Coal fire mapping of East Basuria Colliery, Jharia coalfield using vertical derivative technique of magnetic data

S K PAL*, JITENDRA VAISH, SAHADEV KUMAR and ABHAY KUMAR BHARTI

Department of Applied Geophysics, Indian School of Mines, Dhanbad 826 004, India.

**Corresponding author. e-mail: sanjitism@gmail.com*

The present study deals with the coal fire mapping of East Basuria Colliery, Jharia coalfield, India, using the magnetic method. It is based on the fact that rise in temperature would result significant changes in magnetic susceptibility and thermo-remanent magnetization (TRM) of the overlying rocks. Magnetism increases slowly with the rise of temperature until the Curie temperature. Generally, rock/overburden loses magnetization and becomes paramagnetic due to heating to Curie temperature, which results with significant reduction in magnetic susceptibility. However, magnetism increases significantly after cooling below the Curie temperature. Several data processing methods such as diurnal correction, reduction to pole (RTP), first and second vertical derivatives have been used for analysis of magnetic data and their interpretation. It is observed that the total magnetic field intensity anomaly of the area varies approximately from 44850 to 47460 nT and the residual magnetic anomaly varies approximately from -1323 to 1253 nT. The range of the magnetic anomaly after RTP is approximately 1050–1450 nT. About 20 low magnetic anomaly zones have been identified associated with active coal fire regions and 11 high magnetic anomaly zones have been identified associated with non-coal fire regions using vertical derivative techniques.

1. Introduction

Coal seam fire, coal mine fire as well as fire in coal waste or storage piles are a general phenomenon worldwide and pose a great threat to national economy, environment, ecology and health of people living in its proximity. The mapping and understanding of hidden subsurface coal fire is a challenging task. Coal fire is a serious problem in major coal producing countries, including, China, India, USA and South Africa (Rosema *et al.* 1999; Bell *et al.* 2001; Stracher 2004; Stracher and Taylor 2004; Zhang *et al.* 2004; Gangopadhyay 2006; Kuenzer *et al.* 2008; Mishra *et al.* 2011; Bharti *et al.* 2014, 2016; Singh *et al.* 2015; Srivardhan *et al.* 2016), Australia, Russia, Poland and Indonesia (Wachiwicz 2008; Ide *et al.* 2011; Ide and Orr 2011).

Remote sensing technique is being used for coal mine fire study with airborne thermal scanner since

early 1960's. Satellite remote sensing using thermal infrared images are frequently utilized to detect coal fire regions based on surface temperature anomalies at coal fire areas, mostly in China, India and USA (Mansor *et al.* 1994; Prakash *et al.* 1995, 1997; Prakash and Gupta 1998, 1999; Gangopadhyay 2003; Voigt *et al.* 2004; Kuenzer *et al.* 2007a, 2007b, 2008; Kuenzer and Stracher 2011; Mishra *et al.* 2011). Satellite-based thermal images are not sufficient for detection of deeper thermal anomalies (Zhang 1998). The true extent of the subsurface combustion region may not be determined solely from this remote sensing technique. Interferometric Synthetic Aperture Radar (InSAR) can detect subtle surface deformation over time (Massonnet and Feigl 1998). However, the subsidence may or may not always correspond to an active fire region and the expected pixel resolution is about 20–100 m (Burgmann *et al.* 2000).

Keywords. Coal fire mapping; proton precession magnetometer; reduction to magnetic pole; vertical derivatives.

