Petrographic controls on phosphorous distribution in coal seams of the Jharia basin, India

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In recent years, the international coking coal market is experiencing an acute shortage of coal supply which has caused a fluctuation in its price. Degradation of coke, in the blast furnace, is largely controlled by its inherent mineral matter. Phosphorous occurs in all coals in minor or trace amounts and is an important parameter to coal users, particularly in steel industries. The mode of occurrence and distribution of phosphorous minerals in 17 coal samples of the Jharia coal basin were investigated through petrographic examinations, technological characterisation and phosphorous distribution. The results reveal that the dull bands are eight times more enriched in phosphorous than the bright bands. The macerals of the inertinite group and mineral matter positively correlate with the phosphorous content, whereas vitrinite macerals have an apathetic correlation. The impact of the thermal alterations is localised and diminishes away from the contact of the intrusion. In contrast, the faulting does not appear to have any effect on the phosphorous content.

Keywords. Dull band; bright band; phosphorous; maceral; dyke.

1. Introduction

Phosphorous, which is a very important biogenic element and is essential for all living cells, is observed to be around 10 times more concentrated in many present-day plants and dried modern plants than in coal (Francis 1961). Phosphorous is released from the plant structure and, in many cases, re-precipitated elsewhere in the peat bed by processes associated with organic decay (Swain 1970; Ward *et al.* 1996). Swain (1970) observed that phosphorous breaks down to orthophosphate (HPO_4^-) and is removed from rotting vegetation. Phosphorous dissolves more in acid environments

than in ferric iron (Patrick and Khalid 1974). Ionic potential provides a better understanding of the organic and inorganic affinities of phosphorous (Powell 1987). Bertine and Goldberg (1971) estimated the average phosphorous content of coal to be 0.05% or 500 ppm on a worldwide basis. Although this is close to the average phosphorous content of 420 ppm (0.042%) for sedimentary rocks (Ronov and Korzina 1960), it is less than 700 ppm (0.07%) for soils (Swaine 1980). There have been a number of studies investigating the distribution of phosphorous in coal in order to classify them into those having organic and inorganic affinities. Although the occurrence of phosphorous-bearing

organic compounds (phospho-proteins) in plant tissues is well known, there is no direct evidence of organically bound phosphorous in coal (Burchill *et al.* 1990). Swaine (1990) also observed the possibility of organic phosphorous compounds in coal, but the bulk of phosphorous is generally thought to be present as inorganic mineral components. Phosphorous, although generally low in concentration in coal, is a significant factor in the marketing and utilization of coking coals (Ward *et al.* 1996). Phosphorous in steel is known to reduce its flexibility and toughness, thereby increasing the possibility of breakage during processing, fabrication and service. It is therefore generally considered to be an undesirable element in coal (Bloom *et al.* 1990; Ryan and Khan 1997). Virtually all phosphorous in coal is transferred to coke during coke production and interacts with the iron ore (Mahony *et al.* 1981; Ward *et al.* 1996) during steel production. Phosphorous also causes intergranular segregation in the process of continuous casting and deteriorates the ductility and toughness of products (Marique and Nilles 1984). Moreover, it is also known to form superheater deposits in certain types of boilers (Burchill *et al.* 1990) and is also reported to poison the catalysts in liquefaction processes (Kovach and Bennett 1975). Phosphorous provides brittleness to steel due to its presence as an oxide impurity, whereas desired concentration of phosphorous is necessary in maintaining high-quality steels (Stubbles 1986). Phosphorous content entering the hot metal can be estimated as it is all retained in the coke (Mahony *et al.* 1981) and therefore it is possible to calculate the phosphorous content in the coke by an estimate of coke yield in the samples. Significant works on the phosphorous content of coals have been carried out by many workers, viz., Gluskoter *et al.* (1977), Zhou *et al.* (1982), Kilby (1986), Hill (1988), Burchill *et al.* (1990), Goodarzi *et al.* (1990), Bohor and Triplehorn (1993), Raza *et al.* (1995), Ryan and Boehner (1995), Ward *et al.* (1996), Ward (2016), Seredin (1996), Rao and Walsh (1997, 1999), Hower *et al.* (1999), Burger *et al.* (2000, 2002), Willett *et al.* (2000), Mardon and Hower (2004), Dai *et al.* (2012a), Moore and Esmaeili (2012), Seredin and Dai (2012), Spears (2012) and Dai *et al.* (2015a). Apatite is the most common phosphorous-bearing minerals found in coal (Ward *et al.* 1996; Ward 2002; Querol *et al.* 1997; Reifenstein *et al.* 1999; Wang 2009; Hackley *et al.* 2005; Kalkreuth *et al.* 2006; Dawson *et al.* 2012; Hower *et al.* 2012). In addition to apatite, Mahony *et al.* (1981) noted

