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Detection and delineation of coal mine fire in Jharia coal field, India using geophysical approach: A case study

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Coal mine fire is a serious problem in Jharia coal field, India. The coal mine fire can be detected with different techniques such as borehole temperature measurement, thermo-compositional analysis, remote sensing techniques, thermo-graphic measurement and geophysical methods. In this study, various geophysical methods were used to detect the surface and subsurface coal mine fires. Geophysical techniques used in the present study are apparent resistivity, self-potential (SP), magnetic method and thermography. Geophysical anomalies such as low SP value of −60 mV, high negative magnetic response and low apparent resistivity value helped us to detect and delineate the fire and non-fire areas laterally as well as depthwise. Furthermore, the thermography survey was carried out in the coal field using thermal imaging camera in order to substantiate the geophysical methods. This integrated approach was found to be more advantageous for the detection and delineation of surface and subsurface fire with respect to use of any specific techniques. Moreover, the level of threat towards the locality, national railway line was also assessed unambiguously using the above techniques. Hence, proper planning and implementation towards the mitigation of hazard can be achieved on the basis of the reported results.

Keywords. Geophysical; thermography; resistivity meter; self-potential (SP); magnetometer; thermal imaging camera.

1. Introduction

Coal mine fire is a global event reported in different countries such as India, China, the United State of America (USA), Australia, South Africa, Indonesia, Poland (Zhang *et al.* 2005; Kuenzer *et al.* 2008; Kuenzer and Stracher 2012; Shao *et al.* 2014; Pandey *et al.* 2016). Coal is a primary source of energy in India. India has the third largest prime coking coal resource in the world (Sinha and Singh 2005). It has been estimated that nearly 50 million tons of good-quality coking coal has been lost and about 200 million tones are locked due to fire (Mishra *et al.* 2014; Pandey *et al.* 2016). The coal fires release toxic, noxious and greenhouse gases during the fire. The gases and heat flow liberated by coal fire destroys the vegetation of the area (Dai *et al.* 2002; Mishra *et al.* 2012). Detection and delineation of coal mine fire is a challenging task for coal industry.

Jharia coal field fire in India has been identified using the remote sensing technique (Prakash *et al.* 1997; Prakash and Gupta 1999). The fire is distributed in various parts of the coal field causing economic loss due to burning of coal, creating threat on national road and railways, environmental and societal set up of countries (Pandey *et al.* 2016). Thermo-compositional studies, temperature and gas analysis are carried out to determine the presence and intensity of fire in mines (Sinha and Singh 2005). Detection and delineation of coal fire area has been carried out on the basis of temperature difference (Zhang *et al.* 2005). Geophysical resistivity method uses variation of apparent resistivity of the burnt coal with respect to host rock, which was measured with the help of standard electrodes profiling spread (Gangopadhyay 2003; Bharti *et al.* 2016).

Using suitable approach, detection of the burning fronts which are creating hazards is required. The extent of coal fire is required to be quantified prior to strategic extinguishing attempt which was accomplished in the past using geophysical methods such as controlled source audiomagnetotelluric, time domain electromagnetic (Bartel 1982; King 1987; Schaumann *et al.* 2005; Ide *et al.* 2011) measurements (Rodriguez 1983; Sternberg and Lippincott 2004) electrical resistivity method or imaging (Corwin and Hoover 1979; Rodriguez 1983; Hatherly 2013; Revil *et al.* 2013; Xin *et al.* 2015). The low resistivity associated with burning fire, magnetic susceptibility due to temperature above the Curie temperature and ionic current flow due to current density gradient along with the thermoelectric effect contributes to physical parameter contrasts leading to information for quantification of coal fire extent (Hatherly 2013; Karaoulis *et al.* 2014). Chatterjee (2006) and Chatterjee *et al.* (2007) have attempted the detection of coal mine fire in Jharia coal field using the Landsat band 6 satellite data by the remote sensing technique.