Several researchers around the world have used magnetic method to characterize underground coal fires (Zhang 1980; Hooper 1987; Schueck 1990; Bandelow and Gielisch 2004; Sternberg and Lippincott 2004; Wei *et al.* 2005; Gielisch 2007; Schaumann *et al.* 2008; Sternberg *et al.* 2008; Chen and Shao 2010; Ide *et al.* 2011; Vaish and Pal 2013, 2015a, 2016; Kumar *et al.* 2015). Magnetic survey provides high resolution coal fire mapping, which delineates previously burned, active coalfire and non-coalfire regions. Generally, mapping and understanding of subsurface coal fires are carried on the basis of magnetic properties of materials, and those changes with the temperatures rise, either above or below, the Curie temperature. The combustion of subsurface coal releases much heat, making the temperature of overlying rock higher than the Curie temperature. This high temperature causes significant changes in magnetic properties (magnetic susceptibility and thermo-remnant magnetization (TRM)) and thereby results in an observable magnetic anomaly at the surface in an active coal fire area (Shao *et al.* 2014). The characteristics of magnetic behaviour with temperature (Xiong and Yu 2013; Song and Kuenzer 2014) are classified into four main stages:

- Magnetism is very small if temperature is lower than 400°C;
- Magnetism increases slowly with temperature rise until the Curie temperature;
- Magnetism disappears, if temperature is higher than the Curie temperature; and
- Magnetism greatly increases after cooling below the Curie temperature.

Different minerals are formed due to coal fire activity and their magnetic strengths depend on the temperature and the amount of oxygen available during thermal alteration process (Hooper 1987; Gielisch 2007; Ide *et al.* 2011).

Different aspects of coal fires in Jharia coalfield and its surroundings have been extensively studied by various researchers (Bhattacharya *et al.* 1991; Saraf *et al.* 1995; Prakash and Gupta 1998, 1999; Michalski 2004; Tripathi 2005; Agarwal *et al.* 2006; Chatterjee 2006; Kuenzer *et al.* 2007a, 2008; Singh *et al.* 2007) using satellite remote sensing methods only. So far, only a few surface geophysical methods have been applied for coal fire research in India. In the present study, magnetic method of geophysical investigation has been used for coal fire mapping of East Basuria Colliery, Jharia coalfield, India. Initially, a brief history of coal fires of the Jharia coalfield followed by East Basuria Colliery have been discussed. Subsequently, details of magnetic data acquisition and processing have been conversed. Further, detail observations on the obtained results

are discussed to characterize the subsurface coal fires.

2. Study area

The Jharia coalfield is a major coal producing basin in India, consisting 23 large underground and 9 large open cast mines, which is severely affected by coal fire. The Jharia coalfield is located in Dhanbad district, Jharkhand, India which is one of the most important Gondwana coalfields of Damodar valley in India. Owing to the presence of high quality coking coal in Jharia coalfield, it is significant to study the subsurface coal fire activity, which started since 1916, due to excessive and unplanned coal exploration. Jharia coalfield was nationalized in 1970 and over the past four decades, the coal fires spread in many areas. Different researchers have reported that coal fires are still active at about 70 collieries in Jharia coalfield (Michalski 2004). Most of the coal fires in Jharia coalfield were ignited by spontaneous combustion of coal, subsequent to opencast and underground mining. Unplanned coal exploitation without fire-prevention arrangements prior to nationalization might have been a possible reason for these fires (Bharat Coking Coal 2003; CMPDI 2003; Coal International 2003; World Bank Group 2003; Agarwal *et al.* 2006).

The rock formations of Jharia coalfield unconformably overlay the Archean basement and belong mainly to the Lower Gondwana group of Permian age comprising Talchir, Barakar, Barren measures and Raniganj formations, from bottom to top. The present study area lies within the geographical coordinates between 23°47'34"–23°47'53"N latitudes and 86°21'59"–86°22'16"E longitudes. All the working coal seams lie in the Barakar Formation of Lower Gondwana group of Early Permian age. Barakar Formation comprises predominantly sandstone of variable grain size, intercalation of sandstone and shale, grey and carbonaceous shale and coal seams. The general strike of the formation is E–W and dip of the coal seam varies from 10° to 15° towards south (Singh *et al.* 2004). The natural topography has been severely affected due to mining activities, dumping of overburden material and land subsidence. Some parts of active coal fire zone have been covered by dumping of overburden material to prevent and combat against further exaggeration of coal fire in the surroundings.

