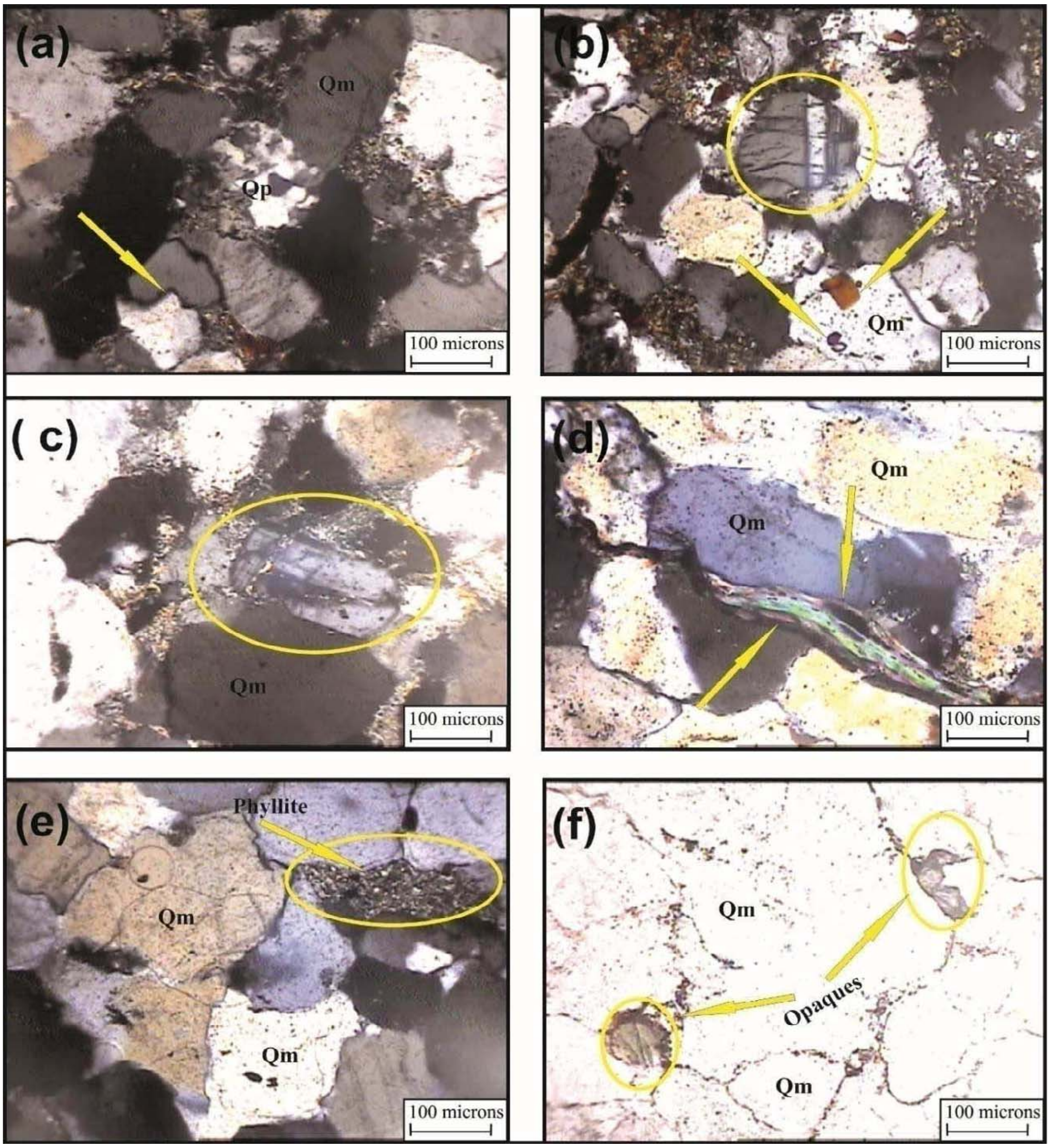


Fig. 5.2. Representative photomicrographs of Scarp sandstone from UKG showing (a) Photomicrograph showing monocrystalline quartz (Qm) grains with a few polycrystalline quartz (Qp) grains, see also the concavo-convex grain to grain contacts. (b) Inclusion of zircon in non-undulose monocrystalline quartz grain (arrow); altered microcline (circle) (c) Matrix around altered K-feldspar grain (d) Optical micrograph of deformed mica flakes, squeezed between detrital quartz grains due to mechanical compaction (e) Lithic fragment (phyllite) (f) opaque minerals in engulfed between monocrystalline quartz, plane polarized light.

mica grains are of two varieties which are brown and green colour. Detrital mica grains of relatively large size occur with defined detrital boundaries. Some of the mica grains appear to have been formed by recrystallization of clay minerals during deformation. In addition, detrital mica grains usually show the effect of compaction. The large laths of mica show bending and kinking around detrital grain as a result of compaction (Fig. 5.2d). Such grains are seen to occur around the adjacent quartz grains.

Lithic fragments: Lithic fragments in the Scarp sandstone of the UKG consist metamorphic and sedimentary lithic fragments. Sedimentary lithic fragments are most common and contain claystone/ shale and siltstone fragments**.** Metamorphic lithic fragments are limited to mainly schist plus a few phyllite grains (Fig. 5.2e).

Heavy Minerals: Heavy minerals in Scarp sandstone range from 0 to 0.54% with average 0.09%. The dominant heavy minerals are zircon, epidote, tourmaline and opaque minerals (Fig. 5.2f).

BULK MINERALOGY (XRD)

The X-ray diffraction pattern of the sandstone and shale of the UKG rocks are illustrated in Fig.6. The bulk mineralogy (XRD patterns) mainly reveals the presence of quartz (3.34Å and 1.82Å peak), and mixed layer illite/mica (9.8Å), However, the primary peak of mica is not identified because of dominance of quartz peaks. The minor amounts of illite (9.8Å), kaolinite (7.17Å) and (3.58Å) are clearly observed. Based on relative intensity of characteristic peaks, it is noticed that quartz is the abundant mineral followed by illite, kaolinite, mica and feldspar (Fig. 6 a, b and c). Semi-quantitative analysis as described by Moore and Reynolds (1997) and Srodon (2006) also suggests quartz is the most abundant mineral (average ~95%) followed by illite (average ~2%), kaolinite (average ~1%), mica (~1%) and K-feldspar and plagioclases (~1%). Dhandraul sandstone chiefly consists of quartz and deficient in clay minerals. Similarly, the Scarp sandstone has quartz (90–100%) and illite (<5%). However, slightly increased

Table 2. Mineralogical composition of upper Kaimur Group rocks, Son valley

	Monocrystalline quartz	Polycrstalline quartz		Feldspar		Mica		Chert	Rock fragments	Heavy minerals
	Common quartz	Recrystallized metamorphic quartz	Stretched metamorphic quartz	Plagioclase	Microcline	Muscovite	Biotite			
Dhandraul Sandstone										
Range	83.02-97.46	0.00-4.17	0.87-13.27	0.00-0.39	0.00-1.06	0.00-10.46	0.00-0.87	0.00-1.47	0.00-2.77	0.00-1.11
Average	91.49	1.2	4.88	0.02	0.1	1.37	0.07	0.32	0.36	0.19
Scarp Sandstone										
Range	82.22-96.71	0.00-2.80	1.35-17.04	0.00-0.35	0.00-1.93	0.00-2.64	0.00-0.61	0.00-1.70	0.00-0.62	0.00-0.54
Average	90.88	0.6	6.16	0.03	0.13	0.08	1.26	0.72	0.05	0.09

Table 3. Percentage of framework mode of sandstones of upper Kaimur Group, Son valley

	Qt	F	L	Qm	F	Lt	Qp	Lv	LS	Qm	P	K
Dhandraul Sandstone												
Range	98.20-100.00	0.00-1.07	0.00-4.23	71.43-98.23	0.00-1.07	1.77-28.57	72.22-100.00	0.00-56.00	0.00-17.20	99.13-100.00	0.00-0.47	0.00-1.26
Average	99.04	0.12	0.84	92.2	0.12	7.67	89.86	5.67	4.47	99.86	0.03	0.11
Scarp Sandstone												
Range	97.15-100.00	0.00-2.32	0.00-1.50	82.84-96.71	0.00-0.00	3.29-17.16	54.55-100.00	0.00-8.20	0.00-45.45	97.44-100.00	0.00-0.39	0.00-2.17
Average	99.06	0.16	0.78	92.34	0.00	7.66	87.74	0.61	11.65	99.82	0.04	0.14

Note: 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

percentage of clay minerals are observed in the Bijaigarh shale in comparison to Dhandraul and Scarp sandstones.