the presence of evansite and wavellite in some British coals. Mackowsky (1968), in some European coal samples, described the occurrence of non-crystalline phosphate gel or cellophane. Moreover, aluminophosphate minerals of goyazite group have been reported in the residues of a numbers of Australian coal samples by X-ray diffraction studies of low temperature (oxygen plasma) ash (Ward 1974, 1978). These represent a range of solid solutions involving members of the goyazite–gorceixite–crandallite–florencite group (Finkelman and Stanton 1978; Crowley *et al.* 1993; Creelman and Ward 1996; Ward *et al.* 1996; Rao and Walsh 1997, 1999; Alastuey *et al.* 2001; Dai *et al.* 2012b, 2015b). Skeletal fragments and coprolite particles rich in phosphate may also be present in coal in some cases (Diessel 1992). Electron microscope and optical studies indicate that the aluminophosphates and phosphates in many coals occur as pore and cell infillings (Cook 1962; Ward *et al.* 1996; Rao and Walsh 1999). Dai *et al.* (2016) observed the abundance of cavities in inertinites in comparison with vitrinite macerals, making more channels available for water movement and pore spaces for subsequent mineral deposition. Information on the mineral matter in coal is helpful in estimating the likely effects of beneficiation on trace-element reductions (Huggins *et al.* 1993; Singh *et al.* 2010; Prachiti *et al.* 2011; Singh *et al.* 2015a, b, 2016a, b). Furthermore, the knowledge of the minerals and their characteristics of the relevant feed coal can be used to provide a basis for understanding the interactions they may have in different coal utilisation processes (Singh and Singh 1995; Singh *et al.* 2015a; Dai *et al.* 2016; Hower *et al.* 2016; Ward 2016). Phosphorous content of coals varies geographically through geological time. Cretaceous coals from Western Canada and Permian coals from India and Australia have higher phosphorous concentrations than carboniferous coals from USA and Europe (Ryan and Grieve 1996; Ward *et al.* 1996; Varma and Mishra 2005). However, very little information is available related to phosphorous content of Indian coals (Varma and Mishra 2005; Prachiti *et al.* 2011). Authors have chosen 17 coal samples belonging to the Barakar Formation of Lower Permian age of the Jharia basin to investigate nature and occurrence of phosphorous. Special emphasis is given on the occurrence of phosphorous in dull and bright bands within the samples, effect of faulting and igneous intrusion on phosphorous content of coals.

2. Geological setting

The Jharia coal basin is located in the Dhanbad district of Jharkhand state, and it is the prime source of coking coal in India. The coal basin is a Gondwana sedimentary basin of the Damodar valley of eastern India (Fox 1930; Mehta and Murthy 1957). The field is roughly sickle shaped and has an areal extent of about 458 km² with about 40 km length in the east–west direction and about 20 km width in the north–south direction (figure 1; Fox 1930; Chandra 1992). Overlying the Archaean basement, unconformably, the sedimentary sequence of this basin has the Talchir Formation at its base, which is, successively, overlain by the fluvial as well as fluvio-lacustrine sediments of the Barakar, the Barren Measures and the Raniganj Formations (Fox 1930; Mehta and Murthy 1957; Sengupta *et al.* 1979). The sediments

