Significance of the tuffaceous beds associated with the Bijaigarh Shale of the Kaimur Group, Vindhyan Supergroup, Central India and their correlation with tuffs in other contemporaneous Proterozoic basins

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Bijaigarh Formation is lithologically heterogeneous with grain size varying from fine to medium sand to clay. About ~1 m thick tuffaceous beds of rhyolitic to rhyodacitic nature, sandwiched between the Bijaigarh siliciclastics have been reported. We have attempted to distinguish the tuffaceous beds from the adjacent terrigenous sediments of Bijaigarh Shale on the basis of their field disposition, petrographic and geochemical characteristics. The tuffs are characterised by a relatively high content of LILE, HFSE and LREE as compared to Bijaigarh siliciclastics. They reflect their affinity to the felsic magmatic source. The geochemical signatures of the Bijaigarh tuff exhibit quite comparable characters to the contemporaneous (~1000 Ma) tuffs from other Proterozoic basins, viz., Chhattisgarh and Indravati. The extrabasinal sources for the deposition of the Bijaigarh tuff at ~1000 Ma can be inferred which can possibly be correlated with tectonothermal events of the Grenville orogeny. The integration of elemental compositions with mineralogical and textural observations makes possible the establishment of the tuffaceous beds as a stratigraphic marker in the Upper Vindhyan stratigraphy. This will have wider implications for the precise and reliable correlations of the Proterozoic basins of India.

Keywords. Volcanic ash beds; tuff; Bijaigarh Shale; Kaimur Group; Proterozoic basins.

1. Introduction

Volcanic ash or tuff layers within the monotonous sedimentary sequences provide the remarkable stratigraphic marker beds. The explosive volcanic eruptions can produce large amounts of fine-grained material which spread laterally and the resulting fallout of ash tends to cover the pre-eruptive topography of the depositional surfaces. Tuffs have been reported from the majority of the Proterozoic basins of the Indian subcontinent, viz., Sukhda tuff (Patranabis Deb 2003; Subba Rao

et al. 2006; Patranabis Deb *et al.* 2007; Basu *et al.* 2008; Bickford *et al.* 2011a), Dhamda tuff (Bickford *et al.* 2014) and the Singhora tuff from Chhattisgarh (Das *et al.* 2009). Tuffs have also been reported from Proterozoic basins like the Pranhita–Godavari (Chaudhuri and Chanda 1991; Saha and Ghosh 1998; Patranabis Deb 2003), Cuddapah basin (Dasgupta and Biswas 2005; Goswami *et al.* 2018), Kurnool (Saha and Tripathy 2012) and the Indravati and Sukma basins (Mukherjee *et al.* 2012; Bickford *et al.* 2014). The Vindhyan basin in central India has also been

punctuated by tuffaceous beds at different stratigraphic levels (Soni *et al.* 1987; Chakraborty *et al.* 1996, 2010; Bose *et al.* 2001). The extensively investigated Porcellanite Formation of the Semri Group/Lower Vindhyan comprises volcanic ash and tuffaceous beds which are the product of intrabasinal volcanism deposited in the subaqueous/subaerial environment (Auden 1933; Roy and Banerjee 2001; Srivastava *et al.* 2003; Chakrabarti *et al.* 2007; Mishra and Sen 2008; Sen and Mishra 2014; Bickford *et al.* 2017; Mishra *et al.* 2017a, b, c, 2018). The volcanoclastic inputs at the basal part of the Kaimur Group and at different stratigraphic levels within the Rewa Group from the Vindhyan basin have been reported by Chakraborty *et al.* (1996, 2010).

The present study was carried along the Son valley in the area located in the northern part of Sonbhadra district of Uttar Pradesh in central India (figure 1). The present communication, for the first time, reports the volcanic ash/tuffaceous beds sandwiched within the sedimentary layers of Bijaigarh Formation of Mesoproterozoic Kaimur Group, Vindhyan Supergroup. The field observations, petrographic, mineralogical and geochemical studies indicate that the tuffs associated with the Bijaigarh Shale are of igneous origin. We have also

attempted to correlate the geochemical signatures of Bijaigarh tuff with the tuffs from other contemporaneous Proterozoic basins.

2. Geological setting

The Vindhyan Supergroup consists of a thick repository (~4500 m) of sedimentary rocks deposited in the largest intracratonic basin of India (Valdiya *et al.* 1982; Soni *et al.* 1987; Bhattacharya 1996). This supergroup has been divided into four groups which comprise (in ascending order) the Semri, the Kaimur, the Rewa and the Bhandar groups (Auden 1933; Prakash and Dalela 1982). Son valley sector classically exposes two groups, i.e., older Semri and the younger Kaimur (figure 2) of the Vindhyan supergroup. The Kaimur group consists of a huge pile (thickness ~400 m) of siliciclastics which unconformably overlie tilted, mildly deformed and partially eroded Rohtas formation which is the uppermost carbonate rich unit of the Semri group (figure 3). In fact, the Kaimur group unconformably overlies all the formations of the Semri group along the Markundi–Jamwal fault (figure 2). The Semri–Kaimur boundary is considered as a distinctive shift from the calcareous

Figure 1. Sample location map showing the northern part of the Sonbhadra district, Uttar Pradesh. Filled square marks sample location.

Figure 2. Geological map of the study area in the eastern part of the Son valley (modified after Auden 1933).

Figure 3. Generalised lithology of the Kaimur group. SS: Sasaram sandstone; GS: Ghurma shale; MS: Markundi sandstone; BS: Bijaigarh shale.

(Rohtas limestone) to a silica-rich environment during the deposition of Kaimur siliciclastics. The Kaimur group has been divided into six formations (arranged in stratigraphic order) comprising the oldest Sasaram Sandstone, Ghurma Shale, Markundi Sandstone, Bijaigarh Shale, Mangesar

Table 1. Generalised stratigraphic succession of the Vindhyan supergroup in the Son valley, central India (modified from Prakash and Dalela 1982). References for ages are given in the table.