The record of first fire in East Basuria colliery was noticed in V/VI seam quarry in 1976. Afterwards, in 1993, during the construction of nearby railway sidings, the top soil cover of East Basuria region was excavated. This helped (to the breathing of air) the V/VI seam-fire of East Basuria Colliery. Then, the quarry was filled with overburden

and the surface area was sealed with soil. Later on, blazing fire was reported in three different galleries of V/VI coal seam. Again in 1995, a blazing fire was noticed on the eastern edge of the quarry. To prevent further advance of fire towards the adjoining area, the siding area was refilled by overburden material. Water pools were made over the filled up area in 1996 but by that time, the fires spread to the VIII and VIIIA seams, which resulted in uncontrolled subsidence and potholing, etc. In

1997–1998, an attempt was made to control the eastward advance of the fire by cutting a trench, keeping V/VI seam as base. However, this attempt also proved futile as the fire crossed into the trench, while trench cutting was in progress (Bharat Coking Coal 2003; CMPDI 2003; Coal International 2003; World Bank Group 2003). Location map of the study area (East Basuria Colliery) along with generalized geological map of Jharia coalfield is shown in figure 1.

Figure 1. Location map of the study area (East Basuria Colliery) along with generalized geological map of Jharia coalfield.

3. Methodology

GSM-19T proton precession magnetometer with an in-built GPS (resolution 0.6 m) has been used for magnetic data acquisition. Total magnetic field intensity has been measured with resolution of 0.01 nT, sensitivity of 0.15 nT/Hz and absolute accuracy of 0.2 nT. Total 2865 magnetic data points have been taken along 42 magnetic profiles over different parts of East Basuria Colliery, in different directions with 10 m profile spacing and 5 m data station spacing along the profile direction. At the start of each traverse, a base station has been established over a non-coal fire area at which base station readings have been obtained at 30-min interval for the correction of diurnal variations of total magnetic field.

GSM-19T proton precession magnetometer has a signal quality indicator, which is presented in the form of XY, where X and Y are between '0' and '9' (Breiner 1999; GSM-19T v7.0 instruction manual, 2008 GEM Systems, Canada). X is associated with measurement time. This is one sort of gradient indicator, where '9' means measurement time is maximum and '0' means measurement time is too short. Y represents the area under signal amplitude coincident with the time of measurement, where '9' means optimal conditions and '0' means unacceptable reading. The value of X=0 causes Y=0, but not *vice versa*. Different spikes and dropped signals are characterized by low quality signal with 00 to 88 (X=0–8 and Y=0–8). In the physical domain, spikes and dropped signals (00–88, i.e., X=0–8 and Y=0–8) have been removed. Only the good readings with signal 99 (X=9 and Y=9) have been selected for further processing. Generally, data spikes are encountered close to large metallic objects at the surface.

Diurnal correction is applied to rectify the temporal variation of the geomagnetic field, which is primarily caused by electro-magnetic radiation from the Sun (Khalil 2012). The acquired magnetic readings have been corrected for diurnal variation of Earth's ambient magnetic field based on the drift observed in the repeated base station readings. Generally, the Earth's magnetic field except for the magnetic poles is inclined from the vertical (Baranov 1957; Baranov and Naudy 1964; Mendonca and Silva 1993). The most obvious approach to this problem is to reduce the data to the magnetic pole (RTP), assuming that all the observed magnetic fields are due to induced magnetic effects. This pole reduction has been calculated in the frequency domain (Grant and Dodds 1972).