Moreover, feldspar is the less frequent (~1%) non clay mineral in the upper Kaimur Group sandstone. Low values of feldspar may indicate intensive recycling, dissolution, and kaolinitization. The origin of kaolinite in the studied sandstones and shale has been previously interpreted as being a product of chemical weathering and leaching of rocks which occur especially in the exposed basement areas of the Mahakoshal belt and the Chhotanagpur gneissic complex. Kaolinite formation is favored under tropical to sub-tropical humid climatic conditions (Chamley, 1989; Hallam et al. 1991). In addition to a detrital origin, kaolinite may also develop by diagenetic processes due to the circulation of acid solutions (Ghandour et al. 2003). Presence of illite and kaolinite suggests prominent chemical weathering of feldspar (albite or K-feldspar) and mica (muscovite). Under acidic conditions, weathering or hydrothermal alteration of alumino-silicate minerals (feldspar) facilitate leaching of Na, Ca, Mg and Fe ions (Sheldon and Tabor, 2009). The presence of kaolinite and absence of illite/smectite mixed-layer aggregates indicates sedimentary origin under continental weathering condition in non-marine environment.

MAJOR ELEMENT GEOCHEMISTRY

The major-oxide concentrations of the Dhandraul sandstone (DS), Scarp sandstone (SS) and Bijaigarh shale (BS) of the upper Kaimur Group, Son valley are given in (Table 4). The table also shows accuracy of measurements for major oxides, given in terms of % deviation (Δ%) of measured value from the true/representative value and similarly for trace elements.

The sandstones of the upper Kaimur Group have higher SiO_2 (DS= av. 93.13%, SS= av. 90.92), and correspondingly lower Al_2O_3 (DS= av. 4.05%, SS= 5.46%), K_2O (DS=av. 1.03%, SS=av. 1.16%), Fe_2O_3 (DS=av. 0.60%, SS=av. 1.13%), MgO (DS= av. 0.0%, SS= av. 0.05%) CaO (DS= av. 0.79%, SS=0.80%) contents. Bijaigarh shales contain SiO_2 (av. 75.98%), Al_2O_3 (av. 14.60%), K_2O (av. 2.81%), Fe_2O_3 (av. 4.09%), MgO (av. 0.83%) and CaO (av. 0.76%). All the major elements except SiO_2 increase in their concentration from the Dhandraul sandstone to the Bijaigarh shale. Although the main source of silica is attributed to quartz, it is not unlikely that Al-bearing minerals also contributed to it. Likely, Al_2O_3 and K_2O contents may be related to the presence of K-feldspars and also K-bearing clay minerals. The upper Kaimur Group of rocks possesses low concentrations of Na_2O, TiO_2, MgO, CaO and NiO. The source of Na_2O is principally plagioclase feldspar. Opaque minerals and rutile are main source of TiO_2. MgO content is mainly related to the presence of ankerite and dolomite cements. Fe_2O_3 concentrations may be related to the abundance of iron oxide heavy minerals and partly to Fe-containing clay minerals. Carbonate cement and diagenesis of plagioclase are the key sources for CaO.

The depletion of Na_2O (<1%) in the upper Kaimur Group of rocks can be attributed to a relatively smaller amount of Na-rich plagioclase. K_2O and Na_2O contents and their ratio ($K_2O/Na_2O > 1$) are consistent with the petrographic observations, wherein K-feldspar dominates over plagioclase feldspar. A higher K_2O/Na_2O ratio (av. DS= 5.42%, SS= 6.01%, BS=13.73%) indicates gradual dominance of the feldspar from DS to BS. Since Al_2O_3 primarily resides in feldspars and TiO_2 in mafic minerals, the Al_2O_3/TiO_2 ratio (av. DS= 40.75%, SS= 31.13%, BS=26.91%) indicates that the sediments of these rocks come from felsic source. This is also supported by the low content of MgO in these rocks (av. DS=<0.01%, SS=0.05% and BS=0.83%). However, a relatively high concentration of Fe_2O_3 (DS=av. 0.60%, SS=av. 1.13%, BS=av. 4.09%) in the Dhandraul sandstone, Scarp sandstone and Bijaigarh shale could be attributed to the presence of ferruginous cement.

To assess the mobility of elements during weathering and transport, major oxides are plotted against immobile Al_2O_3 (Fig. 7). For comparison average values of upper continental crustal (UCC; Rudnick and Gao, 2003) and Post-Archean Australian Shale (PAAS; Taylor and McLennan, 1985) are also shown. The upper Kaimur Group sandstones show depletion in major elements, except for SiO_2, relative to the UCC and PAAS abundances. In comparison to sandstones,

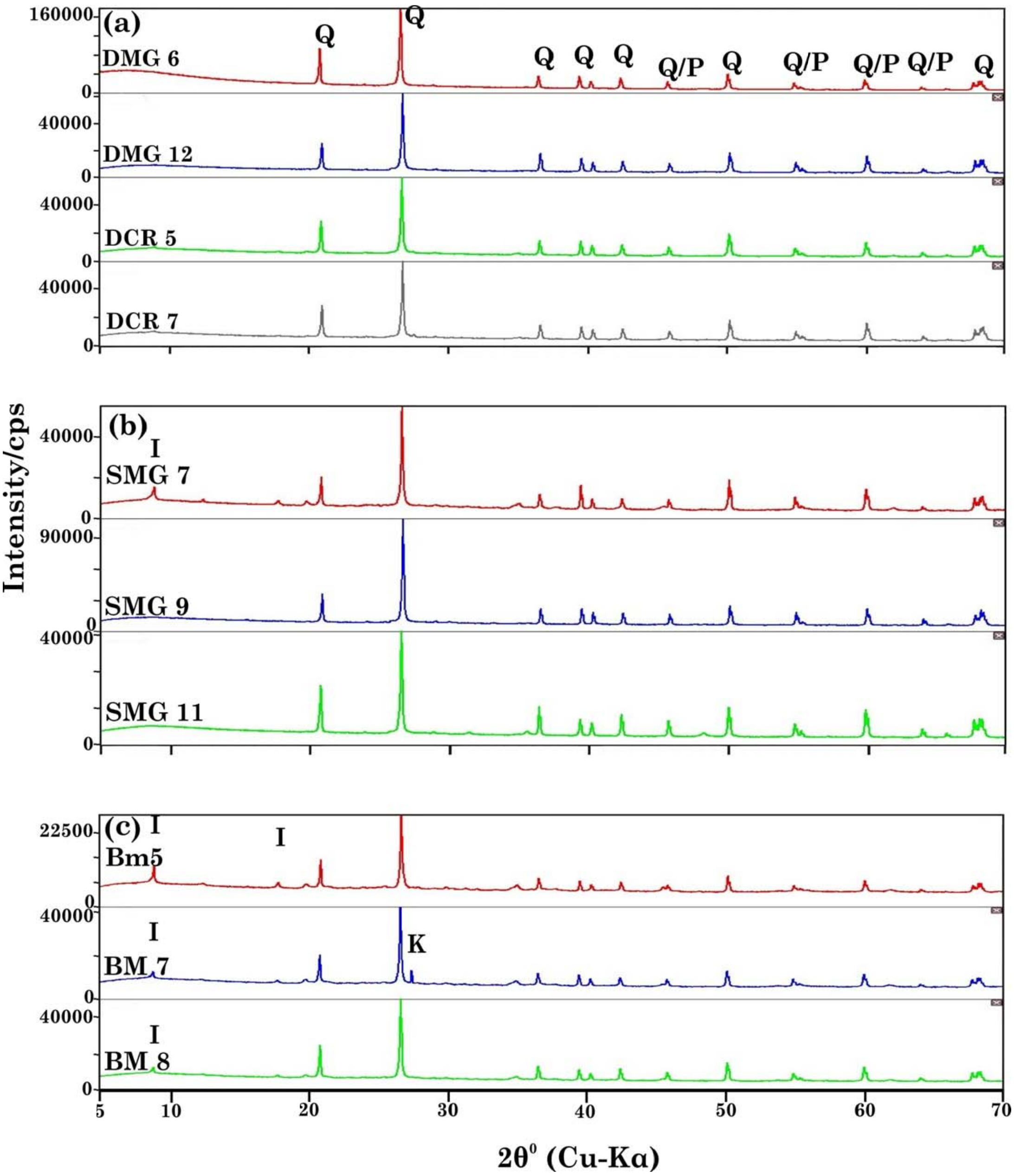


Fig. 6. X-ray diffractometer patterns of the clastic rocks of the upper Kaimur Group **(a)** Dhandraul sandstone **(b)** Scarp sandstone **(c)** Bijaigarh shale. (Q=Quartz, I=Illite and K=Kaolinite).

Bijaigarh shale shows PAAS like composition for SiO_2, Al_2O_3, Fe_2O_3, K_2O and MgO, and clear depletion in MnO, TiO_2, Na_2O, P_2O_5 and CaO. More depletion of CaO and Na_2O relative to K_2O indicates weathering of plagioclase to be dominant in the Bijaigarh shale compared to K-feldspar (Nesbitt et al. 1980).