Group with thickness	Formation with thickness and available ages
Kaimur group/Upper Vindhyan (400 m)	Dhandraul Quartzite (100 m) Mangesar Formation (155 m) Bijaigarh Shale (50 m) Markundi Sandstone (40 m) Ghurma Shale (16 m) Sasaram Sandstone (30 m) 1070±160 Ma (Srivastava and Rajagopalan 1988) -----Unconformity/normal contact-----
Semri group/Lower Vindhyan (3000–4000 m)	Rohtas limestone 1599±48 Ma (Sarangi <i>et al.</i> 2004) Glauconitic sandstone 1504±15 Ma (Kumar <i>et al.</i> 2001) Fawn limestone Olive shale Porcellanite shale 1630 Ma (Rasmussen <i>et al.</i> 2002; Ray <i>et al.</i> 2002); 1642±7 (Bickford <i>et al.</i> 2017); 1647±18 (Mishra <i>et al.</i> 2018) Kajrahat limestone 1729±119 (Sarangi <i>et al.</i> 2004) Basal sandstone and conglomerate -----Angular unconformity/non-conformity-----
	Mahakoshal Group/Jhirkadandi granite 1753±9 Ma (Bora <i>et al.</i> 2013)

Formation and the youngest Dhandraul Quartzite (Auden 1933; Prakash and Dalela 1982; table 1 and figure 3). These formations have been petrologically and geochemically characterised by Sen (2010), Mishra and Sen (2011, 2012, 2015) and Sen *et al.* (2014).

Vindhyan sedimentation initiated before 1700 Ma and continued shortly after 1000 Ma (Sarangi *et al.* 2004; Gregory *et al.* 2006). However, the upper limit for the closure of the Vindhyan basin has been bracketed down to 1000 Ma by Malone *et al.* (2008) and Turner *et al.* (2014). This is supported by the Pb–Pb isochron ages ranging from 980 to 1073 Ma (Gopalan *et al.* 2013) for the top-most limestone beds of the Vindhyan succession. The Pb–Pb isochron age of 750 ± 50 for Bijaigarh shale has been given by Balasubramanian and Chandy (1976). However, the Re–Os depositional age for Bijaigarh shales from the Kaimur group has been given as 1210 ± 52 Ma by Tripathy and Singh (2015).

The siliciclastics of the Kaimur group were initially deposited in the transgressive environment followed by the regressive phase in the upper part, of the Vindhyan shallow sea (Bose *et al.* 2001). The

Bijaigarh shale has been considered to have been deposited in a lagoonal environment with access to open sea (Singh 1980). Bijaigarh shale exhibits lithological heterogeneity, with variation in grain size from fine to medium sand, silt and clay. The shales are buff to brownish and reddish in colour. The micaceous minerals can be observed in hand specimen. The maximum thickness of these shales is about 50 m. The generalised lithology of the Kaimur group is shown in figure 3. In the study area, it comprises shales, mudrocks and finely laminated carbonaceous black shales (Paikaray *et al.* 2003; Banerjee *et al.* 2006). They are friable in nature with fissile bedding giving a crinkled appearance to the outcrop (figure 4). Sedimentary structures like ripple marks, current bedding and orthogonal sun cracks are abundant.

Interestingly, we observed that the tuffaceous/indurated ash beds (~1 m thick) are intimately associated with the Bijaigarh shale. Their outcrops comprise a distinct and conspicuous horizon characterised by very fine-grained, hard and compact, olive green, buff or grey thinly ash beds or bedded tuff layers. They break along curved and smooth surfaces (perlitic cracks). On the basis of physical

Figure 4. Crumpled and folded Bijaigarh shale. Notice the reddish colour of the outcrop.

appearance, these tuffaceous beds could be easily distinguished from the overlying and underlying carbonaceous black to buff to bleached soft and friable Bijaigarh shale (figure 5a and b). Their lateral extension was traced in Markundi Ghat section and on both sides of the highway from Varanasi to Chopan before Markundi, near Son pumping station at Churk and near Bijaigarh fort (figures 2 and 5b). For the purpose of present study, the tuffaceous beds associated with Bijaigarh shale have been referred as Bijaigarh tuff.

3. Sampling and analytical techniques

Relatively fresh and compact samples were collected from the middle part of the tuff beds, thus avoiding contamination from adjacent Bijaigarh siliciclastics as far as possible. The sampling of tuffaceous beds was carried out from Markundi Ghat, Son pumping station and the southern slope of the Bijaigarh fort (figure 5a and b). The samples from Bijaigarh shale were systematically collected based on the lithological variation. The bulk samples were reduced to small chips and powdered to –60 mesh size. After homogenisation, about 100 g of each sample was ground to less than –200 mesh size, using the pulveriser malle RETSCH and Agate Mortar Pestle at Banaras Hindu University, Varanasi. The powdered samples were used for X-ray powder diffraction (XRD) and geochemical analysis. The XRD pattern for each sample was recorded using a Rigaku DMAX III diffractometer at Banaras Hindu University, Varanasi. The powdered samples were scanned from 9° to $76^\circ 2\theta$ with a scanning speed of $0.05^\circ/\text{s}$. Minerals were identified by using JCPDS data file of 1987.

A total of 18 samples (10 and 8 samples from Bijaigarh tuff and Bijaigarh siliciclastics, respectively) were analysed for major, trace and rare earth element (REE) compositions. The geochemical analysis was carried out at the Geochemistry Division of the National Geophysical Research Institute (NGRI), Hyderabad. 0.1 g of sample powder was taken in a Teflon beaker to which 7 ml of HF (48%), 3 ml of conc. HNO_3 and 1 ml HClO_4 were added. This mixture was digested by keeping the beaker over a hot plate. After confirming complete digestion, 10 ml of HNO_3 of 1:1 concentration was added and was kept on hot plate until a clear solution was obtained. When the solution had cooled down, the volume was brought to 100 ml with double distilled water after adding 10 ml of 1 ppm rhodium solution as an internal standard (Balaram *et al.* 1996). ICP-mass spectrometer model ELAN dynamic reaction cell (DRC) II (PerkinElmer Sciex Instrument, USA) was used for analysis. The instrument is equipped with the state-of-the-art features such as the DRC and other technical advancements leading to extremely low background, better sensitivity and precision. The detection limit for most of the elements is in pg/ml (ppt) and fg/ml (ppq) level. The system was optimised for maximum intensity ($\sim 40,000$ counts/s) across the mass range 1 ng/ml solution of Mg, Rh, In, Ba, Ce, Pb and U. International rock standards GSR-4 and GSR-5 were used as the external reference material. The precision of REE and trace element data are better than 5% RSD with comparable accuracies (Balaram *et al.* 1996, 1999). Out of 10 tuff samples, 2 (the number needed to treat (NNT-1, NNT-2) were analysed at Activation Laboratory, Canada using inductively coupled plasma atomic emission spectroscopy (ICP-AES) (model – Thermo Jarret Ash ENVIRO II) for major oxides and for trace and REE concentrations, inductively coupled plasma mass spectrometry (ICP-MS) (model: Perkin Elmer Sciex Elan 6000). The precision is $<5\%$ for all analysed elements when reported at a $100\times$ detection limit for the samples analysed from Actslab.