are deposited within an intracratonic extensional setting (Ghosh and Mukhopadhyay 1985). The Barakar Formation with 18 persistent seams and Raniganj Formation with 12 persistent seams are the main coal-bearing formations (Fox 1930). In the Barakar Formation, Fox (1930) had identified 18 coal seams from bottom to top starting with seam I to seam XVIII. However, 46 seams have been reported later by Verma *et al.* (1989) in the Barakar Formation including 18 major seams and 5 local seams, and the remaining 23 seams are actually the splits of the major seams. The coal seams are affected by faults that are of both post- and syn-depositional origins (Ghosh and Mukhopadhyay 1985). The Barren Measures Formation outcrops in the central part of the basin and has a thickness of 750 m.

The regional faults against the lithology of the Barakar Formation demarcate the northern

Figure 1. Geological map of the Jharia coal basin (Fox 1930; Verma *et al.* 1989; Chandra 1992; CIL 1993). The study areas are shown in the map. B: Bhelatand colliery; J: Jamadoba colliery; L: Loyabad colliery; S: Sijua colliery.

Table 1. Generalised stratigraphic succession of the Jharia coal basin (Mukhopadhyay *et al.* 2010).

Age (Ma)	System/Period	Series/Epoch	Stage/Age	Symbols (as in map)	Formation (Thickness)	Lithotype
Present	RECENT					
2.38					Alluvial [#]	
66	TERTIARY			Unconformity		
110					Igneous intrusives	
252.2	CRETACEOUS			Unconformity		
	PERMIAN	Upper	Changhsingian		(Raniganj) (800 m)	Fine grained feldspathic sandstone, shales with coal seams
			Lopingian			
			Wuchiapingian			
260					Barren Measures (730 m)	Buff coloured sandstone, shales and carbonaceous shales
			Guadalupian			
271		Lower	Kungurian		Barakar (1250 m)	Buff coloured coarse and medium grained feldspathic sandstone, grits, shales and carbonaceous shales and coal seams
			Artinskian		Karharbari	
			Cisularian			
			Asselian		Talchir (245 m)	Greenish shale, very fine grained sandstone, sandy shale, conglomerate and basal tillite
290		Carboniferous				
299			Gzhelian			
302				Metamorphics		Granite gneiss, mica schist, quartzite, amphiboles

and eastern boundaries of the basin (Fox 1930; Ghosh and Mukhopadhyay 1985). The generalised lithostratigraphic succession of the Jharia coal basin is shown in table 1 (Fox 1930; Chandra 1992; Mukhopadhyay *et al.* 2010).

3. Materials and methods

3.1 Collection of samples

Samples were collected from the Jamadoba (J), Sijua (S), Bhelatand (B) and Loyabad (L) collieries of the Jharia basin. A total of 17 coal samples including four igneous intrusive affected samples and two samples in proximity to a fault were

collected through channel sampling methods following ASTM (2015). The location of the samples is provided in figure 1. Dull and bright bands were manually separated following the classification system suggested by Thiessen (1920) and Francis (1960) from samples JJ14, JJ16, JS11, JS12, JB13 and JB15 to see the distribution of phosphorous.

3.2 Technological properties

The technological properties, viz., moisture content (W^a), ash yield (A^d), volatile matter yield (VM^{daf}) and fixed carbon content were determined for the coal samples following the IS (1984).

3.3 Micropetrographic analysis

Coal samples were crushed to <1 mm size to prepare pellets and were studied under reflected light with a 'Leitz MPV2' reflectance microscope with an oil immersion lens and fluorescence attachment following standard procedures (ICCP 1971, 1998, 2001) at Coal Geology and Organic Petrology Laboratory, Department of Applied Geology, Indian Institute of Technology (Indian School of Mines), Dhanbad, India, and macerals were identified following ICCP classification of macerals (ICCP 1971, 1998, 2001). The vitrinite reflectance measurements were carried out on prepared coal pellets (ASTM 1994).