The correlation between SiO_2 and Al_2O_3 is negative for the studied sandstone samples (r = -1.0 for Dhandraul sandstone, r = -1.0 for Scarp sandstone and r = -1.0 for Bijaigarh shale; **(**Table 5 a-c**)**. Such correlation is expected, because in sedimentary rocks the Al_2O_3 and SiO_2 contents are controlled by aluminous clay and quartz content respectively. A positive correlation between K_2O and Al_2O_3 (Dhandraul sandstone: r = 0.96, Scarp sandstone: r=1.0 and Bijaigarh shale: r=0.93) implies that the concentrations of the K-bearing minerals have significant influence on Al distribution and suggests that the abundance of these elements is primarily controlled by the content of clay minerals (McLennan et al. 1983; Jin et al. 2006; Akarish and El-Gohary, 2008). Al_2O_3 and TiO_2 are moderately positively correlated in the upper Kaimur Group rocks (r= -0.01 for Dhandraul Sandstone, r=0.95 for Scarp Sandstone and r=0.98 for Bijaigarh shale). Since, Al and Ti are immobile elements they are enriched in the residual weathering profile. The binary mixing of these components in sediments gives rise to their moderate to strong correlation (Young and Nesbitt, 1998).

Essentially, the upper Kaimur Group of rocks is depleted in most of the major oxides except SiO_2 (due to enrichment in quartz and chert), suggesting an intense degree of weathering and reworking that removed ferromagnesian minerals and feldspars. Using the geochemical classification diagram of Herron (1988) and Pettijohn et al. (1972), the studied rocks of the upper Kaimur Group – the Dhandraul sandstone, Scarp sandstone and Bijaigarh shale are quartz arenite, sub-lithicarenite to lithicarenite and lithicarenite to shale in composition, respectively (Fig. 8 a and b). Due to the gradational behavior of the major and trace elements in these three rock types from the Bijaigarh shale to the Dhandraul sandstone, they have been considered as a single sequence irrespective of the stratigraphy where they have been defined as different members. The depletion of Na_2O content in the upper Kaimur Group sandstone and shale (0.14-0.22%) can be attributed to the relative absence of Na plagioclase. K_2O (0.09-3.39%) and Na_2O (0.14-0.22%) contents and their ratios (0.66-17.30%) are

Table 4. Major element oxide abundances (wt%) in the upper Kaimur Group of rocks obtained from XRF analysis

Sample ID	Dhandraul Sandstone						Scarp Sandstone						Bijaigarh Shale		
	DS6	DS9	DS12	DS2	DS5	DS7	SS7	SS8	SS9	SS4	SS10	SS11	BS5	BS7	BS8
Al_2O_3	0.52	1.65	1.51	8.22	8.65	3.78	14.29	9.05	2.92	2.14	1.99	2.35	17.76	14.53	11.52
Fe_2O_3	0.38	0.58	0.43	1.01	0.80	0.43	1.36	1.61	1.46	1.28	0.60	0.47	5.00	4.32	2.94
SiO_2	98.08	96.24	96.70	86.91	87.46	93.40	79.29	86.05	93.69	94.92	95.88	95.69	70.64	75.68	81.62
CaO	0.67	0.78	0.77	0.98	0.83	0.70	0.71	0.84	0.82	0.82	0.79	0.79	0.82	0.74	0.71
MgO	0.00	0.00	0.00	0.00	0.01	0.00	0.28	0.01	0.00	0.00	0.00	0.00	1.18	0.74	0.58
K_2O	0.09	0.28	0.28	2.28	1.87	1.36	3.39	1.97	0.47	0.38	0.36	0.39	3.33	3.11	1.99
Na_2O	0.14	0.21	0.17	0.22	0.19	0.15	0.20	0.20	0.18	0.19	0.18	0.17	0.22	0.20	0.19
P_2O_5	0.03	0.05	0.03	0.23	0.05	0.09	0.05	0.06	0.34	0.12	0.08	0.04	0.34	0.08	0.04
TiO_2	0.07	0.19	0.09	0.11	0.11	0.07	0.41	0.18	0.09	0.12	0.09	0.09	0.68	0.59	0.38
MnO	0.02	0.02	0.02	0.04	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.02
NiO	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
MgO/K_2O	0.00	0.00	0.00	0.00	0.01	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.35	0.24	0.29
Na_2O/K_2O	1.51	0.77	0.61	0.09	0.10	0.11	0.06	0.10	0.39	0.50	0.50	0.43	0.07	0.06	0.10
K_2O/Na_2O	0.66	1.30	1.63	10.53	9.59	8.79	17.30	9.94	2.53	1.99	2.01	2.31	15.18	15.80	10.23
K_2O/Al_2O_3	0.18	0.17	0.19	0.28	0.22	0.36	0.24	0.22	0.16	0.18	0.18	0.17	0.19	0.21	0.17
SiO_2/Al_2O_3	190.43	58.49	64.01	10.58	10.11	24.69	5.55	9.50	32.06	44.31	48.21	40.75	3.98	5.21	7.08
Fe_2O_3/K_2O	4.04	2.09	1.53	0.44	0.43	0.32	0.40	0.82	3.14	3.39	1.67	1.21	1.50	1.39	1.48
Al_2O_3/TiO_2	7.60	8.67	16.82	75.31	81.92	54.19	35.15	51.30	31.84	17.88	23.10	27.54	25.99	24.79	29.95
CIA	55.80	44.25	43.17	64.02	69.23	55.81	73.00	69.41	55.93	49.17	48.26	52.40	76.48	74.27	75.36
CIW	26.22	48.15	47.26	79.30	82.56	71.29	89.86	82.97	61.89	54.26	53.32	57.86	90.56	89.69	87.73
PIA	22.19	43.15	41.73	72.81	78.40	60.27	86.82	78.84	57.34	48.98	47.86	52.96	88.43	86.99	85.32
ICV	3.71	1.65	1.59	0.66	0.53	0.90	0.52	0.59	1.16	1.50	1.34	1.10	0.71	0.72	0.66

Table 5. Correlation Coefficient of (a) Dhandraul sandstones, (b) Scarp sandstones, (c) Bijaigarh shales

	SiO_2	Al_2O_3	TiO_2	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
(a) Dhandraul Sandstone										
SiO_2	1.00									
Al_2O_3	-1.00	1.00								
TiO_2	-0.01	-0.01	1.00							
Fe_2O_3	-0.90	0.88	0.30	1.00						
MnO	-0.84	0.82	0.07	0.95	1.00					
MgO	-0.57	0.63	0.00	0.38	0.30	1.00				
CaO	-0.79	0.76	0.32	0.94	0.92	0.18	1.00			
Na_2O	-0.57	0.54	0.78	0.80	0.63	0.19	0.83	1.00		
K_2O	-0.97	0.96	-0.11	0.83	0.78	0.44	0.72	0.46	1.00	
P_2O_5	-0.70	0.64	0.04	0.78	0.80	-0.18	0.80	0.53	0.77	1.00
(b) Scarp Sandstone										
SiO_2	1.00									
Al_2O_3	-1.00	1.00								
TiO_2	-0.95	0.95	1.00							
Fe_2O_3	-0.57	0.52	0.42	1.00						
MnO	-0.48	0.50	0.30	0.19	1.00					
MgO	-0.86	0.86	0.97	0.25	0.18	1.00				
CaO	0.57	-0.60	-0.77	0.19	-0.04	-0.89	1.00			
Na_2O	-0.76	0.73	0.65	0.87	0.18	0.47	-0.05	1.00		
K_2O	-1.00	1.00	0.96	0.49	0.47	0.88	-0.63	0.72	1.00	
P_2O_5	0.30	-0.35	-0.35	0.37	-0.41	-0.30	0.39	-0.06	-0.37	1.00
(c) Bijaigarh Shale										
SiO_2	1.00									
Al_2O_3	-1.00	1.00								
TiO_2	-0.99	0.98	1.00							
Fe_2O3	-0.99	0.98	1.00	1.00						
MnO	-0.89	0.92	0.81	0.81	1.00					
MgO	-0.95	0.97	0.90	0.90	0.99	1.00				
CaO	-0.96	0.98	0.90	0.91	0.98	1.00	1.00			
Na_2O	-0.88	0.91	0.80	0.80	1.00	0.98	0.98	1.00		
K_2O	-0.95	0.93	0.99	0.99	0.70	0.81	0.82	0.68	1.00	
P_2O_5	-0.90	0.93	0.82	0.83	1.00	0.99	0.99	1.00	0.72	1.00

also consistent with the petrographic observations. Furthermore, Al_2O_3 content is low in upper Kaimur Group sandstone and shale (0.52-17.76%), supporting the minor presence of K-feldspar, clay minerals, and mica. Similarly, low concentrations of TiO_2 (0.07-0.68%) reflect less abundances of Ti-opaque minerals and rutile in the analyzed samples. On the other hand, TiO_2 vs. Zr (ppm) plot of Hayashi et al. (1997) shows that rocks of the upper Kaimur Group are primarily derived from felsic igneous rocks (Fig. 9a).