The normalised values used are taken from Sun and McDonough (1989). The values for post-Archaeon Australian Shale (PAAS) and Upper Continental Crust (UCC) have been taken from Condie (1993). Major oxide and trace element data including REE are presented in table 2. In the present study, the published geochemical data of contemporaneous rhyolitic tuffs of ~ 1000 Ma age from the Indravati basin (Mukherjee *et al.* 2012)

Figure 5. Field photograph showing tuffaceous/ash beds sandwiched within the Bijalgarh Shale. (a) Markundi Ghat section; and (b) Bijalgarh section.

and Sukhda (Bickford *et al.* 2011b) and Dhamda (Basu *et al.* 2008) from the Chhattisgarh basin were obtained. Das *et al.* (2009) have reported ages of ~ 1500 Ma of tuff from Singhora of the Chhattisgarh succession. Data for comparison for Sukhda, Indravati and Dhamda tuff have been obtained from Bickford *et al.* (2014). The geochemical data of Singhora tuff (Das *et al.* 2009) have been considered for comparison.

4. Petrography

The petrographic study was carried out under a high-resolution Leica DMRX microscope. Thin section study of Bijalgarh tuff reveals the highly

welded nature, aphyric and vitrophyric texture. Quartz, K-feldspar, albite and muscovite occur as phenocrysts. Accessory minerals include euhedral zircon, rutile, ilmenite mica and opaques. Quartz phenocrysts consist of embayed or bipyramidal crystals (figures 6a and 7). The primary relict igneous texture is evidenced by the presence of fine-grained vitric fragments and devitrified cusate and sickle-shaped glass shards in association with the abundance of altered clay minerals which are set in a vitrophyric groundmass. They may be categorised as vitric tuff (Schmid 1981). The tuffs are vitric to cristo-vitric in nature. Due to their very fine-grained nature, tuff has undergone alteration to clay minerals identified as illite. However, few grains of quartz, feldspar and glass shards have

Table 2. Major oxide, trace and REE data of tuffaceous ash beds and Bijaigarh siliciclastics, Kaimur Group, Son valley.

	Bijaigarh tuffaceous beds									
	BJT-1	BJT-2	BJT-3	BJT-4	BJT-5	BJT-6	BJT-7	SPC-Tff	NNT-1	NNT-2
Major oxides (wt%)										
SiO ₂	67.49	64.05	66.21	66.26	66.65	65.74	69.11	64.5	70.23	69.85
TiO ₂	1.09	1.05	0.95	0.95	1.2	1.51	0.71	0.8	0.758	0.762
Al ₂ O ₃	20.37	23.76	21.92	22.85	22.97	20.83	16.41	19.27	17.76	18.58
Fe ₂ O ₃	1.44	1.39	2.21	1.6	1.37	1.98	5.29	5.49	1.52	1.7
MnO	0.01	0.01	0.04	0.01	0.01	0.01	0.13	0.02	0.007	0.011
MgO	0.84	0.85	0.98	0.81	0.82	0.75	0.9	1.57	0.71	0.84
CaO	0.14	0.1	0.23	0.14	0.13	0.21	0.16	0.2	0.05	0.06
Na ₂ O	0.21	0.13	0.12	0.1	0.09	0.06	0.1	0.11	0.1	0.11
K ₂ O	5.71	5.61	5.42	5.38	5.47	6.35	3.55	5.11	4.21	4.47
P ₂ O ₅	0.05	0.06	0.05	0.05	0.05	0.06	0.07	0.04	0.03	0.04
LOI	2.51	2.64	1.98	1.65	1.55	2.59	3.96	2.96	4.07	4.27
Total	99.86	99.65	100.11	99.8	100.31	100.09	100.38	100.07	99.45	100.6
CIA	75.36	78.98	77.50	78.87	78.78	74.29	79.89	76.32	76.32	76.32
PIA	97.67	98.75	97.92	98.64	98.76	98.17	98.02	97.86	98.91	98.81
Trace element (ppm)										
Rb	258	140	153	267	292	230	176	157	192	223
Sr	109	63	65	105	114	57	78	60	35	38
Ba	657	239	387	304	336	257	678	346	385	424
Y	140	46	36	90	100	73	45	23	36	39
Zr	1096	193	1127	369	384	260	489	173	252	253
Hf	25	6	28	12	12	9	15	6	6	8
Nb	25	14	27	26	27	15	16	12	13	15
Ta	2	1	2	2	2	2	1	1	1.4	1.5
Th	28	25	29	29	23	18	29	17	21.2	22.5
U	12	6	14	13	13	3	5	4	4	4.3
Ni	48	6	50	22	21	26	25	12	19	21
Co	2.8	1.4	3.6	4.7	6.6	5.6	8.7	4.8	4	7
V	122	66	146	134	132	99	58	108	87	93
Cr	132	31	143	119	127	110	111	28	150	120
Sc	23	15	27	18	24	24	17	22	13	13
Pb	76	54	77	25	22	20	48	14	18	18
Rare earth elements										
La	91.45	65.28	39.61	98.45	99.16	42.45	64.40	38.71	45.5	49.5
Ce	122.56	91.32	71.23	131.96	137.28	69.44	133.75	73.91	95.7	104
Pr	16.49	11.52	8.92	17.62	18.51	8.43	14.58	8.42	10.1	10.9
Nd	51.76	35.73	30.35	56.4	58.87	28.58	53.91	29.34	36.5	37.2
Sm	8.6	5.41	5.56	9.76	10	5.24	11.05	4.95	7	7.2
Eu	1.69	1.01	0.95	2.061	1.94	1.04	1.91	0.85	1.19	1.31
Gd	8.41	5.11	3.98	10.13	10.36	4.63	8.79	3.88	6.2	6.9
Tb	1.71	1.04	0.77	2.14	2.31	0.87	1.47	0.66	1.1	1.1
Dy	12.01	7.1	4.13	14.27	15.44	5.27	8.29	3.97	6.8	7.4
Ho	2.6	1.59	1.12	3.24	3.42	1.18	1.64	0.86	1.4	1.4
Er	7.59	4.49	3.01	9.04	9.71	3.45	4.51	2.54	4.1	4.2
Tm	1.32	0.74	0.532	1.56	1.7	0.61	0.76	0.43	0.6	0.61
Yb	8.54	4.82	3.06	9.54	10.21	3.90	5.10	2.84	4.1	4.3
Lu	1.21	0.74	0.56	1.54	1.63	0.66	0.78	0.46	0.64	0.63
∑REE	335.94	235.90	173.78	367.71	380.54	175.74	310.95	171.82	220.93	236.65
[La/Yb] _N	7.7	9.7	9.30	7.4	7.0	7.8	9.1	9.8	7.96	8.3
[Gd/Yb] _N	0.81	0.88	1.08	0.88	0.84	0.98	1.43	1.13	1.3	1.3
[Ce/Yb] _N	3.99	5.26	6.47	3.84	3.73	4.94	7.28	7.23	6.5	6.7
Eu/Eu*	0.61	0.58	0.62	0.63	0.58	0.65	0.59	0.59	0.55	0.57

Table 2. (Continued.)

