Downward continuation and tilt derivative of magnetic data for delineation of concealed coal fire in East Basuria Colliery, Jharia coal field, India

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The present study deals with the characterization of subsurface coal fires of East Basuria colliery in Jharia coal field, India using tilt derivative and downward continuation of magnetic data. Magnetic data processing methods such as diurnal correction, noise removal, reduction to pole, tilt derivative and downward continuation have been used to process the data and for the interpretation of results on the basis of magnetic properties of overlying materials which change with the temperature variation above or below the Curie temperature. Most of the magnetic anomalies are associated with coal fire and non-coal fire regions which are correlated with tilt-derivative anomaly and corresponding downward-continued anomaly at different depths. The subsequent surface and subsurface characteristics are explained with good agreement. Approximate source depth of principal anomaly inferred from tilt derivatives method are corroborated with multi-seam occurrences, mine working levels and surface manifestation which are also correlated well with 3D model of downward continued anomaly distribution.

Keywords. Downward continuation; tilt derivative; magnetic data; coal fire mapping; Jharia coal field; India.

1. Introduction

Underground coal fires result in loss of the national economy, pose a threat to the environment, ecology and human health living in their proximities. Coal fires also result in emission of greenhouse gases, toxic gases and vegetation deterioration. The mapping and understanding of hidden subsurface coal fire are challenging tasks. Underground coal fires are severe problems in most of the coal producing countries, viz., China, India, USA, South Africa (Stracher and Taylor 2004; Zhang *et al.* 2004; Mishra *et al.* 2011; Revil *et al.* 2013; Revil

and Jardani 2013; Bharti *et al.* 2014, 2016a, b; Bhattacharya and Shalivahan 2016; Singh *et al.* 2015; Srivardhan *et al.* 2016), Australia, Russia, Poland and Indonesia (Ide *et al.* 2011; Ide and Orr 2011). Generally, satellite remote sensing is the most widely utilized technique for temperature mapping (Majumdar *et al.* 2012) detection of coal fire regions on the basis of surface temperature anomalies over coal fires affected areas (Prakash *et al.* 1995, 1997; Prakash and Gupta 1998, 1999; Kuenzer and Stracher 2011; Mishra *et al.* 2011). The thermal image generated using satellite remote sensing is hardly capable for detection of deeper

thermal anomalies which may misguide in mapping of subsurface combustion regions (Zhang 1998).

With the advancement of technology, a number of researchers (Hooper 1987; Schaumann *et al.* 2008; Ide *et al.* 2011; Vaish and Pal 2013, 2015a, 2016; Shao *et al.* 2014; Kumar *et al.* 2015) have used magnetic method for underground coal fire characterization. Generally, magnetic properties of the rocks changing with the temperature variation above or below the Curie temperature is the basis of underground coal fire mapping. The heat produced by burning of coal increases the temperature beyond Curie temperature which results in loss of natural magnetism in nearby areas. Small regions within the crystal structure reorient themselves during cooling by aligning themselves more or less in the direction of the ambient magnetic field. The remnant magnetism may be several times greater in magnitude than the natural magnetism (Shao *et al.* 2014). The minerals which are formed and their respective magnetic strengths depend on the temperatures and the amount of oxygen available (Hooper 1987; Ide *et al.* 2011).

In India, coal fires have been studied by various researchers (Prakash and Gupta 1998, 1999; Ghose and Majee 2000; Michalski 2004; Tripathi 2005; Agarwal *et al.* 2006; Chatterjee 2006; Gangopadhyay 2006; Chatterjee *et al.* 2007; Singh *et al.* 2007) by mainly using satellite remote sensing methods on the basis of ambient surface temperature variation. Hitherto in India, only a few studies for coal fire investigation have been carried out in recent years using magnetometer data (Vaish and Pal 2013, 2015a, 2016; Kumar *et al.* 2015; Pal *et al.* 2016a). In recent years, potential field data have been effectively used by means of different derivative techniques for various geological investigations (Pal and Majumdar 2015; Narayan *et al.* 2016; Pal *et al.* 2016b, c). Present study deals with the delineation of subsurface coal fires of East Basuria Colliery in Jharia coal field, India using tilt derivative and downward continuation techniques of magnetic data.