3.4 Phosphorous determination

The gravimetric (phosphomolybdate) method (IS 1979) was applied to determine the content of phosphorous. In the adopted method, it is assumed that the total phosphorous is retained in the ash. In this procedure, sample of the coal is completely burnt into ash as specified in IS (1984). The extraction was carried out. First, the ash was powdered in an agate mortar to pass through 63- μ m IS sieve. A preliminary determination is carried out using 0.5 g of ash, and depending upon the phosphorous content, an appropriate quantity of the ash (0.5–4 g) is weighed into a platinum crucible of about 30 ml capacity following the standard. Then, 10 ml concentrated nitric acid solution and 5 ml of hydrofluoric acid solution were added and left for 45 min to dry. To ensure the complete removal of the hydrofluoric acid, further 5 ml of concentrated nitric acid was again added and left to dry. Furthermore, 15 ml of dilute nitric acid solution was added and evaporated until it becomes to about 7 ml. The solution was then transferred to a 250 ml beaker, and the washings of the crucible were added to it, so that the combined volume of the washings and the original solution was 80 ml. Then beaker is covered with a clock glass and is boiled for 15 min. The extract obtained is filtered with a filter paper into a 40-ml beaker and washed with water until 10 ml of remaining washings give an alkaline reaction with final volume of the filtrate up to 250 ml. Afterwards, the solution was evaporated to about 50 ml, and the concentrated ammonium hydroxide solution was added till the precipitate of iron and aluminium hydroxide appears. Then precipitate was redissolved by adding concentrated nitric acid and the excess of concentrated nitric

acid solution and 3–4 g of potassium nitrate were added. The volume of the liquid should not now exceed 70 ml. The solution is then heated to 75°C with subsequent addition of ammonium molybdate solution and maintained at 50°C for 30 min. The beaker containing the phosphomolybdate precipitate was kept with stirring for about 2.5 hr at room temperature (25–30°C) and allowed to settle down, and then the precipitate was filtered through the weighed sintered-glass crucible. Finally, the phosphomolybdate precipitate was washed four times with weak nitric acid solution (II), using 15 ml each time, two times with dilute ammonium nitrate solution, using 15 ml each time, two times with water, using 5 ml each time and, finally, three times with absolute alcohol using 3 ml each time. Later, it was dried at 125–130°C in an oven for 30 min and cooled in a freshly charged desiccator containing concentrated sulphuric acid solution. A blank determination was carried out in the same way as described above but by the substitution of a pure phosphorous compound diluted to contain an amount of phosphorous approximately equal to that in the ash.

Phosphorous content is calculated in ash yield in the following equation:

$$(A) = 1.65[X - (V - 60.6Z)/M], \quad (1)$$

where A is the mass of the phosphomolybdate precipitation g , V the mass of the phosphomolybdate precipitate obtained from the pure phosphorous compounding g , Z the calculated mass of the phosphorous taken for the blank determination in g and M the mass of the ash yield taken for the testing.

The phosphorous content in coal is determined by the following equation:

$$(P) = 0.01 \times A \times C, \quad (2)$$

where P is the phosphorous content in coal (wt%), A the mass of phosphorous in ash (wt%) and C the ash yield of coal (wt%).

4. Results and discussion

The results related to technological properties of the collected coal samples of the Jharia basin show a significant relation with the phosphorous content (table 2). The ash yield (dry basis) for the studied coal samples varies from 15.56 to 27.02 wt% and the phosphorous content ranges between 0.030 and 0.284 wt% and exhibits a strong positive

Table 2. *Technological properties, vitrinite reflectance and phosphorous content of coal samples collected from different collieries of the Jharia basin.*