	Bijaigarh siliciclastics							
	MR-8	MAR-4	MAR-22	MR-6	SPC-7	MAR-25	SPC-6	MAR-10
Major oxides (wt%)								
SiO ₂	74.50	74.78	72.47	72.50	72.5	78.41	81.74	81.94
TiO ₂	0.62	0.61	0.56	0.57	0.53	0.45	0.42	0.44
Al ₂ O ₃	12.39	12.09	13.7	14.2	13.12	10.15	9.65	8.6
Fe ₂ O ₃	3.30	3.26	3.53	3.10	4.7	4.0	2.23	3.6
MnO	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.01
MgO	0.9	0.7	1.2	1.50	1.24	0.91	0.92	0.41
CaO	0.20	0.12	0.2	0.30	0.14	0.14	0.11	0.06
Na ₂ O	0.11	0.07	0.12	0.12	0.14	0.11	0.14	0.04
K ₂ O	3.40	3.39	3.78	3.50	3.63	2.47	2.72	2.22
P ₂ O ₅	0.04	0.04	0.06	0.05	0.07	0.03	0.02	0.06
LOI	3.6	3.6	3.93	3.82	3.99	3.56	2.28	2.72
Total	99.07	98.63	99.58	99.68	100.08	100.25	100.25	100.10
CIA	75.00	75.58	75.28	76.30	75.56	77.00	74.42	77.94
PIA	96.67	97.86	96.88	96.22	97.13	96.85	96.52	98.46
Trace element (ppm)								
Rb	155	151	180	169	158	123	115	106
Sr	55	51	59	65	40	34	26	30
Ba	350	342	437	435	446	282	301	217
Y	32	31	31	32	32	37	30	21
Zr	240	231	259	255	180	274	233	244
Hf	5	6	9	5	6	11	7	6
Nb	15	11	15	15	14	12	11	8
Ta	1	1	2	2	2	2	1	1
Th	10	14	22	20	19	14	11	12
U	5	4	6	7	4	4	5	3
Ni	19	20	13	16	21	26	10	20
Co	2	3	nd	3	nd	nd	nd	2.0
V	nd	59	nd	nd	nd	nd	nd	42
Cr	59	60	nd	59	nd	nd	nd	60
Sc	9	10	7	9	9	7	7	7
Pb	8	8	6	9	7	10	8	7
Rare earth elements								
La	35.80	35.60	40.43	29.50	38.48	35.07	29.58	29.70
Ce	69.40	69.90	82.34	59.80	75.55	70.38	59.98	60.60
Pr	7.85	7.83	8.61	6.42	8.13	8.03	6.32	6.43
Nd	30.10	30.20	35.52	24.30	33.11	34.01	25.78	24.10
Sm	5.90	6.00	6.88	4.60	6.96	7.44	5.45	4.40
Eu	1.30	1.20	1.24	0.95	1.37	1.46	1.07	0.84
Gd	5.60	5.50	5.35	4.10	6.00	6.43	4.43	3.90
Tb	1.00	0.90	1.03	0.90	1.08	1.32	0.80	0.70
Dy	5.20	5.10	6.03	4.20	6.45	8.19	4.62	4.00
Ho	1.20	1.10	1.25	0.95	1.33	1.66	0.98	0.80
Er	3.40	3.30	3.91	2.80	4.07	4.93	2.99	2.50
Tm	0.51	0.51	0.61	2.43	0.59	0.72	0.43	0.40
Yb	3.40	3.40	3.76	0.43	3.67	4.58	2.82	2.60
Lu	0.53	0.52	0.59	0.43	0.61	0.75	0.47	0.40
∑REE	171.19	171.06	197.55	141.81	187.39	184.99	145.72	141.37
[La/Yb] _N	7.6	7.5	7.7	49.2	7.5	5.5	7.5	8.2
[Gd/Yb] _N	1.36	1.34	1.18	7.89	1.35	1.16	1.30	1.24
[Ce/Yb] _N	5.67	5.71	6.09	38.63	5.71	4.27	5.91	6.47
Eu/Eu*	0.69	0.64	0.62	0.67	0.65	0.64	0.66	0.62

Figure 6. (a) Photomicrograph of tuff showing microphenocryst of bipyramidal quartz in the vitrophyric ground mass. Arrow shows glass shard; (b) fine-grained clastic nature of Bijagarh shale showing ferruginous sediment; (c) backscattered image of altered cusped glass shard and fibrous illite; and (d) backscattered image of spiky illite and subrounded rutile.

survived alteration (figure 7). Other minerals identified are muscovite, biotite, altered volcanic glass, muscovite, zircon, rutile, hypersthene and illite (figures 6 and 7). The igneous texture observed in the tuff could be easily distinguished from the overlying and underlying sedimentary layers of the Bijagarh shale, which exhibits a texture, typical of siliciclastics (figure 6b) with quartz as the dominant detrital mineral in addition to subordinate feldspars like orthoclase, plagioclase and microcline. The binding materials comprise clay minerals and ferruginous cements of haematite (figure 6b).

5. Mineralogy

XRD analysis for the Bijagarh tuff and siliciclastics shows that illite is the common clay mineral with subordinate kaolinite and montmorillonite. The fine-grained volcanic ash has altered to fibrous and

spiky illite (figure 6c and d). Thus, illite is the dominating clay mineral which is in conformation with the XRD data. About 100 g of coarsely crushed tuffaceous sample was macerated with conventional techniques using HCl, HF, HNO₃ and KOH. The slide was prepared using polyvinyl alcohol solution and Canada balsam and studied under the petrological microscope. The angular to subangular zircon (figure 7i), glass shards (figure 7f), rutile (figure 7e) and hypersthene (figure 7g and h) were observed in the mounted section. The altered cusped glass shard (figure 6c), fibrous and spiky illite and angular rutile (figure 6d) are visible in the backscattered images.