TRACE-ELEMENT GEOCHEMISTRY

Trace elements (e.g. Zr, Y, Hf, Sc, Nb, Th and REE) in clastic sedimentary rocks are considered to be immobile during weathering,

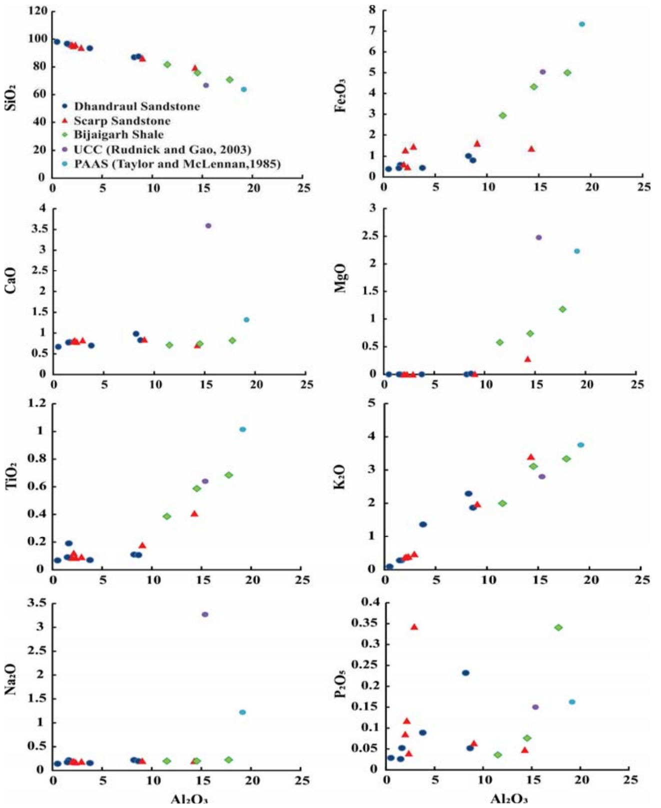


Fig. 7. Variation in major oxides abundances vs. Al_2O_3 content of UKG rocks; data shown are in wt%. Also, shown for comparison with upper continental crust (UCC) abundances from Rudnick and Gao, (2003) and Post-Archean Australian Shale (PAAS) abundances from Taylor and McLennan, (1985).

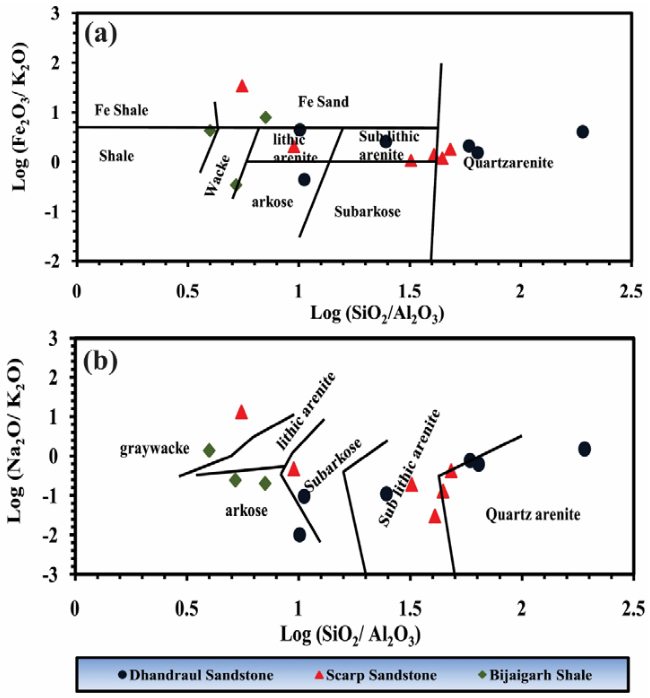


Fig. 8. Chemical classification of the UKG of rocks based on **(a)** The log (SiO_2/Al_2O_3) vs. log (Fe_2O_3/K_2O) diagram after Herron, (1988) and **(b)** The log (SiO_2/Al_2O_3) vs. log (Na_2O/K_2O) diagram after Pettijohn et al., (1972).

diagenesis and low to moderate grade of metamorphism; and their signatures are commonly preserved in sedimentary rocks (Bhatia and Crook, 1986; McLennan et al. 1993). Hence, the trace elements ratios are representative of provenance, tectonic setting and paleo-environment conditions (Bhatia and Crook, 1986; Nesbitt et al. 1996; McLennan, 2001).

The trace element concentrations and elemental ratios are presented in Table 6. The Dhandraul sandstone show higher concentrations of Zr (av. 86.16 ppm), La (av. 23.33 ppm), Ce (av. 38.16 ppm), Rb (av. 29.5 ppm), Sr (30.5 ppm), Ba (4.33 ppm), Y (9 ppm), V (21.16 ppm) and Th (3.66 ppm) with respect to Scarp sandstone. The trace elements show variable concentrations both in Dhandraul and Scarp sandstones. Dhandraul sandstone have higher concentrations of Zr, Sc, Y and V, whereas Scarp sandstone shows higher Nb, Th, Rb, Ce, Nd and Sm. Bijaigarh shale shows higher values of Ba (av. 287 ppm), Sr (av. 121.33 ppm), Ce (av. 111.66 ppm), Zr (av. 95 ppm), Y (Av. 73.33 ppm) and La (av. 66.66 ppm).

In view of their immobile character, Hf, Th and La concentrations have been used to determine the provenance and tectonic setting of upper Kaimur clastics. In Hf–La/Th diagram (Floyd and Leveridge, 1987; Hayashi et al. 1997) majority of the samples of the clastic rocks of the upper Kaimur Group plots in the field of acidic source (Fig. 9b).

DISCUSSION

Tectonic Setting

The tectonic setting of the provenance for the UKG sandstones has been determined using the ternary Qt-F-L, Qm-F-Lt, Qp-Lv-Ls and Qm-P-K diagrams (Dickinson and Suezek, 1979; Dickinson et al. 1983). The Qt-F-L plot emphasizes the grain stability and maturity, relief in the provenance, transport mechanism and the source rock composition. The Qm-F-Lt 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). 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 sub-fields, as described in Fig. 10 A-D. 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 UKG sandstones.

In the Qt-F-L diagram of Dickinson and Suczek (1979), (Fig. 10A), the majority of sandstone samples plot in the continental block provenance with stable craton and uplifted basement source. In the Qm-F-Lt plot (Fig. 10B), the samples fall in the continental block provenance with almost equal contribution from recycled orogen provenance and mixed provenance. More than half of the samples plot in the subduction complex field in the Qp-Lv-Ls provenance diagram (Fig. 10C). In the Qm-P-K provenance diagram, samples from the UKG have higher maturity or stability (Fig.10D), which is also confirmed by outcrop observations.

In the Qt-F-L diagram all the UKG sandstones show a craton interior continental block provenance (Fig. 10A). Few samples from the Dhandraul sandstones have shifted from the craton interior field to the recycled orogen 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 enhancing the L pole of the ternary plot and weakening the F pole. Therefore, the general petrographic attributes and various diagrams to determine provenance suggest a mixed source for the sandstones of UKG.

In the Qm-F-Lt diagram the UKG sandstones fall in the field of the craton interior continental block provenance with minor

Table 6. Selective trace elements abundances (ppm) in the Upper Kaimur Group of rocks

Sample	Dhandraul Sandstone						Scarp Sandstone						Bijaigarh Shale		
ID	DS6	DS9	DS12	DS2	DS5	DS7	SS7	SS8	SS9	SS4	SS9	SS11	BS5	BS7	BS8
Ba	0	0	0	14	0	12	0	0	0	0	0	0	592	166	103
Sr	28	43	15	44	31	22	62	28	14	11	21	15	281	51	32
Zr	40	220	71	68	68	50	231	67	45	57	53	32	155	307	123
Y	8	12	6	11	9	8	15	6	0	0	4	0	163	38	19
Hf	1.3	6	2	1.7	1.8	1.3	6	1.8	1.2	1.5	1.3	0.8	3.4	8	3.4
Sc	12	13	11	11	12	11	12	11	9	9	11	12	17	13	14
Nb	1	3	3	2	1	1	8	3	1	1	5	6	11	12	6
Th	2	3	3	5	5	4	16	6	0	0	3	2	19	17	9
U	5	4	3	3	4	4	6	4	1	3	3	3	6	4	4
Rb	5	8	8	61	48	47	115	42	11	10	9	9	162	137	106
La	26	29	22	21	26	16	30	24	20	17	30	20	129	31	40
Ce	45	55	27	34	44	24	62	42	42	35	48	34	200	66	69
Nd	1	3	3	2	1	1	8	3	1	1	5	6	11	12	6
Sm	2	0	0	1	4	1	3	1	3	2	0	0	18	8	7
Eu	1	1	0	0	0	0	2	1	0	0	1	0	4	1	2
Yb	1	1	1	1	1	1	1	1	0	0	1	1	16	4	2
V	14	34	18	19	30	12	46	12	19	24	8	11	98	81	57
Zn	0	2	0	2	3	1	7	3	2	4	0	0	38	23	18
Th/U	0.40	0.75	1.00	1.67	1.25	1.00	2.67	1.50	0.00	0.00	1.00	0.67	3.17	4.25	2.25
Rb/Sr	0.18	0.19	0.53	1.39	1.55	2.14	1.85	1.50	0.79	0.91	0.43	0.60	0.58	2.69	3.31
La/Th	13.00	9.67	7.33	4.20	5.20	4.00	1.88	4.0	-	-	10.0	10.0	6.79	1.82	4.44

contribution from quartzose recycled orogen provenance (Fig. 10B). However, it should be considered that in the Dhandraul and Scarp sandstones of the UKG, the feldspars and the lithic grains like cherts may have been removed 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. Conversely, like the feldspars, the lithic fragments like cherts, too, must also have suffered dissolution during diagenesis.

