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SUMMARY AND CONCLUSION

The Vindhyan basin is the largest (exposed area 104,000 Km$^2$) of the Precambrian intracratonic sedimentary basins in India. This basin comprises of nearly 4 km thick sequence of largely undeformed rocks- shales, sandstones, limestones, 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; Chaudhri et al., 1999; Bose et al., 2001; Ray and Chakraborty, 2006). The Vindhyan Basin is bordered by the Aravalli–Delhi orogenic belt (2500–900 Ma, Roy, 1988) in the west and the Satpura orogenic belt (1600–850 Ma, Verma, 1991) in the south and east. The Bundelkhand granite massif (3.3–2.5 Ga) (Mondal et al., 2002) occurring at the center of the basin divides the basin into two sub-basins—the Son Valley Vindhyan to the east and the Aravalli–Vindhyan to the west. The entire basinal sequence belongs to two distinct depositional cycles. The first is dominantly calcareous and argillaceous and is characteristically developed in the lower part (Lower Vindhyan). The second is arenaceous and argillaceous nature of rocks is developed in the upper part (Upper Vindhyan). The Lower Vindhyan comprising Semri Group and the Upper Vindhyan comprising Kaimur, Rewa and Bhander Groups each separated by conglomerate units (Auden, 1933).

Sedimentation in the Vindhyan started before 1.7Ga until shortly after 1Ga (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±90Ma and U–Pb ages of 1630– 1631Ma, respectively (Rasmussen et al., 2002; Ray et al., 2002; Sarangi et al., 2004). Thus, the sedimentation in the Son valley basin started sometime prior to 1721Ma and continued till ~650Ma. However, the upper limit of Vindhyan sedimentation has been bracketed down to 1Ma (Malone et al., 2008).

The Kaimur Group (400m) 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 bounded by Bundelkhand Gneissic Complex (BGC) to the north and Mahakoshal Group and
Chhotanagpur 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 lithounits-Bijaigarh Shale being the lowermost followed by the Scarp Sandstone and the Dhandraul Sandstone.

For the present study, four traverses were taken along Markundi Ghat section, Churk Markundi Road section, Barkacha Ghat section and Lakhania Dari section in Sonbhadra and Mirzapur districts, respectively. In these sections the Upper Kaimur Group (Dhandraul Sandstone, Scarp Sandstone and Bijaigarh Shale) is well exposed whereas Lower Kaimur Group dislocated by the Markundi-Jamwal Fault (Prakash and Dalela, 1982). Consequently, Bijaigarh Formation directly rests over the Semri Group.

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. Four well exposed lithostratigraphic sections were measured from Markundi Ghat section, Churk Markundi Road section, Barkacha Ghat section and Lakhania Dari section. Lithologs were prepared on the basis of field data and lithofacies were identified. 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. The lithofacies are-(i) Inter-bedded shale within the thinly bedded sandstone facies (Fi-S), (ii) Parallel laminated sandstone facies (Si), (iii) Herringbone cross bedded facies (S-hb), (iv) Massive sandstone facies (Sm), (v) Rippled bedded sandstone facies (Sr), (vi) Trough cross bedded facies (St), and (vii) Planar cross bedded facies (Sp).

Thin section of sandstone samples were prepared and used for the petrographic study. For petrographic study a total of forty six indurated sandstone samples selected and 300 points were counted following Gazzi-Dickinson point-counting method (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. The textural attributes of the sandstones, such as size, roundness and sphericity were studied with a view to interpret the provenance and estimate the influence of texture on the detrital modes and petrofacies. Statistical parameters of grain size were computed according to the method of Folk (1980). The bivariate plots are designed to differentiate among beach, fluvial and various eolian sediments, they appear ideally suited for resolving the diverging viewpoint on the origin of the Upper Kaimur Group Sandstone. The 46 samples of the Upper Kaimur Sandstone were plotted on six different combinations of bivariant grain size parameters. The depositional environment is based on field data. Detrital mineralogy of the sandstones was studied for the purpose of description and petrographic classification of the studied sandstones and interpretations of the provenance and tectonic setting. Heavy mineral study of the Upper Kaimur Group sandstones aims (i) to provide constraints on the provenance of the sandstones, (ii) to determine the tectonic setting of the Upper Kaimur Group of rocks. The diagenetic study provides valuable information on texture, composition, microstructure and diagenetic modifications of the Upper Kaimur Subgroup sandstones. The fluid inclusion study covers the fluid inclusion petrography, fluid chronology and microthermometry. The fluid chronology helps to explain the entrapment of various generation of fluid with time. The micro thermometric measurements of fluid inclusions provide the temperature of initial melting/eutectic temperature (Tim), final melting temperature (Tfm) and homogenization temperature (Th). These measurements will help to understand the fluid composition, salinity, density and exhumation/upliftment history of the study area. The geochemical study aims to reconstruct the parent rock assemblages, their tectonic provenance, mineralogy, weathering intensity, hydraulic sorting and depositional tectonic setting.