6. Geochemical results

6.1 Major oxides

Tuffs exhibit SiO₂ ranging between 64 and 70.23 wt% (table 2). TiO₂ has concentration

Figure 7. (a) Photomicrograph of welded bipyramidal quartz and muscovite in vitrophyric ground mass; (b) strained muscovite; (c) euhedral zircon showing halo; (d) resorbed and irregular quartz in vitrophyric ground mass; (e) euhedral rutile; (f) cusped glass shard; (g) and (h) orthopyroxene-hypersthene; (i) subangular euhedral zircon showing zoning and inclusions. Note that photomicrographs (b) and (e)–(i) are from macerated slides.

varying from 0.75 to 1.5 wt%, which may be attributed to the presence of rutile. Al_2O_3 shows higher values of about 16.4–23.8 wt%, probably due to the presence of a good proportion of clay minerals like illite, corroborated by XRD and EPMA data. Elevated values of $\text{Fe}_2\text{O}_3\%$ in few samples are evident from the reddish colouration in some of the samples (SPC-Tff and BJT-7) due to the oxidation on their surface. Major oxide data of tuffs when compared with that of Bijaigarh siliciclastics reflect significant disparity. Except for SiO_2 , the tuffs are enriched with TiO_2 , Al_2O_3 and K_2O as compared to the latter (table 2).

In all the bivariate scatter plots, using Al_2O_3 as the index of differentiation, the tuff samples cluster

quite distinctly in a separate field from Bijaigarh siliciclastics (figure 8). The major oxide data of Bijaigarh tuff have also been compared with the tuffaceous beds associated with different Proterozoic basins, i.e., Singhora (Das *et al.* 2009), Sukhda tuff, Indravati tuff and Dhamda tuff (Bickford *et al.* 2014). In all the plots, i.e., Al_2O_3 vs. SiO_2 , MgO , TiO_2 , CaO , $\text{Fe}_2\text{O}_3(\text{T})$, P_2O_5 , K_2O and $\text{REE}(\text{T})$ Bijaigarh tuff samples fall distinctly into separate fields as compared to other tuff samples. The Al_2O_3 vs. the SiO_2 plot exhibits that all the five tuffs (Bijaigarh, Singhora, Sukhda, Indravati and Dhamda) have varying silica percentage. The general scattering of samples is clearly visible along Al_2O_3 , i.e., the x -axis. This can be attributed to

Figure 8. Bivariate plots for major oxides (in wt%) using Al_2O_3 as the index of differentiation, showing the clustering of tuff and Bijaigarh shale. Data sources for Singhora tuff, Suhkda tuff, Indravati tuff and Dhamda tuff are mentioned in the text.

varying degrees of alteration of feldspars to clay minerals. The Al_2O_3 vs. the K_2O plot corroborates this, wherein it is evident that the Bijaigarh tuff has undergone the highest degree of alteration to clay minerals, i.e., illite as evident from mineralogical data. The Al_2O_3 vs. the TiO_2 plot exhibits that the Bijaigarh tuff is enriched with TiO_2 wt% which is indicated by the presence of rutile in the thin section study. Thus, the major oxide data are suggestive of the marked similarity in the geochemical characters of the Bijaigarh tuff as compared to other tuffs taking into consideration the general scattering of samples along Al_2O_3 , i.e., the x -axis. Interestingly, in all the bivariate plots (figure 8), the distinctness in the siliciclastic nature of the Bijaigarh shale in comparison with the Bijaigarh tuff is reflected. This is also corroborated by the higher $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio (5–9.5) in comparison

with that of the Bijaigarh tuff, ranging from 2.7 to 4.2. The SiO_2 vs. the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio diagram shows the scattering of samples from Bijaigarh shale in contrast to tuff samples which exhibits close clustering (figure 9). $\text{SiO}_2/\text{Al}_2\text{O}_3$ values for Bijaigarh siliciclastics show a gradual increase during weathering, transport and recycling, due to the increase of quartz in the modal framework at the expense of less-resistant components (Gallala *et al.* 2009). The $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio is often used as a grain-size indicator (Dypvik 1979). In contrast, both the tuff and associated siliciclastics exhibit similar $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ (0.2–0.3), $\text{Na}_2\text{O}/\text{K}_2\text{O}$ (0.02–0.05) and $\text{Al}_2\text{O}_3/\text{TiO}_2$ (18–25) ratios. The unique similarity in these ratios, in spite of the differences in the elemental concentration, could be possibly due to the exposure to similar post-depositional processes.

Figure 9. SiO_2 vs. $\text{SiO}_2/\text{Al}_2\text{O}_3$ plot to decipher between sedimentary and igneous parentage.

6.2 Trace elements

Higher Rb concentration and their positive correlation with K_2O and Al_2O_3 could be attributed to the presence of clay minerals, i.e., illite as evident from mineralogical and major oxide data. Zr values for tuff are higher (193–1126 ppm) as compared to Bijaigarh siliciclastics (180–260 ppm) due to the presence of zircon in the former, corroborated by petrographic data and also reflected by substantially higher Th, U and Yb values. Trace element data of tuff beds when compared with that of Bijaigarh siliciclastics show ubiquitously higher concentrations of LILE, HFSE and heavy metals (table 2). The Zr/Sc vs. the Th/Sc plot (McLennan *et al.* 1993) exhibits the clustering of Bijaigarh siliciclastics and tuffs from other Proterozoic basins separately (figure 10). The Th/Sc ratio is a pointer of the fractionation of the magmatic detritus and does not vary much in the sediment recycling. In contrast, the Zr/Sc ratio will increase significantly during sediment recycling with zircon enrichment/addition and can be considered as a useful indicator of heavy mineral concentration and recycling (McLennan *et al.* 1993). However, Bijaigarh tuffaceous samples when compared to Bijaigarh siliciclastics cluster separately. Overall, ubiquitously, Zr addition is evident in all the tuff samples perhaps indicative of the recycling process during deposition. Similarly, the Zr/Sm vs. the Nb/Ta (Foley *et al.* 2002) plot exhibits that the Bijaigarh tuff samples plot in the Archaean tonalite–trondhjemite–granodiorite (TTG) field is quite comparable to other tuffs, i.e., Sukhda,

Figure 10. Th/Sc – Zr/Sc diagram (McLennan *et al.* 1993) shows the Bijaigarh siliciclastics and tuff cluster in separate fields. Values of FV: felsic volcanic is after Condie (1993) and UCC: Upper Continental Crust after Taylor and McLennan (1985).

Figure 11. Zr/Sm vs. Nb/Ta plot (Foley *et al.* 2002) shows that Bijaigarh tuff and other basinal tuffs fall in the Archaean TTG field.

Dhamda and Indravati (figure 11). This indicates the similar tectonic setting of the source to tuffs.