2. Study area

The present study covers an area of $\sim 0.25 \text{ km}^2$, lying within the geographical coordinates $23^\circ 47' 34''$ – $23^\circ 47' 53''$ N latitudes and $86^\circ 21' 59''$ – $86^\circ 22' 16''$ E longitudes. Generally, coal seams occur in the Barakar Formation of Lower Gondwana group of rocks of the Early Permian period. Barakar Formation mostly consists of sandstone of different

grain size, intercalation of sandstone and shale, grey and carbonaceous shale and coal seams (Vaish and Pal 2015b; Das *et al.* 2017). The natural topography is harshly affected due to old mining actions, severe underground coal fire activities, land subsidence and overburden dumping. The overburden materials have been dumped over coal fire affected regions to prevent and combat against further exaggeration of coal fire in the surroundings. Initially, the coal fire over East Basuria colliery was observed in V/VI seam quarry in 1976. Afterwards, intense fire was noticed in V/VI coal seam at three different galleries in 1995. Water ponds were constructed over the fire affected area in 1996. However, by that time the fire had spread up to VIII and VIIIA seams and resulted in parallel cracking, subsidence, potholing, etc. Keeping V/VI seam as a base, an endeavour against eastward advancement of coal fire was made by cutting a trench during 1997–1998. This effort also showed fruitless because the fire spread through the trench during trenching (Bharat Coking Coal 2003; CMPDI 2003; Coal International 2003; World Bank Group 2003; Pal *et al.* 2016a). Location map of the East Basuria Colliery, Jharia Coal Field, India along with generalized geological map of Jharia Coal field (figure 1a) and underground mine workings plan (figure 1b) are shown in figure 1. Borehole lithologs of SBJ-56, SBJ-6 and SBJ-4, showing coal seams and shaly coal seams at different depth levels are shown in figure 2 (BCCL 2009). The locations of borehole are shown in figure 1. The major coal bearing seams are VIII, V/VI, IV, III and II with average thickness of 7.2, 9.45, 9.57, 3.66, 10.57 m, respectively. L-series of seams are local seam. L-series of seams are thin and not suitable for mining but have the potential for spreading of coal seam fire. The coal seams have varying slope of about 6.7° – 11.3° , with dip direction NE05°SW to NE15°SW (Singh *et al.* 2004). Characteristics of coal seams over the East Basuria colliery are described in table 1. Different coal seams with varying slope and dip direction may support the occurrences of coal-seam-fire at different depths and locations which may lead to complex nature of fire propagation.

3. Methodology

Total magnetic field intensity with resolution of 0.01 nT have been measured using GSM19T

Figure 2. Borehole lithologies (BCCL 2009) showing coal seams and shaly coal seams at different depths. Locations of (a) SBJ-4, (b) SBJ-56, and (c) SBJ-6 are shown in figure 1.

Proton precession magnetometer. The acquired data have been corrected for diurnal variation. Normally, the earth's magnetic field is shifted from the vertical except, the areas near magnetic poles. As a result, the induced magnetization vector is inclined over magnetically susceptible bodies (Mendonca and Silva 1993). This problem is overcome mathematically by transposing the magnetic data to the

magnetic pole, termed as reduced to magnetic pole (RTP) (Blakely 1996; Salem *et al.* 2008; Rajaram 2009; Ide *et al.* 2011; Shao *et al.* 2014; Pal *et al.* 2016a). The RTP of residual magnetic field has been separately processed using tilt derivative (TDR) technique of Miller and Singh (1994) and downward continuation technique of Ma *et al.* (2013).

Table 1. Characteristics of coal seams over East Basuria Colliery (BCCL 2009).

Sl. no.	Seam	Average thickness (m)	Degree	Dip direction
1	X	0.82	6.71	NE 05° SW
2	IX	0.91	6.71	NE 05° SW
3	VIII	7.2	6.71	NE 05° SW
4	VII	1.8	6.71	NE 05° SW
5	V/VI	9.45	9.46	NE 05° SW
6	IV	9.57	9.46	NE 05° SW
7	III	3.66	9.46	NE 11° SW
8	II	10.57	11.31	NE 15° SW
9	I	0.85	11.31	NE 15° SW

3.1 Tilt derivative

The tilt angle or derivative ratio (TDR) is defined as the arctangent of the ratio of vertical derivative to total horizontal derivative of the magnetic field f (Miller and Singh 1994; Verduzco *et al.* 2004; Salem *et al.* 2008; Rajaram 2009):

$$TDR = \tan^{-1} \left[\frac{\partial f / \partial z}{\sqrt{(\partial f / \partial x)^2 + (\partial f / \partial y)^2}} \right]$$

The TDR values vary between $-\pi/2$ and $+\pi/2$. The TDR crosses through zero at or near the edge of a vertical source and is negative outside the source region (Miller and Singh 1994). The half-distance between $\pm\pi/4$ contours gives an approximation of the source depth for vertical contacts. The distance between zero and $+\pi/4$ or $-\pi/4$ contour obtained from the TDR represent the depth to the top of the vertical contact (Oruc and Selim 2011; Pal and Majumdar 2015; Narayan *et al.* 2016; Pal *et al.* 2016b, c).