Vertical and horizontal derivative of potential-field anomalies have been used by various researchers (Rao *et al.* 1981; Reid *et al.* 1990; Marcotte *et al.* 1992; Boschetti 2005; Fedi and Florio 2001, 2013;

Gonenc 2014; Pal and Majumdar 2015; Vaish and Pal 2015b), for enhancement of anomaly and delineation of shallow structures. Derivative filters have been established as powerful techniques for enhancing the higher wave number components of an anomaly field which also reduce anomaly complexity, allowing a clear imaging of the causative structures (Ravat 1996; Khalil 2012). However, the transformation can be noisy since it may amplify short wavelength noise. Vertical derivatives have been mathematically derived from the magnetic RTP data (Hood *et al.* 1979; Khalil 2012). The first vertical derivative has been obtained through the computation of second horizontal derivatives and their integration, through the application of Laplace equation (Agarwal and Lal 1969; Gupta and Ramani 1982; Fedi and Florio 2002). The second vertical derivative has been obtained from the horizontal derivatives because the potential field satisfies Laplace's equation (Agarwal and Lal 1969; Gupta and Ramani 1982; Blakely 1996).

4. Results and discussions

The diurnal correction has been applied on the recorded magnetic readings based on the drift measured in the base station readings. The diurnal fluctuation observed during data acquisition at the site is about 50 nT. Total magnetic field intensity map has been generated using only the readings with signal of 99. Total magnetic field intensity map and residual magnetic anomaly map of East Basuria Colliery are shown in figure 2(a) and (b), respectively. It is observed that total magnetic field intensity anomaly varies from 44850 to 47460 nT. The coordinate of center point of the study area is 86°21'51.8"E longitude and 23°47'45.56"N latitude. According to the International Geomagnetic Reference Field (IGRF), the geomagnetic declination, inclination and total magnetic field of the study area were: 0.34°, 35.91° and 46,173.9 nT, respectively during the period of the survey in October 2012. The total magnetic field observed over natural topography was about 46,160±10 nT. The residual map has been constructed by subtracting the Earth's main field from the diurnal corrected magnetic data of the area. It has been observed that the residual magnetic anomaly varies from about –1323 to 1253 nT. Further, the residual magnetic data have been corrected by 'reduced to north magnetic pole' (RTP) for the removal of lateral shifts and asymmetries caused by the local orientation of the magnetic anomaly. Magnetic anomaly map after pole reduction of residual magnetic field intensity is shown in figure 3(a). It has been observed that the magnetic anomaly after RTP varies from about –1050 to 1450 nT.

Figure 2. (a) Total magnetic field intensity map and (b) residual magnetic anomaly map of East Basuria Colliery.

Comparing figures 2(b) and 3(a), it is clear that the overall values of magnetic anomalies after RTP, have been increased approximately by 200–250 nT and magnetic anomalies are enhanced.

RTP map (figure 3a) reveals that the study area is characterized by two different patterns of prominent magnetic field variations. Nine magnetic high

anomaly (H1–H9) zones with approximate value of 20–1450 nT and 12 low magnetic anomaly (L1–L12) zones with approximate value of -150 to -1050 nT have been delineated in the RTP map (figure 3a). The low magnetic anomaly zone, L1 is characterized by highly active coal fire/smokes/blaze of about 510°C partially exposed on the surface

Figure 3. (a) Magnetic anomaly map after pole reduction of residual magnetic field intensity map of East Basuria Colliery. L1–L12, results due to subsurface coal fire/blaze affected regions and high anomaly (red colour) denoted by H1 to H9, are due to coalfire/blaze free regions, (b) active fire near L1, (c) active fire near L2, (d) active fire through pothole near L3, and (e) widespread cracks and subsidence due to coal fire near L4 and L5. Photographs of burnt/baked rocks near H1, H3, H5 and H6 are shown in (f), (g), (h), and (i), respectively. Photographs of temperature measurements near L2 (340°C) and L5 (195.4°C) are shown in (j) and (k), respectively.