6.3 Rare earth elements

$\sum \text{REE}$ of Bijaigarh tuff range from 171 to 380 ppm which are higher as compared to Bijaigarh siliciclastics 167–197 ppm (table 2). The tuffs are also enriched in LREE (236 ppm) and HREE (32 ppm) as compared to the siliciclastics with 146 and 20 ppm, respectively. Tuffs exhibit a well-fractionated pattern with $[\text{La}/\text{Yb}]_N = 8.4$, nearly flat $[\text{Gd}/\text{Yb}]_N = 1.06$ and well developed $\text{Eu}/\text{Eu}^* = 0.59$. These characteristics indicate their derivation from a felsic source and the negative Eu anomaly is regarded as an evidence of a differentiated source, similar to granite (Taylor and McLennan 1985;

McLennan 1989). Similar to major oxides and trace elements, the chondrite normalised REE plot exhibits distinct abundances and pattern for the Bijaigarh tuff and the associated siliciclastics (figure 12a). A similar behaviour is reflected in the PAAS normalised REE plots (figure 12b). In both the plots, the tuff samples indicate the enrichment of REE as compared to siliciclastics. The PAAS normalised pattern for the Bijaigarh tuff when compared to other tuffs (Singhora, Sukhda, Indravati and Dhamda) exhibits an overlap in REEs, viz., Pr, Nd, Sm, Eu, Gd, Tb and Er pointing towards comparable geochemical characteristics of the former to the latter (figure 13). The chondrite normalised REE patterns of the Bijaigarh tuff were compared with other tuffs (figure 13), exhibit overall highly fractionated REE patterns and a strong negative Eu anomaly. Indravati, Sukhda and Dhamda tuffs exhibit overall highly fractionated REE patterns with $[La/Yb]_N = 39.2, 64.2, 70.7$ and

$[Gd/Yb]_N = 7.8, 11, 13.2$, respectively, in comparison with Bijaigarh tuff with $[La/Yb]_N = 8.4$, $[Gd/Yb] = 1.06$ and Eu anomaly = 0.59. Indravati, Sukhda and Dhamda tuffs exhibit a strong Eu anomaly ranging from 0.3 to 5.3. The Singhora tuff is quite comparable to the Bijaigarh tuff in terms of overall REE fractionation with $[La/Yb]_N = 8.7$ and $[Gd/Yb]_N = 1.5$ and $Eu/Eu^* = -0.6$. The overall enrichment of HREEs is observed in the Bijaigarh tuff in comparison with tuffs from other Proterozoic basins (Singhora, Sukhda, Dhamda and Indravati). This is indicated by a higher abundance of Zr (173–1096 ppm) in the Bijaigarh tuff in comparison with tuffs (59–230 ppm) from other Proterozoic basins.

The multielement patterns of Bijaigarh tuff are compared to Singhora, Sukhda, Dhamda and Indravati tuffs (figure 14). The incompatible elements Zr, Hf, Sr, Ti, Ce, Tb, Y, Tm and Yb are enriched in the Bijaigarh tuff in comparison with

Figure 12. (a) Average chondrite normalised patterns of Bijaigarh tuff and Bijaigarh shale; (b) PAAS normalised patterns showing a range of Bijaigarh tuff, other basinal tuffs and Bijaigarh shale. Values of PAAS taken from Condie (1993).

Figure 13. Average chondrite normalised pattern of Bijaigarh tuff and its comparison with tuffs from other basins mentioned in the text.

these tuffs, while LILE (Rb, Ba, U, Th and K) and (Nb and Ta) of the Bijaigarh tuff are comparable to other tuffs (figure 14).

7. Interpretation and discussion

The field observations (figures 4, 5a and b), petrological (figures 6 and 7) and mineralogical data support the igneous parentage of the tuffaceous beds sandwiched within the Bijaigarh shale. The differences in the geochemical characters of the Bijaigarh tuff and shale are corroborated by the bivariate diagrams (figure 8), incompatible elemental ratio plots (figures 9 and 10), chondrite (figure 12a) and PAAS normalised diagrams (figure 12b). In all the discrimination plots, the

Bijaigarh tuff samples cluster separately when compared to the associated Bijaigarh shale/siliciclastics signifying their igneous parentage. Bijaigarh tuff/ash beds bear their testimony to the magmatic origin of felsic nature.

7.1 Classification and tectonic setting

Since the tuffaceous beds have undergone extensive alteration to clay minerals as evident from their petrography and major oxides, trace elements were used to infer their nature and tectonic setting. When plotted in the Nb/Y *vs.* Zr/TiO₂ * 0.0001 classification plot, Winchester and Floyd (1976) point to rhyolitic to rhyodacite affinity (figure 15) which is in conformation with the tuffs from other

Figure 14. Primitive mantle normalised (Sun and McDonough 1989) plot of trace elements of average Bijaigarh tuff and its comparison with Bijaigarh shale and Singhora tuff. Data sources for Singhora tuff, Sukhda tuff, Dhamda tuff and Indravati tuff are mentioned in the text.

Figure 15. $Zr/TiO_2 \times 0.0001$ vs. Nb/Y plot shows the composition of Bijaigarh tuff as rhyolitic to rhydacitic. Various fields are after Winchester and Floyd (1976). Data sources for Singhora tuff, Sukhda tuff and Indravati tuff are mentioned in the text.

Proterozoic basins like Singhora, Sukhda, Indravati and Dhamda. Tectonic discrimination diagrams using $Y + Nb$ vs. Rb (figure 16a) and Yb vs. Ta plots (figure 16b) show that the samples from the tuffaceous beds fall in the within-plate granite (WPG) field indicating passive margin setting. The tuff samples from Singhora (Das *et al.* 2009), Sukhda and Dhamda tuffs (Bickford *et al.* 2014) and the Indravati basin (Bickford *et al.* 2014) show quite similar tectonic affinity when compared with Bijaigarh tuff. The plots (figure 16a and b) show clustering and a partial overlapping of Bijaigarh tuff samples with other basinal tuff in the WPG

field. This is in conformation with the Zr/Sm vs. Nb/Ta (Foley *et al.* 2002) plot (figure 11) which exhibits TTG source for all tuffs.