Although chemical components can be altered by diagenesis during plate tectonic movements, the major element compositions of sandstones can still be used to interpret the tectonic setting of the provenance to supplement petrographic analysis (e.g. Bhatia, 1983; Roser and Korsch, 1986; Yan et al. 2007; Perri, 2014). Roser and

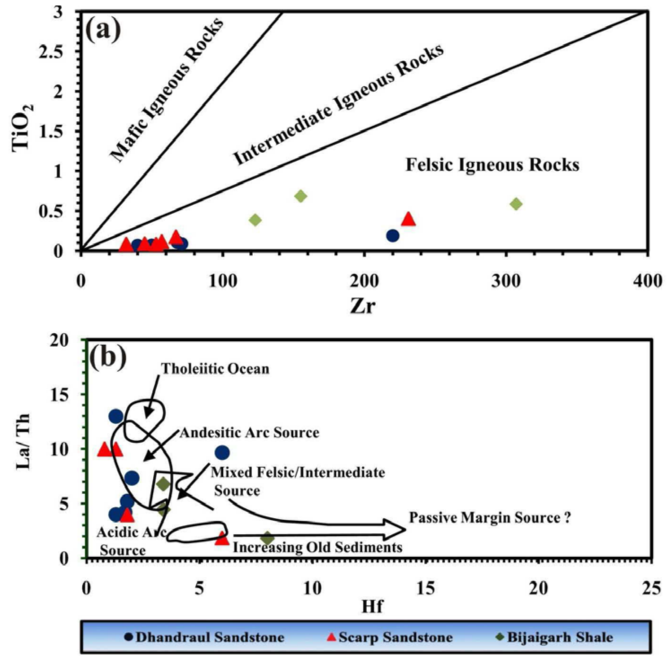


Fig. 9. (a) TiO_2 versus Zr plot after Hayashi et al., 1997 for the UKG of rocks **(b)** La/Th versus Hf diagram to ascertain tectonic setting of the UKG of rocks (after Floyd and Leveridge, 1987).

Korsch, (1986) used a discrimination diagram (K_2O/Na_2O vs. SiO_2) to determine the tectonic setting of the sandstone–mudstone suites that shows increase in SiO_2 content and K_2O/Na_2O values from volcanic arc to active continental margin to passive margin settings. Bhatia (1983) also discriminated tectonic settings of Paleozoic greywacke sandstones on the basis of major element data and oceanic island arc (OIA), continental island arc (CIA), active continental margin (ACM) and passive margin (PM) settings. Subsequently, tectonic discrimination diagrams (Fig. 11a and b) after Roser and Korsch (1988) and Bhatia (1983) respectively suggests passive continental margin setting for both sandstones as well as for shale of the UKG. The collective petrographic and geochemical data strongly suggest that the UKG sandstone and shale are derived from granites and low grade metamorphic rocks and deposited in passive continental basin. Further the chemical characteristics of the UKG sandstone and shale (e.g. high SiO_2/Al_2O_3, K_2O/Na_2O, Al_2O_3/TiO_2; see Table 4), suggest that they are derived from old upper continental crust and/or old continental foundations of passive tectonic settings.

Source Area Weathering

The intense chemical weathering of the upper crust leads to the alteration of feldspars and the neo-formation of clay minerals. In addition, during weathering processes the Ca^{2+}, Na^{1+}, and K^{1+} are removed from feldspars (Nesbitt et al. 1980). Chemical Index of Alteration (CIA; Nesbitt and Young, 1982) is widely used to determine the intensity of chemical weathering. For this study, CaO was corrected following the procedure proposed by McLennan et al. (1993). The CIA values of the Dhandraul sandstone and Scarp sandstone have wide range 44.25–69.23 and 48.26–73 respectively whereas Bijaigarh shale ranges from 74.27–76.48 (Table 4). These CIA values of the upper Kaimur Group sandstones and shale indicate low to moderate degree of chemical weathering, which may reflect humid conditions in the source area.

Furthermore paleoweathering conditions can also be detected using the Al_2O_3–CaO + Na_2O–K_2O (A–CN–K) ternary diagram of Nesbitt and Young (1984) (Fig. 12). In the A-CN-K plot, the upper Kaimur Group samples plot near the plagioclase-K-feldpar join indicating low to moderate chemical weathering in the source area (Nesbitt and Young, 1984). All the samples analyzed here plot parallel to the A-CN line (Fig. 12), and the normal weathering is recorded towards illite

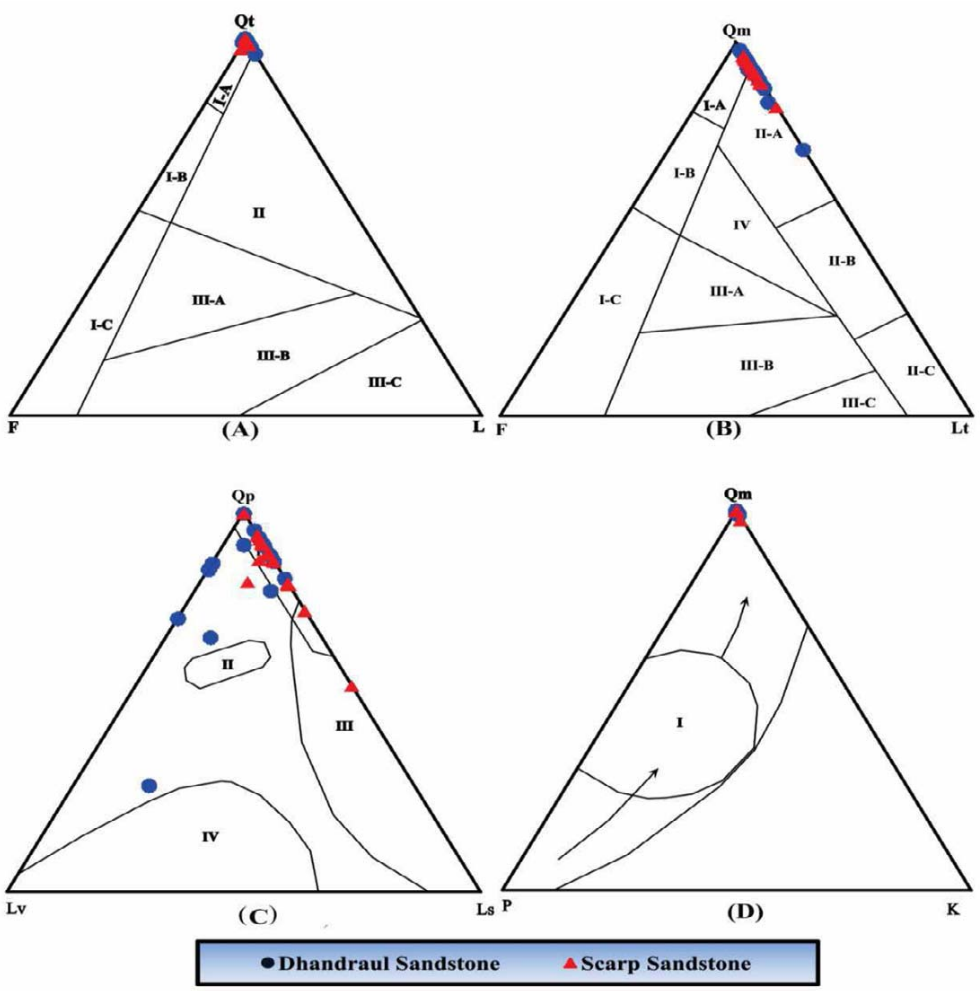


Fig. 10. Classification of the sandstones of UKG (according to Dickinson, 1985). The provenance field in **(A)** and **(B)** are **Continental Block (I):** I-A: Craton Interior, I-B: Transitional Continent, I-C: Continent uplift, **Recycled Orogen (II):** II-A Quartzose, II-B: Transitional, II-C: Lithic **Magmatic Arc (III):** III-A: Dissected, III-B: Transitional III-C: Undissected and Mixed (IV). In **(C),** Rifted continental margin: I, Subduction complex: II, Collision suture and fold thrust belt: III, Arc Orogen: IV, whereas in **(D)**, Circum pacific volcano plutonic suites: (I), the arrow indicates maturity and stability from continental block provenance

indicating the presence of more illite than kaolinite and smectite which is confirmed by the bulk mineralogical analysis also. Some samples plotted towards illite are interpreted to be the effect of potassium metasomatism, where postdepositional processes convert kaolinite to illite; however, there is no conversion trend observed toward K_2O. From the ternary diagram, the samples mostly plotted between average granite and granodiorite line, suggesting the protolith of the area to be of intermediate to felsic source rocks.