Figure 3. (Continued.)

through some cracks and fissures (figure 3b). L2 is dominated by subsurface coal fires (figure 3c) with surface temperature of 340°C (figure 3j). Some small potholes are observed near L3 (figure 3d) caused by subsurface coal fire with surface temperature of 335°C . Widespread cracks and subsidence due to coal fire are observed near L4 and L5 (figure 3e) with surface temperature of 284° and 195.4°C (figure 3k), respectively. Generally, temperatures over cooled and baked rocks near high magnetic anomaly regions vary from 30° to 34°C . Photographs of burnt/baked rocks near H1, H3, H5 and H6 are shown in figure 3(f–i), respectively. Overburden materials were dumped over H1, H6 and L1, L4, L5, L8 to prevent coal fire activity. However, cracks, fissures, potholes and subsidence are generated due to coal fire resulting in low magnetic anomaly. Details of low magnetic anomaly and high magnetic anomaly and their surface characteristics are given in tables 1 and 2, respectively.

The first vertical derivative (FV) and second vertical derivative (SV) have been calculated from magnetic RTP data (figure 3) of the study area which are shown in figures 4 and 5, respectively. Details of FV anomaly and SV anomaly and their surface characteristics are given in tables 1 and 2, respectively. The different low and high magnetic anomaly zones have been delineated well in the first vertical derivative anomaly map (figure 4) as in the RTP map (figure 3). Further, these anomalies have also been delineated prominently in second vertical derivative anomaly map (figure 5). In figure 4, 11 distinct high anomaly regions (FVH1–FVH11) have been identified, characterized by first vertical derivative high anomaly (figure 4) which could be related to non-coal fire/blaze free zones. About 19 distinct low anomaly regions (FVL1–FVL19) have been identified characterized by first vertical derivative low anomaly, which are mostly affected by coal fire activity as observed on the

Table 1. *Details of low magnetic anomaly and vertical derivative low anomalies with their surface characteristics.*

Sl. no.	Magnetic anomaly	First vertical derivative anomaly	Second vertical derivative anomaly	Central longitude	Central latitude	Surface characteristics
1	L1	FVL1	SVL1	86°21'56.25"E	23°47'45.98"N	Active fire/blaze/smoke through wide fractures/fissure
2	L2	FVL2	SVL2	86°21'58.53"E	23°47'44.41"N	Active fire/blaze/smoke through fissures/cracks
3	L3	FVL3	SVL3	86°22'0.11"E	23°47'43.38"N	Active fire through pothole and cracks and subsidence
4	L4	FVL4	SVL4	86°21'50.58"E	23°47'45.61"N	Widespread cracks and subsidence due to fire/blaze
5	L5	FVL5	SVL5	86°21'50.28"E	23°47'50.952"N	Cracks and subsidence due to fire/blaze
6	L6	FVL6	SVL6	86°21'47.47"E	23°47'50.34"N	Smoke through pothole/fissure
7	L7	FVL7	SVL7	86°21'44.69"E	23°47'47.637"N	Cracks and subsidence
8	L8	FVL8	SVL8	86°21'42.98"E	23°47'55.047"N	Pothole and cracks and subsidence
9	–	FVL9	SVL9	86°21'49.10"E	23°47'49.35"N	Cracks and subsidence
10	–	FVL10	SVL10	86°21'48.55"E	23°47'47.77"N	Cracks and subsidence
11	–	FVL11	SVL11	86°21'48.46"E	23°47'46.7"N	Smoke through fractures/fissure
12	–	FVL12	SVL12	86°21'47.73"E	23°47'43.05"N	Natural topography
13	L9	FVL13	SVL13	86°21'58.31"E	23°47'40.53"N	Shallow fire/smoke through fractures/fissure
14	L10	FVL14	SVL14	86°21'58.40"E	23°47'41.9"N	
15	L11	FVL15	SVL15	86°21'56.94"E	23°47'42.8"N	
16	L12	FVL16	SVL16	86°21'55.61"E	23°47'43.69"N	
17	–	FVL17	SVL17	86°22'0.066"E	23°47'38.09"N	Natural topography
18	–	FVL18	SVL18	86°21'59.43"E	23°47'49.14"N	Shallow fire/smoke through fractures/fissure
19	–	FVL19	SVL19	86°21'44.61"E	23°47'53.02"N	Shallow fire/pothole and cracks
20	–	–	SVL20	86°21'47.77"E	23°47'51.92"N	Shallow fire/pothole and cracks