SN	Colliery name	Pit/seam no	Comment	M^a (wt%)	VM ^{daf} (wt%)	A^d (wt%)	P (wt%)
JJ14	Jamadoba	2/XIV	Bright and dull band separated	2.0	25.12	21.22	0.122
JJ16	Jamadoba	6 and 7/XVI	Bright and dull band separated	3.0	35.53	15.56	0.030
JS10	Sijua	2/X	–	3.2	27.96	26.49	0.220
JS11	Sijua	8/XI	Bright and dull band separated	3.1	24.80	27.02	0.230
JS12	Sijua	15/XII	Bright and dull band separated	3.3	27.89	22.89	0.158
JS13	Sijua	15/XIII	–	2.8	27.59	21.70	0.137
JB13	Bhelatand	XIII	Bright and dull band separated	2.6	26.47	22.07	0.144
JB14	Bhelatand	XIV	–	1.9	31.39	21.30	0.130
JB15	Bhelatand	XV	Bright and dull band separated	2.2	25.23	20.45	0.112
JL14	Loyabad	XIV	–	2.0	31.05	21.12	0.131
JL15	Loyabad	XV	–	2.1	26.03	20.33	0.113
JC2*	Jamadoba	2/XIV	Collected between 13th and 14th gallery adjacent to dyke	3.80	9.96	31.18	0.139
JC3*	Jamadoba	2/XIV	Collected between 13th and 14th gallery, at a distance of 10 m from dyke	1.70	24.64	15.36	0.284
JC4*	Jamadoba	2/XIV	Collected between 13th and 14th gallery, at a distance of 30 m from dyke	1.70	19.19	17.29	0.183
JC5*	Jamadoba	2/XIV	Collected between 13th and 14th gallery, at a distance of 50 m from dyke	2.10	25.90	20.33	0.123
JC6A	Jamadoba	2/XIV	Collected in the gallery carrying conveyor belt, adjacent to the fault	0.50	34.58	22.41	0.122
JC6B	Jamadoba	2/XIV	Collected in the gallery carrying conveyor belt, 15 m away from the fault	1.70	27.37	20.45	0.123

SN: sample number; M : moisture content; VM: volatile matter yield; A : ash yield; P : phosphorous content; d: dry basis; daf: dry ash free basis; *: samples affected by dyke; a: analytical state.

correlation with phosphorous content ($R^2 = 0.99$; figure 2). The phosphorous content is mainly concentrated in ash yield derived from the mineral matter content of the coal (Gentzis and Godarzi 1997). Furthermore, the trace-element content in coal or in ash increases with an increase in ash yield, indicating their mineral-matter association (Clark and Swaine 1962; Prachiti *et al.* 2011; Singh *et al.* 2015b, 2016b). Relationship between phosphorous content in the separated bright and dull bands of few samples (JJ14, JJ16, JS11, JS12, JB13 and JB15; table 3) revealed that the bright bands

Figure 2. Relationship between the phosphorous content (wt%) and ash yield (wt%).

of the samples contain approximately eight times less phosphorous than the dull bands.

This may be explained as dull bands, in contrast to bright bands, chiefly contain inertinite macerals. Moreover, the dull bands are also marked by larger ash yield compared to the bright bands (table 3). A similar positive correlation between the phosphorous concentration and dull bands was observed by Harris *et al.* (1981). Berger (1958) has also noticed 8–10 times more concentration of phosphorous in dull bands as compared to that in bright bands in the case of Russian coals, which are rich in inertinite macerals. The above observation is further supported with the micropetrographic results taken into consideration. The results related to micropetrographic analysis are given in table 4. The total content of vitrinite macerals exhibits a strong negative relation with phosphorous content ($R^2 = 0.95$; figure 3), whereas the total content of inertinite macerals shows a strong positive relation with phosphorous content ($R^2 = 0.94$; figure 4). Gluskoter *et al.* (1977) elucidated that the phosphorous is preferentially concentrated in inertinite maceral, which indicates that the inorganic matter is a significant factor in controlling the phosphorous concentration. Moreover, the total amount of mineral-matter content (wt%) determined through micropetrographic analysis also shows a strong positive relation with the phosphorous content ($R^2 = 0.91$; figure 5). These results indicate the inorganic nature of phosphorous mainly within the

Table 3. Technological properties and phosphorous content of bright and dull bands (separately) of individual coal samples.