3.2 Downward continuation of magnetic data

Continuation methods project the observed potential (gravity and magnetic) anomaly field to higher elevations (upward continuation) or lower elevations (downward continuation) and therefore, effectively serve as low-pass and high-pass filters respectively (Khalil 2012), which have been applied in numerous applications (Li and Devriese 2009; Li *et al.* 2013; Ma *et al.* 2013). The main advantage of the continuation methods is that the character of the geopotential field anomaly is retained as long as the continuation does not extend into the sources (Khalil 2012). This method is strongly dependent on the sampling interval of the original data and

is able to downward-continue only to very shallow depths equal to 2–10 times of the sampling spaces (Xu *et al.* 2007).

Downward continuation enhances the responses of sources at a depth by effectively bringing the plane of measurement closer to the source. Downward continuation highlights the components of higher wave-number, increases the anomaly resolution of the individual sources and provides a more accurate determination of both horizontal and vertical extents of near-surface magnetic sources (Boschetti 2005). But, its usefulness depends on the elimination of noise, as the computation of downward continuation is unstable and easily distorts the true feature of potential field data (Fedi and Florio 2001, 2002, 2013; Pasteka *et al.* 2012; Abedi *et al.* 2013). Upward continuation is a stable computation, at higher heights, which is the contribution of the most extended sources. Because the upward continuation and horizontal derivatives are stable, a combination of upward continuation and horizontal derivative is used to complete the downward continuation of potential field data (Ma *et al.* 2013). The downward continuation is expressed using the following Taylor series (Even 1936; Fedi and Florio 2002):

$$T(x, y, h) = T(x, y, 0) + \frac{\partial T}{\partial z} h + \frac{1}{2!} \frac{\partial^2 T}{\partial z^2} h^2 + \cdots + \frac{1}{m!} \frac{\partial^m T}{\partial z^m} h^m \quad (1)$$

where $T(x, y, h)$ is the potential field at the level of h , h is the continuation height, and $T(x, y, 0)$ is the original potential field data. The computation of upward continuation is expressed using the following Taylor series.

$$T(x, y, -h) = T(x, y, 0) - \frac{\partial T}{\partial z} h + \frac{1}{2!} \frac{\partial^2 T}{\partial z^2} h^2 + \cdots + \frac{1}{m!} \frac{\partial^m T}{\partial z^m} (-h^m) \quad (2)$$

where $T(x, y, -h)$ is the potential field at the level of $-h$. Both continuations require m th order vertical derivatives of the potential field. The high-order vertical derivatives are unstable and can enhance the effect of noises (Florio *et al.* 2006). So, the Taylor series terms are limited to three neglecting the higher order terms. Equations (1 and 2) are added to give:

$$T(x, y, h) = 2T(x, y, 0) - T(x, y, -h) + \frac{\partial^2 T(x, y, 0)}{\partial z^2} h^2 \quad (3)$$

where the data $T(x, y, -h)$ at the level of $-h$ is computed by the Fourier transform. The effect of

the noise is nullified by computing the second-order vertical derivative through Laplace equation of potential field. The horizontal derivatives for Laplace equation are computed in the space domain. Then, the downward continuation is computed by the combination of the upward continuation

Figure 3. (a) Total magnetic field map and (b) reduction to pole (RTP) map of residual magnetic field with underground mine workings of different coal seams of East Basuria Colliery.

and horizontal derivatives, which enhances the stability of downward continuation, effectively (Ma *et al.* 2013). The result is only an approximate value at the level of 'h' as the higher order terms of the Taylor series are neglected. So, for more accurate result, an iteration method is used to compute the downward continued data (Ma *et al.* 2013). Initially, equation (3) is used to compute the data at the level of depth h .

$$T_0(x, y, h) = 2T(x, y, 0) - T(x, y, -h) + \frac{\partial^2 T(x, y, 0)}{\partial z^2} h^2. \quad (4)$$