ground (figure 3b, c, d and e). Further, in figure 5, totally 11 distinct high anomaly regions (SVH1–SVH11) have been identified characterized by second vertical derivative high anomaly, which could possibly be related to non-coal fire/blaze free zones. Whereas, about 20 distinct low anomaly regions (SVL1–SVL20) have been identified characterized by second vertical derivative low anomaly, which are mostly affected by coal fire activity, as observed on the ground (figure 3b, c, d and e).

The corresponding position with approximate shape of the anomalies associated with coal fire and non-coal fire regions have been delineated well in the second vertical derivative anomaly map than the first vertical derivative and RTP anomaly maps. These are correlated well with the surface characteristics (figures 3, 4, 5 and tables 1 and 2). The anomalous bodies occurring near the ground surface produce much stronger gradient effects

than those which lie at great depths (Gupta and Ramani 1982; Gupta and Grant 1985; Gupta and Sutcliffe 1990). It is observed that vertical derivatives of residual magnetic anomaly enhance shallow bodies associated with low/high magnetic anomaly caused by coal fire/fire-free regions and remove the effect of regional ambient magnetic anomaly. In general, the red colour indicates the regions with enhanced magnetic anomaly and the blue colour indicates the regions with reduced magnetic anomaly with respect to the ambient magnetic field over the study area. It is inferred that the red regions indicate the locations which were heated and subsequently cooled, whereas the blue regions indicate the locations which are under active fire and the light green regions are unaffected by the coal fire.

Magnetic susceptibilities have been measured for understanding of anomalous magnetic behaviour

Table 2. Details of high magnetic anomaly and vertical derivative high anomalies with their surface characteristics.

Sl. no.	Magnetic anomaly	First vertical derivative anomaly	Second vertical derivative anomaly	Central longitude	Central latitude	Surface characteristics
1	H1	FVH1	SVH1	86°22'0.589"E	23°47'48.16"N	VIII and V/VI seam quarry partially filled with OB, previously burned partially at low O ₂ and cooled, baked rock
2	H2	FVH2	SVH2	86°22'0.79"E	23°47'44.36"N	V/VI seam quarry filled with OB, previously burned and cooled, baked rock
3	H3	FVH3	SVH3	86°22'0.38"E	23°47'40.53"N	Cracks and subsidence, previously burned partially at low O ₂ and cooled, baked rock
4	H4	FVH4	SVH4	86°21'57.27"E	23°47'44.52"N	Cracks and subsidence, previously burned partially at low O ₂ and cooled, baked rock
5	H5	FVH5	SVH5	86°21'47.18"E	23°47'46.96"N	Cracks, burned out crop/indurated sediments, burned at low O ₂ and cooled
6	H6	FVH6	SVH6	86°21'49.92"E	23°47'49.36"N	Cracks, baked rock/burned out crop, burned at low O ₂ and cooled
7	H7	FVH7	SVH7	86°21'45.40"E	23°47'54.06"N	V/VI seam quarry filled with OB, burned at low O ₂ and cooled
8	H8	FVH8	SVH8	86°21'54.51"E	23°47'41.55"N	Normal topography
9	H9	FVH9	SVH9	86°21'58.14"E	23°47'38.54"N	Normal topography
10	–	FVH10	SVH10	86°21'53.45"E	23°47'43.88"N	Cracks and subsidence, burned at low O ₂ and cooled
11	–	FVH11	SVH11	86°21'50.95"E	23°47'43.92"N	Normal topography

over different parts of the study area. Generally, the samples collected over active fire region indicate susceptibility of about 140×10^{-5} to 160×10^{-5} SI. However, some samples of fire-affected regions indicate diamagnetic susceptibility of about -50×10^{-5} to -90×10^{-5} SI. The magnetic susceptibility for the samples (baked) of old fire-affected area are about 420×10^{-5} to 590×10^{-5} SI. Whereas, magnetic susceptibility of fresh rock of fire-free regions are about 12×10^{-5} to 18×10^{-5} SI.