SN	Lithotype	M^a (wt%)	VM^{daf} (wt%)	A^d (wt%)	P (wt%)
JJ14	Bright band	2.00	24.22	14.90	0.025
	Dull band	1.70	24.32	21.36	0.200
JJ16	Bright band	2.80	32.26	10.08	0.006
	Dull band	2.90	36.72	16.99	0.047
JS11	Bright band	3.00	23.92	15.51	0.040
	Dull band	3.10	24.33	27.04	0.357
JS12	Bright band	3.20	22.46	14.46	0.027
	Dull band	3.00	27.42	24.79	0.245
JB13	Bright band	2.50	22.59	12.82	0.037
	Dull band	2.45	26.27	21.56	0.305
JB15	Bright band	2.20	21.57	11.35	0.027
	Dull band	2.00	26.58	17.68	0.239

SN: sample number; M : moisture content; VM: volatile matter yield; A : ash yield; FC: fixed carbon content; d: dry basis; daf: dry ash free basis; a: analytical state; P : phosphorous content.

Table 4. Maceral composition and vitrinite reflectance of coal samples collected from different collieries of the Jharia coal basin.

SN	V ^{mmf} (vol%)					I ^{mmf} (vol%)										L ^{mmf} (vol %)		I ^{mmf} (vol%)					R ^o _{max} (%)	
	Te	Co	Vd	Total		Os ^f	Ps ^f	Of	Pf	Mi	Ma	Ind	Total	MM		Total	MM	R ^o _{max} (%)	Total	MM	R ^o _{max} (%)	Total	MM	R ^o _{max} (%)
JJ14	5.41	40.64	0.98	47.03	0.00	25.46	0.80	17.20	0.00	0.50	2.00	7.00	52.96	23.00	0.80									
JJ16	4.55	49.33	1.02	54.90	0.00	15.25	1.20	18.40	0.50	0.00	1.55	8.20	45.10	18.00	0.76									
JS10	7.25	27.29	2.02	36.56	0.01	30.73	0.00	21.20	0.00	0.00	0.00	11.50	63.43	27.00	0.69									
JS11	8.54	25.92	1.04	35.50	0.00	26.00	1.00	25.40	0.00	0.00	1.60	10.50	64.50	27.50	0.63									
JS12	6.72	35.51	0.96	43.19	0.00	20.81	1.20	22.20	0.00	1.00	2.00	9.60	56.81	25.00	0.60									
JS13	7.64	36.75	1.04	45.43	0.00	22.86	0.80	18.60	0.00	0.00	2.50	9.80	54.56	24.00	0.69									
JB13	5.45	38.14	1.08	44.67	0.02	23.81	0.00	20.40	0.00	1.50	2.00	7.60	55.31	23.50	0.75									
JB14	6.48	36.88	1.82	45.18	0.00	25.01	0.60	18.60	0.60	0.50	1.50	8.00	54.81	24.00	1.01									
JB15	7.52	39.76	1.72	49.00	0.00	24.40	0.60	17.50	0.00	0.00	1.60	6.90	51.00	22.00	0.86									
JL14	12.24	32.18	1.64	46.06	0.02	28.62	0.80	16.20	0.00	0.00	1.50	6.80	53.92	21.00	0.79									
JL15	10.88	31.70	1.42	44.00	0.00	27.20	1.20	18.20	0.20	0.00	2.00	7.20	56.00	21.50	0.70									
JC2*	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.30	nd									
JC3*	0.00	5.05	0.00	5.05	0.00	19.60	0.00	17.33	0.00	0.00	0.00	0.00	36.93	25.00	nd									
JC4*	4.56	26.93	6.80	37.57	0.00	27.03	0.00	18.6	0.80	0.00	0.00	4.6	51.03	23.00	nd									
JC5*	5.44	39.78	1.08	46.30	0.80	24.58	1.00	18.6	0.00	0.00	2.40	6.90	52.90	22.20	nd									
JC6A*	6.45	39.62	1.99	48.06	0.60	25.66	0.00	17.58	0.00	0.50	2.44	5.16	51.34	23.60	nd									
JC6B*	5.48	40.46	1.66	47.60	0.00	26.79	0.00	18.65	0.00	0.00	2.66	4.32	52.4	22.0	nd									