Further, the data $T_1(x, y, 0)$ is generated by upward continuation of the anomaly $T_0(x, y, h)$ to the observation level of '0'. Then the difference between the data of $T(x, y, 0)$ and $T_1(x, y, 0)$ is

$$\Delta T_1(x, y, 0) = T(x, y, 0) - T_1(x, y, 0). \quad (5)$$

The equation (3) is used to downward-continue the data $\Delta T_1(x, y, 0)$ to the level of h , and the result is given by

$$\Delta T_1(x, y, h) = 2\Delta T_1(x, y, 0) - \Delta T_1(x, y, -h) + \frac{\partial^2 \Delta T_1(x, y, 0)}{\partial z^2} h^2 \quad (6)$$

where $\Delta T_1(x, y, h)$ is the downward continuation of the data $\Delta T_1(x, y, 0)$ to the depth level of h , and $\Delta T_1(x, y, -h)$ is the upward continuation of the data $\Delta T_1(x, y, 0)$ to the elevation level of $-h$. Now, the potential field data at the level of depth h is rewritten as (Ma *et al.* 2013):

$$T_1(x, y, h) = T_0(x, y, h) - \Delta T_1(x, y, h). \quad (7)$$

This iteration process is repeated until the root mean square (RMS) error of the data $\Delta T_m(x, y, 0)$ is less than a given value, and the final downward continuation data at the level of h can be expressed as (Ma *et al.* 2013):

$$T_m(x, y, h) = T_0(x, y, h) + \Delta T_1(x, y, h) + \dots + \Delta T_m(x, y, h). \quad (8)$$

Ma *et al.* (2013) have established that the iterative downward continuation through combination of upward continuation using Taylor series expansion

Figure 4. Tilt derivative map generated from RTP of residual magnetic field data of East Basuria Colliery. Underground mine workings of different coal seams are overlaid on the tilt derivative map. Causative magnetic source zone characterized by positive tilt derivative (TDH1–TDH11) and negative tilt derivative (TDL1–TDL19) are shown.

Table 2. Relationship of low of magnetic anomaly (Mag. Am.), low tilt derivative anomaly (TDL), with corresponding downward continued (DCM) low anomaly at different depths and their subsequent surface/inferred subsurface characteristics.

Sl. no.	Mag. Am.	DCM at 20	DCM at 40	DCM at 80	TDL	Anomaly depth (m)	Approx. deepest mine working level in m (figure 1b) and subsurface characteristics	Surface characteristics
1	L1	²⁰ L1	⁴⁰ L1	⁸⁰ L1	TDL1	20/40/80	138 m (III-seam, SBJ-6). Multi seam fire at VIII B, VIII A/VIII/VII, L-3/(V/VII)/L-2/IV-B; burned in high O ₂ condition	Active fire/blaze/smoke through wide fractures/fissure (figure 6a)
2	L2	–	–	–	TDL2	10	138 m (III-seam, SBJ-6). Shallow fire at VIII B; burned in high O ₂ condition	Active fire/blaze/smoke through fissures/cracks (figure 6b)
3	L3	²⁰ L2	⁴⁰ L2	⁸⁰ L2	TDL3	10/20/80	138 m (III-seam, SBJ-6). Multi seam fire at VIII B/VIIIA/VIII/L2, IV-B; burned in high O ₂ condition	Active fire through pothole and cracks (figure 6c)
4	L4	²⁰ L3	⁴⁰ L3	–	TDL4	20/40	188 m (II-seam, SBJ-6). Multi seam fire at VIIIA, VIII/VII, L-3/(V/VII); burned in high O ₂ condition	Wide spread cracks and subsidence due to fire (figure 6d)
5	L5	²⁰ L4	–	–	TDL5	10/20	133 m (II-seam, SBJ-4). Multi seam fire at L3/(V/VII); burned in high O ₂ condition	Smoke through cracks. Subsidence due to fire/blaze (figure 6e)
6	L6	²⁰ L5	⁴⁰ L4	–	TDL6	10/20/40	133 m (II-seam, SBJ-4). multi seam fire at L3/(V/VII)/L2, IVT, IVB; burned in high O ₂ condition	Smoke through pothole/fissure (figure 6f)
7	L7	²⁰ L6	⁴⁰ L5	⁸⁰ L3	TDL7	20/40/80	58 m (IV-seam, SBJ-4). Multi seam fire at (V/VII)/L2, IVT & IVB/III; burned in high O ₂ condition	Cracks and subsidence (figure 6g)
8	L8	–	–	–	TDL8, TDL19	6/12	58 m (IV-seam, SBJ-4). Multi seam fire at VII/L3; burned in high O ₂ condition	Pothole and cracks and subsidence (figure 6h)
9	–	²⁰ L7	⁴⁰ L6	–	TDL9	10/20/40	SBJ-4 multi seam fire at L3/(V/VII)/L2/IVT, IVB; burned in high O ₂ condition	Smoke, cracks and subsidence
10	–	²⁰ L8	⁴⁰ L7	–	TDL10	20/40	SBJ-4. Multi seam fire at (V/VII)/L2, IVT & IVB; burned in high O ₂ condition	Smoke, cracks and subsidence
11	–	–	–	⁸⁰ L4	TDL11	80	VIII seam goaf filled with water, SBJ-56, seasonal water tank observed (figure 1)	Natural topography without fractures/fissures/potholes/subsidence