Generally, total magnetic field intensity of an environment is the summation of all the magnetic anomalies associated with ferromagnetic, antiferromagnetic, paramagnetic and diamagnetic objects. Subsurface coal combustion is a chaotic process involving many ill-defined variables. The low magnetic anomaly may have resulted due to a large amount of diamagnetic gases, viz., Carbon dioxide (CO₂), Methane (CH₄), Nitrogen (N₂), Ammonia

(NH₃), Sulphur dioxide (SO₂); Hydrogen (H₂), Carbon monoxide (CO), Selenium (Se), Arsenic (As), Mercury (Hg), various unsaturated hydrocarbons, water vapour, tar vapours, organic sulphur, hydrogen chlorides and inorganic chlorides, etc., which are generated in underground active coal fire (Schloemer 2006; Engle *et al.* 2013; Gürdal *et al.* 2015, etc.). Further, the pyrolysis of all carbons are characterized by low values of the magnetic susceptibility with both paramagnetic and diamagnetic components. Heat-treatment to graphitizing temperature causes a decrease in the paramagnetic component and a high increase in the diamagnetic part (Jenkins and Kawamura 1976).

Positive magnetic susceptibility of a rock can result from two sources, viz., (i) the presence of iron, nickel, or cobalt-bearing minerals in the rocks and (ii) the degree of alignment of the magnetic moments within these minerals (Hooper 1987).

Figure 4. First vertical derivative anomaly (FV) map generated from RTP of residual magnetic field data of East Basuria Colliery. Magnetic anomaly distribution indicating low anomaly (blue colour) denoted by FVL1–FVL19, and high anomaly (red colour) denoted by FVH1–FVH11, which are in general due to subsurface coal fire/blaze affected regions and noncoal fire/blaze free regions, respectively.

Positive magnetic anomaly may also be associated with fire due to increase in magnetic susceptibility and TRM of overlying rocks (Shao *et al.* 2014). The overburden/overlying sedimentary rocks (sandstone, shale, etc.) contain traces of magnetic minerals. When the overburden is heated approximately to the Curie temperature, the natural magnetic alignment of magnetic moments and thus the magnetization existing over the area become randomized. Thus, heating above the Curie temperature results in a loss of natural magnetism with a local reduction of the total magnetic field in the vicinity of coalmine fire. Once the coal fire migrates from an area and the overburden cools, the magnetic moments in the overburden become aligned to the Earth's ambient magnetic field which enhances the magnetization of the region. The enhancement is attributed with new preferential alignment of magnetic moments and formation of magnetite in the overburden (Gielisch 2007; Ide *et al.* 2011). Enhancement of the susceptibilities in the thermally altered rock is likely due to the formation of ferromagnetic magnetite (Fe_3O_4) in the shales that have been affected by the heat from the coal fire (Ide and Orr 2011). The process of magnetite and hematite formation is a strong function of O_2 availability at

temperatures typically observed at coal fires (200° – 1000°C). Within these temperature ranges, low O_2 concentration in deeper multi-seam fire or surface area covered with overburden material/soil, etc., leads to magnetite formation, while high O_2 concentration in shallow seam fire with high O_2 circulation through widespread fissures, cracks, potholes, etc., leads to hematite formation (Hooper 1987). Rocks such as siltstones and shales over active coal fire regions provide ideal environments for magnetite formation. The low permeability and the low porosity of these rocks limit the diffusion of O_2 into the matrix. Hematite (Fe_2O_3) formation could result owing to heating of shales and siltstones due to subsurface coal fire. This is an antiferromagnetic and thus does not enhance the magnetization of a region upon formation (Ide *et al.* (Ide *et al.* 2011).