Furthermore, Harnois (1988) suggested the use of Chemical Index of Weathering [CIW= (CIA-K) = $Al_2O_3/(Al_2O_3 + CaO^* + Na_2O)^* 100$], to characterize weathering intensity. The CIW index is similar to CIA value except that in the CIW index K_2O is not considered. This is because K_2O does not account for the Al associated with K-feldspar and during weathering it may be leached or may accumulate in the residue (Harnois, 1988). K^+ ions are adsorbed to the negatively charged clay surfaces or often removed by fluid migration (Kronberg et al. 1987). So, generally CIW values are higher than CIA values. The CIW values of the Dhandraul sandstone, Scarp sandstone and Bijaigarh shale ranged from 26.22 to 82.56 (avg. 59.13); 53.32 to 89.86 (avg. 66.70), and 87.73 to 90.56 (avg. 89.32) respectively, (Table 4) which further reflects that the studied sediments are weathered low to moderate chemically.

Chemical weathering can also be calculated by plagioclase index of alteration (PIA; Fedo et al. 1995), especially when the plagioclase weathering needs to be monitored. It is defined as PIA = $[(Al_2O_3\text{-}K_2O)/(Al_2O_3+CaO^*+Na_2O\text{-}K_2O)^*100]$. The PIA values of the Dhandraul sandstone, Scarp sandstone and Bijaigarh shale ranges from 22.19 to 78.40 (avg. 53.09); 47.86 to 86.82 (avg. 62.13), and 85.32 to 88.43, (avg. 81.91), respectively (Table 4). The PIA values of the studied samples also prescribe low to moderate plagioclase weathering in the source area.

The selective trace element ratio particularly Th/U is also used for palaeoweathering studies as Th and U are relatively immobile at neutral pH condition. However, the surface weathering process elevate the Th/U ratio than average upper continental crust (Th/U = 3.8; Taylor and McLennan, 1985) due to the oxidation of U^{4+} to the more soluble U^{6+}. Th/U ratio above 3.8 is expected to be indicative of weathering history (McLennan et al. 1993). The Th/U ratios of the Dhandraul sandstone (1.01), Scarp sandstone (0.97) and Bijaigarh shale (3.22), indicating a low degree of chemical weathering for Dhandraul and Scarp sandstones and moderate degree of chemical weathering for Bijaigarh shale in the source area (Fig. 13). Intensive chemical weathering and diagenesis often leaches Sr compared to Rb (Nesbitt and Young 1982). This leads to increase in Rb/Sr ratio which indicates strong weathering (McLennan et al. 1993). The Rb/Sr ratios of Dhandraul Sandstone (0.99), Scarp Sandstone (1.01) and Bijaigarh Shale (2.19) are higher than the average post-Archean Australian shale (0.80; Taylor and McLennan, 1985). The low Rb/Sr and

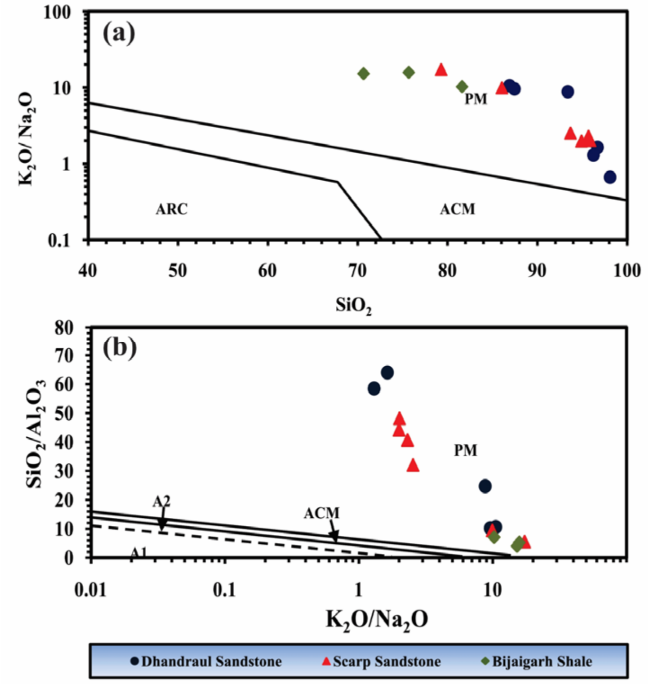


Fig. 11. Plots of the major element composition for the UKG of rocks on the tectonic setting diagrams **(a)** after Roser and Korsch, (1986) and **(b)** after Bhatia, (1983). Note: **ACM**: active continental margin, **ARC:** oceanic island arc margin, **PM**: passive margin, **A1**- Arc setting, basaltic and andesitic detritus, and **A2**- evolved arc setting, felsitic-plutonic detritus.

Th/U ratios also indicate low to moderate weathering in the source area.

Although the composition and association of source rocks are controlled by plate tectonics and structural evolution of the area; the process of weathering, production and composition of detritus are determined primarily by climate (Basu, 1985; Suttner and Dutta, 1986; Akhtar and Ahmad, 1991). The palaeoclimate condition can be derived from the study of composition of modal sandstone. Bivariant log/log plot of the ratio of polycrystalline quartz to feldspar plus rock fragments (Suttner and Dutta, 1986) has been used for interpreting the palaeoclimate of the UKG sandstones. This diagram indicates a humid climate for the region (Fig. 14a). A combination of low relief, hot humid climate and ample vegetation can produce quartz rich detritus (Franzinelli and Potter, 1983). Low relief provides prolonged residence time of sediments, thereby increasing the duration of chemical weathering. The mineralogical data plotted on Weltje et al., (1998) diagram, of this study, represents the 4th field which indicates sedimentation of UKG rocks in a low relief and tropical humid climatic condition (Fig. 14b). According to Laird (1972), the sediments plotted in such fields are mainly derived from deeply weathered granite-gneissic terrain, which are quartz-rich sandstones, poor in feldspar and rock fragments. Thus, climate might have been an important factor in the production of compositionally mature quartz rich sandstones. The QFR ternary diagram of Suttner et al. (1981) indicates a metamorphic source rock in a humid climate (Fig. 15). 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.

To make use of the chemical parameters, the ratio of SiO_2/Al_2O_3 against that of quartz, quartzite, and chert/ (feldspar + rock fragments), (Q/F+Rf) was plotted (Fig. 16a), which reflect the maturity of sandstones (Pettijohn, 1975). A higher SiO_2 ratio coincides with higher silica phases of quartz, quartzite, and chert, which in turn reflect that the maturity of the UKG of rocks which increases from Bijaigarh shale to Dhandraul sandstone. A bivariate plot of SiO_2 against total $Al_2O_3+K_2O+Na_2O$ as proposed by Suttner and Dutta (1986) was used in order to identify the maturity of the UKG of rocks as a function of climate (Fig. 16b). This plot also revealed humid climatic conditions for the samples investigated.

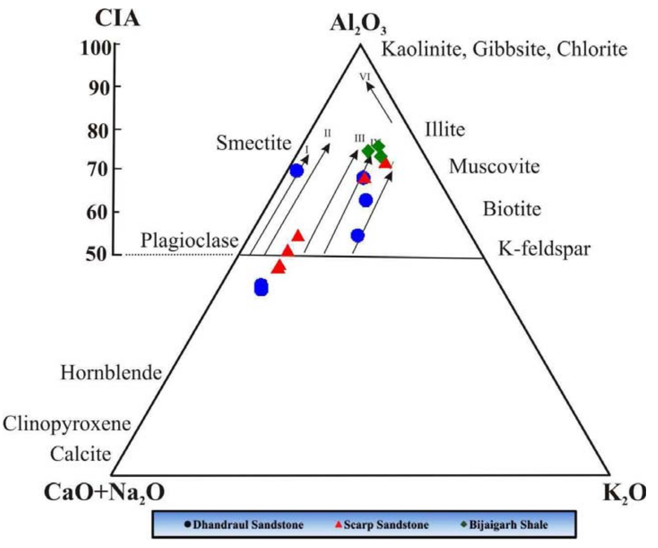


Fig. 12. A-CN-K ternary diagram of molecular proportions of Al_2O_3, $(CaO+Na_2O)$ and K_2O respectively for the UKG rocks (after Nesbitt and Young, 1984).