7.2 Comparison of Bijaigarh tuff with tuffs from other Proterozoic basins

Bijaigarh tuff and the four other tuffs are compositionally similar in terms of petrography and mineralogy and their geochemical signatures are also quite comparable. This has been validated with various plots. Bijaigarh tuff similar to other tuffs exhibits rhyolitic to rhyodacitic affinity. The

Figure 16. (a) $Y + Nb$ vs. Rb , (b) Ta vs. Yb discrimination diagrams (Pearce *et al.* 1984) to determine the tectonic setting for tuffaceous beds/ash associated with Bijaigarh shale of Kaimur group. VAG: volcanic arc granite; ORG: ocean-ridge granite; Syn-COLL: syncollisional granite; and WPG: within-plate granite. Data sources for Singhora tuff, Dhamda tuff, Sukhda tuff, Indravati tuff are mentioned in the text.

bivariate plots with Al_2O_3 as the differentiation index (figure 8) and various discrimination plots, the Zr/Sc vs. Th/Sc plot (figure 10; McLennan *et al.* 1993), Zr/Sm vs. Nb/Ta plot (Foley *et al.* 2002) and the $Y + Nb$ vs. Rb plot (figure 16a and b; Pearce *et al.* 1984) clearly indicate the comparable geochemical behaviour of the Bijaigarh tuff to other basinal tuffs such as Sukhda, Singhora, Dhamda and Indravati. Chondrite normalised REE patterns also corroborate this (figures 12a and 13). This is supported by the multielement diagram (figure 14) which indicates the comparable behaviour of LILE, Nb and Ta in the Bijaigarh tuff. However, the REE pattern of the Singhora tuff is quite similar to that of the Bijaigarh tuff.

7.3 Post-depositional K-metasomatism

Glassy rhyolitic volcanic ash beds are highly susceptible to alteration and the rapid erosion of volcanic rocks and diagenetic alteration of volcanic fragments into clay is a common phenomenon (Huff *et al.* 1996). Fine-grained volcanic ash also alters to clay minerals very rapidly (García-Romero *et al.* 2005). Volcanic glass begins to convert to clay minerals almost immediately upon its formation (Fiore 1993) and is known to be the parent material for smectite. The recognition of these materials is the easiest in geologically younger deposits where smectite is a major constituent. Weaver and Beck (1977) indicate that the relative abundance of various clay minerals is a function of geologic age. But with time and deep burial, smectite undergoes a transition to more illite-rich deposits. Thus, the volcanogenic nature of the primary constituents becomes more difficult

to distinguish from detrital clays (Nadeau and Reynolds 1981). In such cases, the recognition of the primary magmatic texture can provide clues to their volcanic origin.

In the A–CN–K plot proposed by Nesbitt and Young (1984), the tuff beds and Bijaigarh siliciclastics cluster near illite on the A–K tie line (Mishra and Sen 2012). A higher degree of chemical weathering and plagioclase alteration can be inferred from enhanced CIA (75–80) and PIA (97–98) values. The glass shards, feldspars and micaceous minerals in the tuff samples have possibly been altered to illite (evident from the XRD analysis). However, a petrographic study shows that primary igneous texture has been retained in the tuff. Their mineralogical data indicate strong evidences for illitisation. The feldspars probably have undergone illitisation (figure 6c and d). Potassium metasomatism involves the conversion of kaolin (alteration product of volcanic ash) to illite by reaction with K^+ bearing pore waters. This can also occur by the replacement of plagioclase by potassium feldspar (Fedo *et al.* 1995). The possibility of post-depositional high degree K-metasomatism in the ash beds similar to its counterpart, i.e., Bijaigarh shale (Mishra and Sen 2012) cannot be denied. This is also supported by the similarity in K_2O/Al_2O_3 , Na_2O/K_2O and Al_2O_3/TiO_2 ratios in the tuff and siliciclastics.

7.4 Intrabasinal vs. extrabasinal input of volcanic ash

The recognition of subaerial or subaqueous depositional environment for a pyroclastic flow product is difficult in the rock record, and often

leads to controversy. A subaqueous flow may either be fed directly from subaqueous eruption or from a subaerial eruption that is reworked and deposited under subaqueous conditions (Fisher and Schmincke 1984; Cas and Wright 1991; McPhie *et al.* 1993). The reworking and transport of pyroclastic flows in subaqueous conditions rather than under subaerial conditions is inferred from features such as the shapes of glass shards, interbedding with non-volcanic sequence, good sorting producing crystal-rich and glass-rich layers, absence of any volcanic vent in the form of dyke or plug nearby (Wright and Mutti 1981; Cousineau 1994). The presence of dominant cusped shards and angular to subangular fragments indicates subaerial eruption (Cashman and Fiske 1991). The minerals in the Bijaigarh tuffaceous beds exhibit typical cusped-shaped glass shards, which are devitrified. The angular to subangular glass shards, muscovite, quartz and accessory minerals like rutile and zircon indicate subaerial eruption rather than phreatomagmatic eruption (Heiken and Wohletz 1985; Nemeth 2010). The absence of pumice and welding texture also negates the possibility of subaqueous eruption. The petrographic and mineralogical data of Bijaigarh tuff show the presence of a vitrophyric texture with bipyramidal quartz and resorbed feldspar, angular to subangular zircon, rutile, quartz, glass shards. The absence of pumice and welding texture is also observed in these tuffs. The Son valley sector is devoid of any evidences of intrabasinal volcanism during the deposition of Upper Kaimur suggest that these tuff beds are possibly the result of the extrabasinal volcanism. It has been observed that the rhyolitic magmas are ejected in violent and explosive eruptions. Their ashes travel great distances, sometimes thousands of kilometres before falling (Coutinho and Hachiro 2005; Self 2006; Poma *et al.* 2009).

Chanda and Bhattacharya (1982) advocated tectonic activity preceded the deposition of Kaimur which is evidenced by frequent changes in its sedimentation pattern. The depositional environment of Kaimur group sediment ranges from a tidal flat environment to a storm-influenced inner shelf setting to a lagoonal environment to nearshore braidplain delta in the lower part to the braidplain aeolian sandsheet as we move upwards during the deposition of Dhandraul Quartzite (Chakraborty and Bose 1990; Bhattacharya and Morad 1993; Chakraborty 2006). Thus, Chanda and Bhattacharya (1982) suggested the evidences of the omnipresent north-westerly wind drift current direction during the

deposition of the Upper Kaimur. This suggests that fine-grained volcanic ashes plausibly had their source towards the south or the south-east. For this reason we have compared Singhora tuff (Das *et al.* 2009), Sukhda tuff and Dhamda tuff (Bickford *et al.* 2014) from the Chhattisgarh basin, which is the second largest of the Proterozoic basins of peninsular India and the Indravati basin (Bickford *et al.* 2014). The fine-grained sediments or volcanic ashes possibly were transported and trapped with depositing Bijaigarh sediments in the lagoonal environment. The geochemical data also suggest that tuffs associated with Bijaigarh siliciclastics also show close affinity to the within-plate type of tectonic setting in the passive margin which supports this deduction. Bose *et al.* (2001), Paikaray *et al.* (2005) and Sur *et al.* (2006) considered the offshore origin of Bijaigarh shale. Singh (1980) considered them to have been deposited in a lagoonal euxinic atmosphere. The atmosphere becomes anoxic due to the influx of greenhouse gases like CO₂ and water vapour resulting from large-scale continental volcanism (Young 1995; Tajika 2003; Kah and Riding 2007). This is evident from the contemporaneity in the occurrence of tuffaceous beds in nearly all the Proterozoic sedimentary successions in the Indian subcontinent.