SN: sample number; Te: telinite; Co: collotelinite; Vd: vitrodetrinite; Os^f: oxysemifusinite; Ps^f: pyrosemifusinite; Of: oxyfusinite; Pf: pyrofusinite; Mi: micrinite; Ma: macrinite; Ind: inertodetrinite; MM: mineral matter; V: vitrinite; L: liptinite; I: inertinite; mmf: mineral-matter free basis; *: samples affected by dyke; R^o_{max}: mean maximum vitrinite reflectance in oil; nd: not determined.

Figure 3. Relationship between the phosphorous content and vitrinite maceral content (vol%).

Figure 4. Relationship between the phosphorous content and inertinite macerals (vol%).

Figure 5. Relationship between the phosphorous content (wt%) and petrographically visible mineral matter content (vol%).

studied coals, which are typically more concentrated within the dull bands and are associated with the inertinite macerals. The vitrinite (Vt^{mmf}) and inertinite (I^{mmf}) contents of coal samples in the studied area vary from 35.50 to 54.90 and 45.10 to 65.50 vol%, respectively (table 2). Lipinites of macerals were identified only in traces in all the coal samples. The mean maximum vitrinite reflectance (R^o max) was determined for JJ14, JJ16, JS10, JS11, JS12, JS13, JB13, JB14, JB15, JL14 and JL15 coal samples (table 2) and was varied between 0.60 and 1.00%. The technological properties of coal samples also reveal that sample JC2*, in immediate contact with the dyke, is marked by least volatile matter yield (9.96 wt%, dry ash free basis; table 2) and largest fixed carbon content (90.04 wt%; daf basis), which might have been caused due to the impact of the intruded dyke. The ash yield was observed to increase from 15.36 wt% (dry basis) in sample JC3* to 31.18 wt% (dry basis) in sample JC2* (in immediate contact with the intrusion). The large ash yield in sample JC2* might have been caused due to the secondary mineralisation that may have taken place due to the impact of the intrusion (Finkelman *et al.* 1998). Mastalerz *et al.* (2009) and Schimmelmann *et al.* (2009) have also observed the presence of carbonates within coal seams associated with igneous intrusions, which might have been formed from the hydrothermal solutions. Sample JC3*, which is at a distance of 10 m from the dyke, shows the largest phosphorous content (0.284 wt%; table 2), indicating that the chemical fluids might have migrated from the dyke. Samples JC3* (1.70 wt%) and JC4* (1.70 wt%) adjacent to the dyke correspond to the lowest moisture content among the heat-affected samples (table 2). The effect of intruded dyke is manifested with the decrease in the moisture and volatiles with concomitant increase in the ash yield, fixed carbon and phosphorous content. The coal seams adjacent to the intrusion are converted to jhama (natural coke). The impact of dyke is confined to a short distance, and the effect of heat dies out away from the dyke. The phosphorous concentration decreases as the distance from the dyke increases to 30–40 m. The concentration of phosphorous in sample JC6A (collected adjacent to the fault) is 0.122 wt%, whereas the concentration in sample JC6B (collected 15 m away from fault) was observed to be 0.123 wt% (table 4). It seems that the faulting has no effect on the phosphorous concentration. Steel industries are developing strategies to limit the phosphorous content in coal

that is used for making steel. This study overall provides an insight into the inorganic nature of phosphorous, which may be helpful for steel industry in targeting the coal seams of the basin having lower phosphorous content. The study also points towards the concentration of phosphorous in coal seam near to lamprophyre dyke and in dull bands/inertinites.

5. Conclusions

- The relationship of phosphorous content with ash yield and mineral matter content indicates its inorganic nature.
- The phosphorous content is mainly concentrated in dull bands.
- The intertinite macerals provide suitable environment for deposition of phosphorous minerals.

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