12	L9	-	-	-	TDL12	-	65 m (V/VI-seam, SBJ-6). Shallow fire at local seam/VIII, burned in high O ₂	Active shallow fire, smoke through fractures/fissure
13	L10	-	-	-	TDL13	-		
14	L11	-	-	-	TDL14	-		
15	L12	-	-	-	TDL15	-		
16	-	²⁰ L9	⁴⁰ L8	⁸⁰ L5	TDL16	20/40/80	178 m (II-seam, SBJ-6). IV-bottom seam goaf filled with water, seasonal water tank observed (figure 1)	Natural topography without fractures/fissures/potholes/subsidence
17	-	-	⁴⁰ L9, ⁴⁰ L10	⁸⁰ L6, ⁸⁰ L7	TDL17	40/80	178 m (II-seam, SBJ-6). Goaf at 80 m filled with water, seasonal water tank observed on the surface	
18	-	-	-	⁸⁰ L8	TDL18	80	SBJ-6, Goaf at 80 m filled with water	

and horizontal derivatives using Laplace equation provide more stable results and is less sensitive to noise compared to the traditional method.

4. Results and discussions

The diurnal corrections have been applied on the recorded magnetic readings based on the drift in the base station readings. The spikes and dropped signals have been removed and only the consistent readings have been used for processing. Total intensity magnetic anomaly map with underground mine workings of different coal seam over the area is shown in figure 3(a). Total intensity magnetic anomaly varies from $\sim 44,850$ to $\sim 47,640$ nT. The residual map has been prepared by subtracting the Earth's main field from the magnetic data of the area. The residual magnetic data have been reduced to north magnetic pole (RTP) to remove the lateral shifts and asymmetries caused by the local orientation of the magnetic anomaly. Reduction to pole (RTP) map of residual magnetic field with underground mine workings of different coal seam of East Basuria Colliery is shown in figure 3(b). RTP magnetic anomaly varies from ~ -1050 to ~ 1450 nT. Low (L1–L12) and high (H1–H9) RTP magnetic anomalies have been delineated from figure 3(b), as different surface anomaly distribution.

Tilt derivative map has been generated from RTP data of residual magnetic data of East Basuria Colliery (figure 4). The TDR image shows contours of 0 and $\pm\pi/4$ (0 to ± 0.785) radian. This figure indicates that the TDR anomaly map could be utilized for recognition of the horizontal location and extent of edges of various sources assuming vertical contact model. The zero contours estimate the horizontal location of abrupt lateral changes in the subsurface features. The TDR map highlights short wavelengths. The half distance between $\pm\pi/4$ contours has been used to estimate the depth of the edge of the magnetized sources. Totally 11 causative source zones characterized by positive tilt derivative responses have been identified (TDH1–TDH11). Further, 19 causative source zones characterized by negative tilt derivative response have been identified (TDL1–TDL19). Details of positive and negative tilt derivative anomaly and corresponding inferred average depths to the top of principal anomaly, their relation with equivalent approximate deepest mine working level, coal seam occurrences and their surface characteristics are given in tables 2 and 3.

Table 3. Relationship of high of magnetic anomaly at surface (Mag. Am.), high tilt derivative (TDH) anomaly with corresponding downward continued (DCM) high anomaly at different depths and their subsequent surface/inferred subsurface characteristics.