The statistical parameters of grain size analysis show that the sandstones are medium to coarse grained, moderately to well sorted, strongly fine skewed to fine skewed. Most of the grains are subangular to subrounded and have low sphericity. Bivariant plots of different parameters indicate that mean size versus sorting has moderate relationship. Mean size versus skewness has poor inverse relationship whereas mean size versus roundness has moderate inverse relationship. Mean size versus sphericity has moderate inverse relationship. Sorting versus roundness and mean sphericity versus sorting has poor relationship. In the light of the scatter plot
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Information obtained from the interpretations of the graphical and relationship between the statistical parameters of grain size, it can be summarized that the Upper Kaimur Group Sandstones of the study area is not restricted to a single depositional environment. It can be broadly inferred that, these sediments were deposited in a mixed environment. However, it can be envisaged that that the marine processes dominates over the fluvial processes.

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 (Leckie and Singh, 1991; Dalrymple et al., 1992; 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 settings.

Petrographically, the Dhandraul and Scarp sandstones 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 Chhotanagpur 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
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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).

The characteristic heavy minerals are zircon, tourmaline, rutile, epidote, biotite, chlorite, staurolite, hornblende, hypersthene, garnet and opaques. The non-opaque heavy mineral assemblage of the sandstone is dominated by zircon, tourmaline and rutile (ZTR). However, abundance of the ZTR minerals favors a recycled sedimentary source over other possibilities. Source area denudation, tectonism and action of intrastratal solution played important roles to account for the vertical variation of the heavy mineral suites. The observed heavy minerals are comparable with the accessory constituents of quartzites, carbonates, chert, Banded Iron Formations (BIFs), greywacke, argillite, mafic volcanic rocks, amphibolite to granulite facies rocks, tonalite trondhjemite-granodiorite (TTG) gneiss and the Proterozoic granite intrusions associated with the BIFs, mafic volcanic and dykes of the Mahakoshal supracrustal belt and Chhotanagpur Gneissic Complex. Proximity of the source area is indicated by euhedral to subrounded grains of most of the heavy minerals. Changes of relative relief of the source area with respect to depositional basin, sudden release of some of the minerals in the source region and/or existence of favorable geochemical condition to escape partial dissolution account for the variation of heavy mineral frequency in stratigraphic column of the Upper Kaimur Group.

The important diagenetic components identified based on the framework grain–cement relationships are mechanical compaction, cements, authigenic clays and dissolution and alteration of unstable clastic grains and tectonically induced grain fracturing. The early to intermediate stage of the diagnostic realm e.g., mechanical compaction, cementation, dissolution, and authigenesis of clays (dominantly kaolinite, mixed illite-smectite and minor illite). Mixed illite-smectite and illite occur as pore-filling and or lining during authigenic phases. Kaolinite and silica (quartz) overgrowth occur as pore-filling and lining cements. Compaction played an added role than the cementation in modifying the primary porosity. Cementation drastically reduced the porosity and permeability. Kaolinite fills pore spaces and caused reduction in the porosity and permeability of the sandstone. Secondary porosity development occurred due to partial to complete dissolution of feldspar. The diagenetic signatures observed in the Upper Kaimur Group Sandstones are suggestive of intermediate burial
condition. The reservoir quality of the studied sandstones is reduced by authigenic clay minerals (kaolinite, mixed illite-smectite and minor illite), cementations, and on other hand, it is increased by alteration and dissolution of unstable grains.

Fluid inclusion studies are carried out on the detrital, and recrystallized quartz grains of Dhandraul and Scarp sandstones to know about the fluid phases present during recrystallization processes at the time of maximum depth of burial. Fluid microthermometry study reveals the presence of two types of fluids: (i) two phase aqueous inclusions, with the vapour phase, (ii) two-phase and aqueous, with the \((\text{CO}_2)\) vapour phase. These fluids were trapped during the development of grains and recrystallization processes. The high salinity in the quartz grain is the range of 5.7 to 13.4% of these inclusions suggests that initially there was lot of marine water when sedimentation process was started. Fluid inclusions having high salinities range 5.7 to 13.4% observed in the quartz grain suggest that the protoliths of these rocks could have a strong affinity with the granite/metamorphic rocks which is also coherent with the petrographical and geochemical data.

The geochemical data interpretation based on discriminate function diagram reveals that the source material was deposited in passive margin setting. The CIA values of the Upper Kaimur Group of rocks suggest that the source rocks of these sedimentary rocks were subjected to low to moderate 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. The ICV values and major element and trace element signatures indicate that the sedimentation took place in an intracratonic or passive margin tectonic setting. This approach has revealed that the Upper Kaimur Group sediments were primarily derived from felsic continental sources typical of a craton interior.

Therefore, the Paleoproterozoic-Mesoproterozoic Chotanagpur Granite Gneiss (CGG) composed of granite, granodiorite, pegmatites and gneisses and Mahakoshal Group of metasediments situated on the southern and southeastern side of the Vindhyan Basin. The westerly and northwesterly palaeocurrent direction is established for the Upper Kaimur Group by (Quasim et al., 2017), with the Mahakoshal belt and the Chhotanagpur Gneissic Complex as the most likely candidates for the source rocks of the Upper Kaimur Group in the Son Valley.