Hydraulic Sorting

Hydraulic sorting of detrital mineral grains can significantly influence the chemical composition of bulk sediments. Geochemical variability due to hydraulic sorting can be evaluated using the Index of Compositional Variability (ICV, Cox et al. 1995). Rock forming minerals such as plagioclase, K-feldspars, amphiboles and pyroxenes show ICV values > 1, whereas typical alteration products such as kaolinite, illite, and muscovite show values < 1 (Cox et al. 1995; Cullers, 2000) (see Table 4). The ICV values of Dhandraul sandstone (range .053-3.71 with an average 1.51) and Scarp sandstones (range 0.52-1.50 with an average 1.03) indicating these sandstone are enriched in rock-forming minerals such as plagioclase, K-feldspar, amphiboles, and pyroxenes while the Bijaigarh shale shows the average ICV values with an average 0.70, suggesting this is enriched in the alteration products such as kaolinite, illite, and muscovite. The average ICV values for the Bijaigarh shale, Scarp sandstone and Dhandraul sandstone indicate that shale and sandstone are the product of recycled sediment or intensive weathering of the first cycle sediment, deposited in passive tectonic setting.

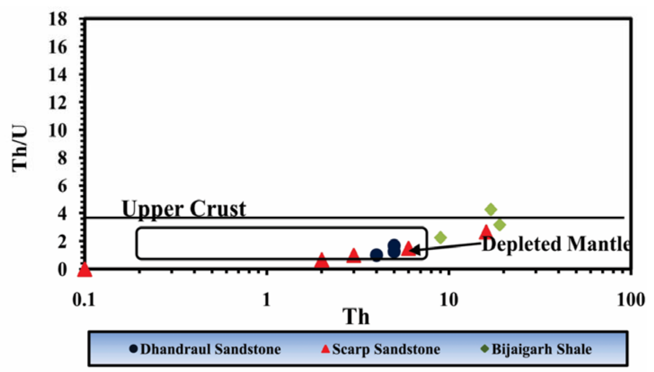
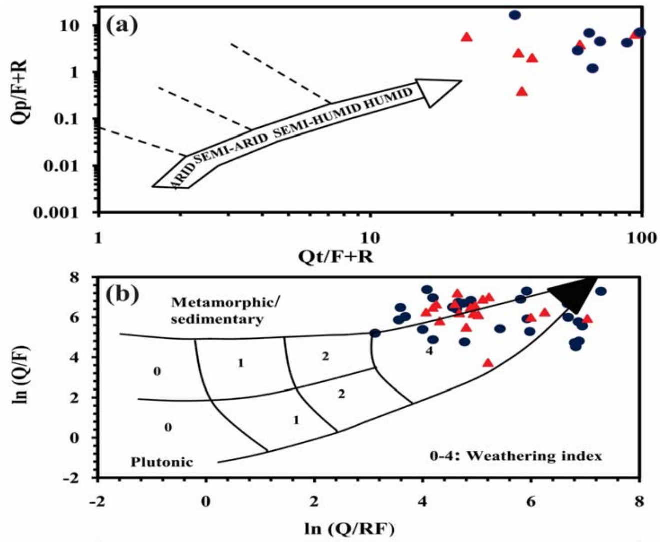


Fig. 13. Th/U vs. Th bivariate plot for the UKG of rocks, after McLennan et al., (1993).



Semi-quantitative Weathering index			Physiography (relief) High (Mountain) 0	Moderate (Hill) 1	Low (Plains) 2
Climate (Precipitation)	(Semi) Arid and Mediterranian	0	0	0	0
	Temperate subhumid	1	0	1	2
	Tropical humid	2	0	2	4

Fig. 14. (a) Bivariant log/log plot for UKG sandstones, according to Suttner and Dutta, (1986) **(b)** Log ratio plot after Weltje et al., (1998). Subscript Q=Quartz, F=Feldspar, RF=Rock fragements and fields 1-4 refers to the semi quantitative weathering indices declined on the basis of relief and climate as indicated in given table.

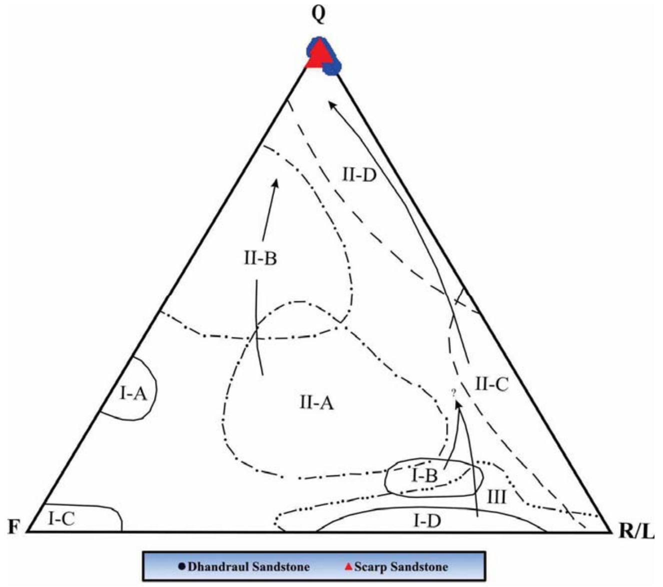


Fig. 15. Postulated idealized evolution model of UKG of sandstones with emphasis on source rocks and climate. Expected petrofacies composition from ideal provenances with different climate and their relationship with primary source rocks by Alam, (2002). The modal modified after Cox and Lowe, (1995b). **Fields- IA, IB, IC, 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).

Similarly, the SiO_2/Al_2O_3 ratio can be used to understand the textural maturity of sediments, high value represents compositionally matured sediments (e.g., Ahmad and Chandra, 2013). The SiO_2/Al_2O_3 ratios vary from 10.11 to 190.43 (avg. 59.7) in Dhandraul abd Scarp sandstones 5.55 to 48.21 (avg. 30.1), whereas 3.98 to 7.08 (avg. 5.4) in the Bijaigarh shale (Table 4). The higher SiO_2/Al_2O_3 ratio of the Dhandraul sandstones compared to the Scarp sandstones and Bijaigarh shale indicates that the compositional maturity is greater for the Dhandraul sandstones. This supports that Dhandraul sandstones are recycled and derived mainly from quartzose recycled rocks with subordinate igneous rocks. Therefore, it is suggested that the Upper Kaimur Group sandstones are partially influenced by hydraulic sorting and indicating medium to high maturity.

Provenance

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).

To evaluate the relative importance of plutonic and metamorphic rocks as quartz sources, we plotted polycrystalline quartz vs. non-undulatory and undulatory monocrystalline quartz is plotted on a double-triangular diagram following the technique of Basu et al. (1975), Fig. 17. From this approach it can be suggested its derivation from a medium to high grade metamorphic source and a minor contribution from the plutonic source. However, in the UKG rocks the presence of cherts and rock fragments of granite parentage suggest their sedimentary and plutonic source respectively. Very less (~1%) presence of feldspars and rock fragments are noted in all samples of UKG sandstones, and also absent in many thin sections. If present, they are cloudy and show evidence of dissolution. Therefore, deficiency of feldspars and rock fragments suggest that the source area for the sandstones underwent a long period of intense chemical weathering in a warm humid climate (Pettijohn et al. 1987; Amireh, 1991). Also, the petrographic characters are consistent with sandstones derived from an area of low relief on a stable shelf margin. Such characters may also indicate that the sandstones were derived from a cratonic interior (Cassinis et al. 1979; Burnett and Quirk, 2001) and were deposited on a passive margin (Emilia and Arribas, 2004).

The above mentioned observations reveal that the sediments of the sandstones of the UKG may have been derived from a variety of source rocks (mixed provenance). This interpretation is also supported by the presence of abundant opaque mineral grains including iron oxides (hematite), which reflect derivation from metamorphic and igneous rocks. The presence of alkali feldspars indicates their source as plutonic and metamorphic rocks (Trevena and Nash, 1981). The suite of heavy minerals including zircon, rutile, and tourmaline indicates an acid igneous source for these sandstones. While the presence of rare rounded grains of rutile and zircon, is an indication of granitic with subordinate recycled sedimentary source.