7.5 Relation between volcanic detritus and microbiota

The volcanic ash falls provide a geochemically favourable substrate that is both nutrient-rich and has high water retention, making them good hosts for microbiota (Parnell and Foster 2012). The value of volcanic ash to plant life is implied by the fact that the most densely populated area of the world in Indonesia, and other high-density populations in Africa, are on young volcanic ash with very high soil productivity (Shoji *et al.* 1993). Kumar (2001), Schieber (2004), Sarkar *et al.* (2006) and Sur *et al.* (2006) suggest that microbial mats colonised in shallow water during the deposition of Bijaigarh shale. Life flourished possibly due to the addition of volcanic ashes with Bijaigarh siliciclastics. This plausibly bears testimony to the effect of extrabasinal volcanism during the deposition of tuff associated with the Bijaigarh shale.

7.6 Regional and global significance of Bijaigarh tuff

The Proterozoic basins have been marked by tuffs at different stratigraphic levels. Bickford *et al.*

(2011a, b, 2014) have interpreted that Sukhda and Dhamda tuffs of the Chhattisgarh basin and tuffs from the Indravati basin were the result of 1000 Ma rhyolite ‘flare-up’ in Peninsular India. This was the consequence of the accretion of parts of east Antarctica, specifically the Rayner terrane (Veevers and Saeed 2009) with the Indian craton during the assembly of Rodinia. This accretion is recorded in the high-grade Eastern Ghats mobile belt (EGMB) in peninsular India (Rogers and Santosh 2004; Rino *et al.* 2008). This tectonothermal event is reported to be correlatable with the ‘Grenville Orogeny’ and is placed at ~ 1100 Ma by Roy *et al.* (2006), at ~ 1000 Ma by Bhowmik *et al.* (2010) which acted as the basement ridge between Rajasthan and the Son valley sector (Sarkar *et al.* 1995; Prasad and Rao 2006). In the absence of evidence of intrabasinal volcanism during the deposition of Bijaigarh shale, frequent changes in the sedimentation pattern of Kaimur and evidences of the omnipresent north-westerly wind drift current direction during the deposition of Upper Kaimur (Chanda and Bhattacharya 1982), this hypothesis favours and supports the extrabasinal and subaerial origin of Bijaigarh tuff of rhyolitic and rhyodacitic nature.

7.7 Stratigraphic marker horizon for Kaimur group sedimentation

The tuff beds contain a significant proportion of volcanic material that makes them more interesting. These beds represent an important stratigraphic marker horizon for Kaimur group sedimentation. Zircon has been used, in particular, and can be a valuable aid in determining the precise ages of the containing tuff beds (Huff *et al.* 1997). Important advances have been made in generating reliable age data from the tuffaceous strata preserved within the Proterozoic basins of India (Rasmussen *et al.* 2002; Ray *et al.* 2002; Patranabis Deb *et al.* 2007; Das *et al.* 2009; Bickford *et al.* 2014, 2017; Mishra *et al.* 2018).

The Kaimur Group basal sequences are intruded by 1073 ± 13.7 Ma Majhgawan kimberlite (Gregory *et al.* 2006). The kimberlite pipes, which intrude the Semri and Kaimur Groups, have been dated at 1140 ± 112 Ma (Paul *et al.* 1975) and 1067 ± 31 Ma (Kumar *et al.* 1993). Therefore, the age of the Kaimur group sedimentation have been constrained between 1100 and 1150 Ma (Kumar *et al.* 1993; Meert and Torsvik 2003; Gregory *et al.* 2006). Malone *et al.* (2008) inferred the closure age

of the Vindhyan sedimentation was about 1000 Ma, with the age of the Kaimur sedimentation being around 1100 Ma. These ash beds are required to be dated as this could provide us the important clue to the initiation of the sedimentation of the Upper Vindhyan succession.

8. Conclusions

The tuffaceous beds and the siliciclastics sandwiching them from the Bijaigarh formation of the Kaimur group were studied. The field observations, petrography, mineralogy and geochemical characteristics of the Bijaigarh tuff have been compared with Bijaigarh shale from the Upper Kaimur group of the Vindhyan supergroup, to ascertain their diverse nature and processes of origin. The geochemical data of the Bijaigarh tuff have been compared with tuffs from (Singhara, Sukhda and Dhamda) Chhattisgarh and Indravati basins. Some of the key aspects are listed below:

- The tuffaceous beds occur sandwiched within the Bijaigarh siliciclastics of the Kaimur Group, Vindhyan supergroup in Son valley, with a lateral continuity of about 10 km.
- On the basis of field disposition, petrographic and geochemical characteristics, magmatic origin can be inferred for the tuffaceous beds which can be distinctly distinguished from the adjacent detrital sediments of Bijaigarh shale.
- Tuffs are rhyolitic to rhyodacitic in nature deposited in the within-plate type of tectonic setting with Bijaigarh siliciclastics. The mineralogical and geochemical data provide strong evidences for post-depositional K-metasomatism.
- The paucity of evidences for intrabasinal volcanism during the sedimentation of the upper Kaimur group supports the deposition of volcanic ash beds from extrabasinal sources along with Bijaigarh sediments in a lagoonal environment.
- Bijaigarh tuff when compared with tuffs from other Proterozoic basins reveals similarity in the geochemical signatures which is indicative of comparable sources. The presence of rhyolitic tuffs at ~ 1000 Ma may possibly be linked to probable large crustal-scale tectonothermal events taking place in the EGMB during the Grenville orogeny.
- Tuffs will provide useful tools for correlation of the contemporaneous tuffs occurring in other

Proterozoic basins of India, viz., Chhattisgarh, Indravati, etc. Integration of elemental compositions with mineralogical and textural observations makes possible the establishment of the tuffaceous beds as stratigraphic markers in the Upper Vindhyan stratigraphy. This would facilitate wider implications for the precise and reliable correlations of the Proterozoic basins of India.

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