Sl. no.	Mag. Am.	DCM at 20	DCM at 40	DCM at 80	TDH	Depth of anomaly (m)	Approx. deepest mine working level (m) and subsurface characteristics	Surface characteristics
1	H1	²⁰ H1	⁴⁰ H1	⁸⁰ H1	TDH1	20/40/80	138 m (III-seam, SBJ-6). Multi seam burned in low O ₂ condition at VIII B/VIII A/VIII/VII, L-3/(V/VI)/L-2/IV-B seam	VIII & V/VI seam quarry partially filled with OB, previously burned partially, baked rock present (figure 7a)
2	H2	²⁰ H2	⁴⁰ H2	⁸⁰ H2	TDH2	20/40/80	138 m (III-seam, SBJ-6). Multi seam burned in low O ₂ condition at VIII B/VIII A/VIII/VII, L-3/(V/VI)/L-2/IV-B seam	V/VI seam quarry filled with OB, previously burned and cooled, baked rock present (figure 7b)
3	H3	²⁰ H3	⁴⁰ H3	–	TDH3	20/40	138 m (III-seam, SBJ-6). Multi seam burned in low O ₂ condition at VIII B/VIII A/VIII/VII, L-3/(V/VI)/L-2/IV-B seam	Subsidence, burned/baked rock present (figure 7c)
4	H4	²⁰ H4	⁴⁰ H4	⁸⁰ H3	TDH4	20/40/80	138 m (III-seam, SBJ-6). Multi seam burned in low O ₂ condition at VIII B/VIII A/VIII/VII, L-3/(V/VI)/L-2/IV-B seam	Subsidence, burned/baked rock present
5	H5	²⁰ H5	⁴⁰ H5	⁸⁰ H4	TDH5	20/40/80	110m (V-seam, SBJ-56). Multi seam burned in low O ₂ condition at VIII B/VIII A/VIII/VII, L-3/(V/VI)/L-2/IV-B seam	Subsidence, burned/baked rock present (figure 7d)
6	H6	²⁰ H6	⁴⁰ H6	⁸⁰ H5	TDH6, TDH11	20/40/80	133 m (II-seam, SBJ-4). Multi seam burned in low O ₂ condition at VII, L-3/(V/VI)/L-2, IV-B/III seam	Subsidence, burned/baked rock present (figure 7e)
7	H7	²⁰ H7	⁴⁰ H7	⁸⁰ H6	TDH7	20/40/80	133 m (II-seam, SBJ-4). Multi seam burned in low O ₂ condition at L3/(V/VI)/L2/IVT & IVB/III seam; fire arrested by OB at the surface	Subsidence, burned/baked rock present (figure 7f)
8	H8	²⁰ H8	⁴⁰ H8	⁸⁰ H7	TDH8	20/40/80	178 m (II-seam SBJ-6). Multi seam burned in low O ₂ condition/possible metallic objects-such as tracks, etc., left in L2 seam/IV-bottom seam goaf	Subsidence, burned/baked rock present (figure 7g)
9	H9	²⁰ H9	⁴⁰ H9	⁸⁰ H8	TDH9	20/40/80	99 m (III-seam, SBJ-6). Multi seam burned in low O ₂ condition at VIII B/VIII A/VIII/VII seam, L-3	Subsidence, burned/baked rock present (figure 7h)
10	–	²⁰ H10	⁴⁰ H10	⁸⁰ H9	TDH10	20/40/80	133 m (II-seam, SBJ-6). Multi seam burned in low O ₂ condition at VIII B/VIII A/VIII/VII, L-3/(V/VI)/L-2/IV-B seam	Subsidence, burned/baked rock present

Figure 5. 3D model of magnetic anomaly distribution indicating low anomaly (L1–L12 at surface, ²⁰L1–²⁰L9 at 20 m depth, ⁴⁰L1–⁴⁰L10 at 40 m depth and ⁸⁰L1–⁸⁰L8 at 80 m depth) and high anomaly (H1–H9 at surface, ²⁰H1–²⁰H10 at depth of 20 m, ⁴⁰H1–⁴⁰H10 at 40 m depth and ⁸⁰H1–⁸⁰H9 at 80 depth) regions are generally caused by coal active fire and coal fire-free regions, respectively. Possible coal seams corresponding to the burning zones are shown with dashed line of fire.

A schematic 3D model showing magnetic anomaly distribution at the surface and downward continued anomaly at different depths, viz., 20, 40, and 80 m has been generated (figure 5). From the 3D model (figure 5), the low magnetic anomaly regions, i.e.,

- (i) L1–L12 (12 in numbers) at surface (figure 3b),
 - (ii) $^{20}\text{L1}–^{20}\text{L9}$ (nine in numbers) at 20 m depth,
 - (iii) $^{40}\text{L1}–^{40}\text{L10}$ (10 in numbers) at 40 m depth,
- and

- (iv) $^{80}\text{L1}$ – $^{80}\text{L8}$ (eight in numbers) at 80 m depth have been prominently identified.