The major elements based on provenance discriminant function diagram of Roser and Korsch (1988) is frequently used by many to identify the provenance of terrigenous sediments (Hofer et al. 2013; Khanchuk et al. 2013; Vdacny et al. 2013) and to reflect the source rock composition (Shadan and Hosseini-Barzi, 2013). This discriminant function diagram favors felsic igneous rocks with subordinate mature quartzose sedimentary provenance (Fig. 18), which is consistent with the bivariate plot of TiO_2 vs. Zr (see Fig. 8). The collective petrographic and geochemical data strongly suggest that the rocks of the UKG were formed from the same Proterozoic felsic

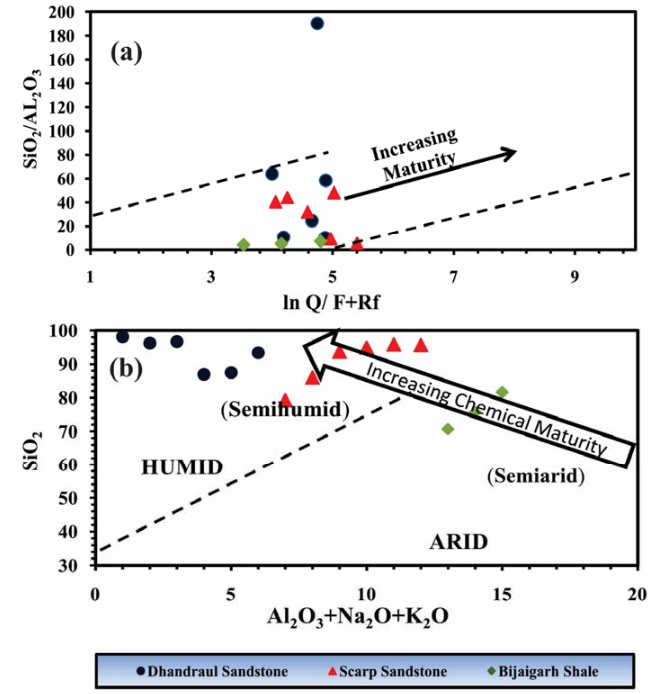


Fig. 16. (a) The ratio SiO_2/Al_2O_3 and ln(Q/(F+RF) in the different types of the UKG of rocks **(b)** Chemical maturity of the UKG of rocks expressed by bivariate plot of SiO_2 versus Al_2O_3+ K_2O + Na_2O; fields after Suttner and Dutta, (1986).

source and the provenance is dominantly granitic with a minor contribution of granodioritic source.

Moreover, the presence of SiO_2 rich rocks (Dhandraul sandstone- 93.19%, Scarp sandstone- 90.92%, Bijaigarh shale- 75.98%) implies that the rocks of the upper Kaimur Group, are rich in quartz, representing quartz rich crystalline provenance. K_2O/Na_2O ratio can be considered as a simplified chemical provenance indicator (Potter, 1978). Higher values of this ratio reflect derivation from granites rather than from basic rocks. The major and trace element concentrations of the upper Kaimur Group provide additional information regarding evolution of the Vindhyan basin and its provenance in the Son valley. Dominantly feldspathic source rocks for the Vindhyan sediments are best evaluated by considering the concentration of immobile elements. Therefore, the Palaeoproterozoic-Mesoproterozoic Chotanagpur granite gneiss (CGG) and Mahakoshal Group of metasediments situated on the southern and southeastern side of the Vindhyan basin are the most likely candidates for the source rocks of the upper Kaimur Group in the Son valley.

CONCLUSION

The UKG is composed mainly of sandstones with shale beds at the base and the average modal composition of Dhandraul (Qt_{99} $F_{0.1}L_{0.8}$), Scarp sandstone (Qt_{99} $F_{0\cdot2}L_{0.8}$), Bijaigarh shale classifies them as quartz arenite with subordinate sublitharenite, which is also supported by geochemical study. The calculated geochemical ratios and mineralogical observations indicate a mineralogical assemblage consisting of abundant quartz and minor kaolinite and illite. Chemical analyses of these reveal that sandstones have high SiO_2, K_2O >Na_2O, and low Fe_2O_3, MgO, MnO values, which are consistent with the modal data. Also, sandstone samples are enriched in most trace elements such as Ce, Sr, V, Sc and Zr and depleted in U and Th.

Qt-F-L and Qm-F-Lt ternary plots of UKG sandstones suggest that the detritus of the sandstone was derived from the granite-gneisses, exhumed in the craton interior as well as low to high grade supracrystals forming recycled orogen. This has been recognized as the Mahakoshal Group of rocks and Chotanagpur granite-gneiss. The sediments were deposited under the rifted basin as indicated by plotting of UKG on the Qp-Lv-Ls diagram. The plot of UKG sandstone on the Qm-P-K diagram suggests the maturness of the sediments and stability of the source area. The ICV values and major element and trace element signatures indicate that the sedimentation took place in an intracratonic or passive margin tectonic setting.

The geochemical data interpretation based on discriminate function diagram reveals that the source material was deposited in passive margin setting. The CIA values of UKG rocks suggest that the source rocks of these sedimentary rocks were subjected low to moderate

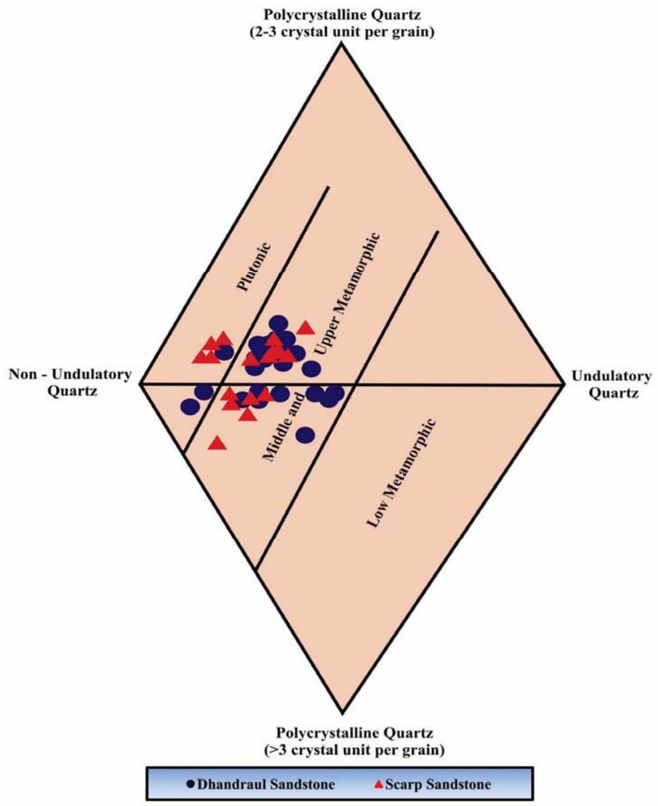


Fig. 17. Varietal quartz diamond plot used to discriminate sands source by different types of crystalline rocks, on the basis of the extinction pattern and polycrystallinity of quartz grains. UKG sandstones are compared with provenance fields after Basu et al., (1975).

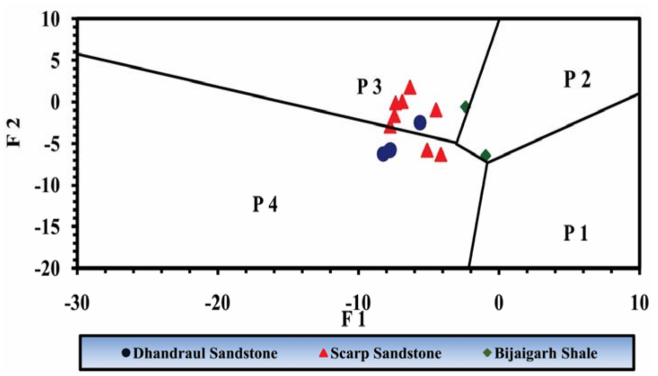


Fig. 18. Major element discriminant function (F) diagram of Roser and Korsch, (1988) for sedimentary provenance where **P1:** Mafic igneous provenance, **P2:** Intermediate igneous provenance, **P3:** Felsic igneous provenance and **P4:** Quartzose sedimentary provenance.

$$F1 = (-1.773\cdot TiO_2) + (0.607\cdot Al_2O_3) + (0.760\cdot Fe_2O_3) + (-1.500\cdot MgO) + (0.616\cdot CaO) + (0.509\cdot Na_2O) + (-1.224\cdot K_2O) + (-9.090);$$

$$F2 = (0.445\cdot TiO_2) + (0.070\cdot Al_2O_3) + (-0.250\cdot Fe_2O_3) + (-1.142\cdot MgO) + (0.438\cdot CaO) + (1.475\cdot Na_2O) + (-1.426\cdot K_2O) + (-6.861).$$

weathering conditions under warm humid climate. The high CIA value may be due to direct input of mature continent detrital minerals into the depositional system. This approach has revealed that the UKG sediments were primarily derived from felsic continental sources typical of a craton interior. The present study can be used to constrain that the Paleoproterozoic Mahakoshal belt and Chotanagpur Gneiss Complex which are situated on the southern and southeastern side of the Vindhyan basin exposures seem to be the potential source of the UKG rocks.

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