Regardless of the advantages of magnetometer survey over other coal fire characterization methods, magnetometer measurement could be ineffective in some coal fire sites. The objects such as any magnetic materials, water tanks, train lines, power lines, etc., spread on the nearby surface, may significantly distort the magnetometer measurements with spikes and dropped signals. Coal fires characterization of abandoned mines may not be suitable

Figure 5. Second vertical derivative anomaly (SV) map generated from RTP of residual magnetic field data of East Basuria Colliery. Magnetic anomaly distribution indicating low anomaly (blue colour) denoted by SVL1–SVL20 and high anomaly (red colour) denoted by SVH1–SVH11, which are generally resulting from subsurface coal fire/blaze affected regions and non-coal fire/blaze free regions, respectively.

by magnetometer measurements if there are metallic objects left which were used during active mining activity. Buried metallic objects can generate several hundred times larger magnetic field than that generated by coal fires. It could overshadow small changes in the anomaly which are associated with coal fires (Ide *et al.* 2011). In the present study, spikes and dropped signals have been removed and only the readings with good quality signal have been used for analysis.

5. Conclusions

It is observed that the total magnetic field intensity anomaly of the area varies from 44850 to 47460 nT and the residual magnetic anomaly varies approximately from –1323 to 1253 nT. Whereas, the RTP magnetic anomaly varies approximately from –1050 to 1450 nT. Pole reduction removed lateral shifts and asymmetries caused by the local orientation of the magnetic field. Nine magnetic high anomaly (H1–H9) zones with approximate value of 20–1450 nT and 12 low magnetic anomaly (L1–L12) zones with approximate value of –150 to –1050 nT have been identified in RTP anomaly map

(figure 3a). The first vertical derivative (FV) anomaly (figure 4) of RTP provides sharper resolution for delineation of coal fire affected and non-coal fire regions than the simple RTP (figure 3). Whereas, the second vertical derivative (SV) anomaly (figure 5) of RTP delineates approximate shape and outlines of coal fire affected and non-coal fire regions better than that of the first vertical derivative anomaly (figure 4). The first vertical derivative anomaly map delineates 11 high anomaly regions (FVH1–FVH11) and 19 low anomaly regions (FVL1–FVL19). Whereas, second vertical derivative anomaly map delineates 11 high anomaly regions (SVH1–SVH11) and 20 low anomaly regions (SVL1–SVL20). The high anomalies are mostly associated with cooled and baked rocks, while low magnetic anomalies are mostly caused by coal fire activity.

Magnetism increases slowly with temperature rise until the Curie temperature. Generally, if the temperature of rock/overburden rises above Curie temperature, it loses magnetization and becomes paramagnetic, which results with significant reduction in magnetic susceptibility. However, magnetism greatly increases after cooling below the Curie temperature. The large amount of diamagnetic gases, such as Carbon dioxide (CO₂), Methane (CH₄),

Nitrogen (N_2), Ammonia (NH_3), Sulphur dioxide (SO_2), Hydrogen (H_2), Carbon monoxide (CO), Selenium (Se), Lead (Pb), Arsenic (As), Fluorine (F), Mercury (Hg), various polycyclic aromatic/unsaturated hydrocarbons, water vapour, tar vapours, organic sulphur, hydrogen chlorides and inorganic chlorides, etc., are generated in underground active coal seam fire. These are the possible sources of low magnetic anomaly. The other possible source of low magnetic anomaly is pyrolysis process which generates paramagnetic and diamagnetic objects with low magnetic susceptibility. Heat-treatment to graphitizing temperature causes a decrease in the paramagnetic component and a high increase in the diamagnetic part.

The results prove the effectiveness of vertical derivative approach applied on magnetic data for coal fire mapping of East Basuria Colliery, Jharia coalfield, India. The time-lapsed magnetic study using vertical derivative approach would be useful for understanding fire propagation and hazard estimation.

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