Further, high magnetic anomaly regions i.e.,

- (i) H1–H9 (nine in numbers) at surface (figure 3b),
(ii) $^{20}\text{H1}$ – $^{20}\text{H10}$ (10 in numbers) at depth of 20 m,
(iii) $^{40}\text{H1}$ – $^{40}\text{H10}$ (10 in numbers) at 40 m depth, and
(iv) $^{80}\text{H1}$ – $^{80}\text{H9}$ (nine in numbers) at 80 depth have
been clearly delineated from the 3D model
(figure 5).

Figure 6. (a–h) are field photographs of active fire regions showing smokes, fissures, cracks, potholes, etc., near L1–L8, respectively.

The red regions show the enhancement of magnetic anomalies with respect to ambient magnetic anomalies over the area. The blue regions are the location where the magnetic anomalies are reduced with respect to natural conditions. Field photographs over active fire through fissures, cracks, potholes, etc., near L1, L2, L3, L4, L5, L6, L7

and L8, are shown in figure 6(a–h); respectively. Further, field photographs of burnt/baked rocks near H1, H2, H3, H5, H6, H7, H8, H9, are shown in figure 7(a–h); respectively. It is inferred that the red regions indicate the locations that were heated and subsequently cooled. The blue regions are the location where some portion of the formation is

Figure 7. (a–h) are field photographs of burnt/baked rocks near H1–H9, respectively.

under fire and heated above the Curie temperature. The light-green regions are inferred to be unaffected by the coal fire. Details of high and low magnetic anomalies and their subsequent inferred depths of subsurface features (figure 5), their relationship to the corresponding approximate deepest

mine working level (figure 1b), coal seam occurrences (figure 2) and their surface characteristics (figures 6 and 7) are described in tables 2 and 3. Further, relationship of magnetic (low, L1–L12 and high, H1–H9) anomaly at surface with corresponding downward continued anomaly map

at different levels and their subsequent surface and subsurface characteristics are also explained in tables 2 and 3 on the basis of comprehensive observations from figures 1, 2, 5, 6 and 7. The occurrences of coal seam fires and complex nature of fire propagation may not be always perfectly corroborated with the borehole lithologies (figure 2) due to varying slope and dip of coal seam.

Fourteen low anomaly locations, viz.,

- (1) L1/²⁰L1/⁴⁰L1/⁸⁰L1/TDL1 (figure 5a);
- (2) L2/TDL2 (figure 6b);
- (3) L3/²⁰L2/⁴⁰L2/⁸⁰L2/TDL3 (figure 6c);
- (4) L4/²⁰L3/⁴⁰L3/TDL4 (figure 6d);
- (5) L5/²⁰L4/TDL5 (figure 6e);
- (6) L6/²⁰L5/⁴⁰L4/TDL6 (figure 6f);
- (7) L7/²⁰L6/⁴⁰L5/⁸⁰L3/TDL7 (figure 6g);
- (8) L8/TDL8/TDL19 (figure 6h);
- (9) ²⁰L7/⁴⁰L6/TDL9;
- (10) ²⁰L8/⁴⁰L7/TDL10;
- (11) L9/TDL12;
- (12) L10/TDL13;
- (13) L11/TDL14; and
- (14) L12/TDL15

have been inferred for coal fire affected area with high O₂ circulation through wide spread crack/pot holes/fissures, etc.

Four low anomaly locations, viz.,

- (1) ⁸⁰L4 by VIII-seam goaf;
- (2) ²⁰L9/⁴⁰L8/⁸⁰L5/TDL16 by IV-Bottom seam goaf;
- (3) ⁴⁰L9/⁴⁰L10/⁸⁰L6/⁸⁰L7/TDL17 by goaf at 80 m;
- (4) ⁸⁰L8/TDL18 by IV-Bottom seam goaf,

have been inferred for the goaf filled with water.

Ten high anomaly locations such as

- (1) H1/²⁰H1/⁴⁰H1/⁸⁰H1/TDH1 (figure 7a);
- (2) H2/²⁰H2/⁴⁰H2/⁸⁰H2/TDH2 (figure 7b);
- (3) H3/²⁰H3/⁴⁰H3/TDH3 (figure 7c);
- (4) H4/²⁰H4/⁴⁰H4/⁸⁰H3/TDH4;
- (5) H5/²⁰H5/⁴⁰H5/⁸⁰H4/TDH5 (figure 7d);
- (6) H6/²⁰H6/⁴⁰H6/⁸⁰H5/TDH6/TDH11 (figure 7e);
- (7) H7/²⁰H7/⁴⁰H7/⁸⁰H6/TDH7 (figure 7f);
- (8) ²⁰H10/⁴⁰H10/⁸⁰H9/TDH8 (figure 7g);
- (9) H9/²⁰H9/⁴⁰H9/⁸⁰H8/TDH9 (figure 7h); and
- (10) ²⁰H10/⁴⁰H10/⁸⁰H9/TDH10

have been inferred to be burned in low O₂ circulation and cooled.

The magnetic field intensity over an area is the aggregate of all the magnetic anomalies associated

with various ferromagnetic, antiferromagnetic, paramagnetic and diamagnetic formations. Generally, the occurrence of ferromagnetic minerals and the degree of alignment of the magnetic moments in the overlying formations (Hooper 1987) result in positive magnetic susceptibility. The magnetization of overlying formations comprising traces of magnetic minerals looses due to heating by coal fire to the Curie temperature. After cooling, the magnetic moments of the thermally altered overlying formation align themselves in the Earth's ambient magnetic field with relatively high magnetization (Gielisch 2007; Ide *et al.* 2011). The thermal alteration process is mainly controlled by presence of O₂ at high temperature environment (200°–1000°C), generally witnessed within coal fires affected regions. The magnetite (Fe₃O₄) is a ferromagnetic formation (Hooper 1987) which may be generated under the low O₂ environment in deeper multi seam fire or shallow coal seam fire blanketed by clay soil (Ide *et al.* 2011). The rocks with low permeability and low porosity such as siltstone, shale, etc., arrest the O₂ circulation to the underneath coal fires, which offer an ideal environment for generation of magnetite. The hematite (Fe₂O₃) is an antiferromagnetic formation and it does not enhance the magnetization of a region which may be generated in shallow seam fire with high O₂ circulation through wide spread fissures, cracks, pot holes, etc. (Ide *et al.* 2011).

A huge amount of diamagnetic gases, viz., Methane (CH₄), Carbon dioxide (CO₂), Ammonia (NH₃), Sulphur dioxide (SO₂); Carbon monoxide (CO), Nitrogen (N₂), Hydrogen, Selenium (Se), Arsenic (As), Mercury (Hg), water vapour, tar vapours, organic sulphur, hydrogen chlorides and inorganic chlorides, various polycyclic aromatic/unsaturated hydrocarbons, etc., are generated in underground active coal fire under a complex chaotic process comprising different indistinct parameters (Engle *et al.* 2013; Gürdal *et al.* 2015; Pal *et al.* 2016a). Additionally, pyrolysis and heating of coal to graphitizing temperature results in production of a small amount of the paramagnetic formation and a large amount of the diamagnetic formation (Jenkins and Kawamura 1976). These are the possible cumulative sources for low magnetic anomaly. Further, goafs at different seams filled with air/water which are diamagnetic in nature and generate magnetic field against the external ambient magnetic field. Thus, it indicates low magnetic anomaly.

5. Conclusions

Fourteen low anomaly locations have been identified as coal fire affected area due to high O_2 circulation through wide spread cracks/potholes/fissures, etc. (table 2). Four low anomaly locations have been inferred corresponding to the goafs filled with water (table 2). Ten high anomaly locations have been delineated as burned in low O_2 environment and subsequently, cooled (table 3). The coal fire affected areas have been delineated using magnetic anomaly map (at the surface, figures 3b and 5) after pole reduction, which correlate well with the surface manifestations (figures 1, 6; tables 2, 3). Most of the magnetic anomalies are matched with coal fire locations observed at the surface (figures 6 and 7) and further, correlated with corresponding tilt derivative anomalies (figure 4) and downward continued anomalies at different depths (figure 5). Their subsequent surface (figures 6 and 7) and subsurface characteristics (figures 4 and 5) are explained with better agreement (tables 2 and 3). Approximate source depths of principle anomaly inferred from 3D model of downward continued anomaly distribution (figure 5) are correlated well with multi seam occurrences (figure 2), mine working levels (figure 1b), tilt derivative anomalies (figure 4) and surface manifestation (figures 6 and 7). These results prove the efficacy of integrated study comprising downward continuation and tilt derivative methods of magnetic data for characterization of concealed coal fire in East Basuria Colliery, Jharia coal field, India. This could be done very effectively by repeated study of the affected area in time lapsed magnetic survey.

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