The Landsat-7 Enhance Thematic Mapper (ETM+) band 6 data was used to identify the coal mine fires and establish the relation between the satellite data and ground data temperature on a regional scale for Jharia coal fields (Mishra *et al.* 2011). However, none of the above approaches is capable of diagnosing the fire area unambiguously and therefore a combination of all these methods is used to detect the fire area (Revil *et al.* 2013; Shao *et al.* 2014).

In the present study, the integrated approach consisting of different geophysical method (self-potential (SP), electrical resistivity, magnetic and thermography) has been used for quantification of coal fire spread unambiguously. The geophysical and thermal survey was carried out in three profile lines of which one line lies inside the fire zone, second line outside the fire zone and third line further outside near railway siding. The extent of fire has been identified by all the three approaches in order to assess the threat to the local and national railway lines. The integrated approach reduced artefacts and ambiguity in quantifying the coal fire extent.

2. Study area

Gondudih Khash Kusunda Colliery (GKKC), Kusunda area belongs to Jharia coal field under the Bharat Coking Coal Limited (BCCL) Dhanbad, Jharkhand, India. It is about 8 km in the west direction from Dhanbad railway station. The mine is located at latitude of 23°65′7″, longitude of 86°21′96″ and elevation of 226 m. GKKC seam fire is advancing towards the Gondudih railway siding through Gondudih village, thus posing a major threat to local population as well as railway line. The main aim of the present study is to detect and delineate the fire of the mine. The study area has been shown in figure 1.

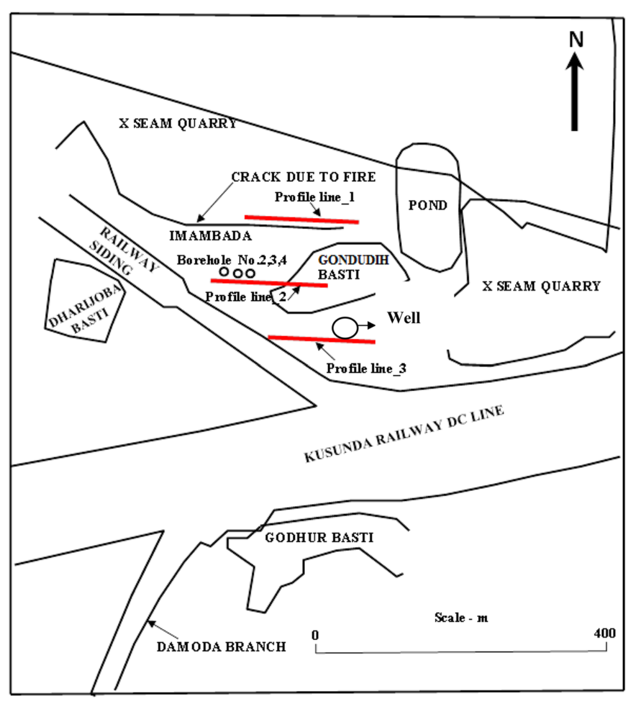

Figure 1. Location map of the study area Gondudih Khash Kusunda Colliery (GKKC) along with fire area, the profile line 1 (over the coal mine fire), profile line 2 (along near the borehole and within the Gondudih Basti) and profile line 3 (along the road side and near to the railway line) are shown in red lines.

3. Methodology

The following geophysical methods have been used in the present study for detection and delimitation of coal mine fire.

3.1 *Self-potential*

SP is the natural potential difference measured between the two points on the earth surface. It depends on a number of physico-chemical properties of soil including the temperature gradient. The SP in coal fire area is developed by oxidation of coal and temperature difference. Thus, the combustion of coal releases a large amount of heat resulting into temperature-induced voltage difference between the two electrodes on the earth surface. The positive anomalies are measured on the surface in a coal fire area, this indicates a shallow depth fire and the temperature near the ground surface is high. Conversely, negative anomalies suggest that the fire is deep seated and temperature anomalies may not exist on the ground surface.

The DDR-3 resistivity meter has been used for measuring the SP. A conventional pot with the copper electrode and copper sulphate solution was used for measuring the minimum potential difference between two selected electrodes. The study area is divided into three lines which are shown in figure 1. The first line was transecting the fire zone. The length of line was 100 m. Boreholes of 8–10 inches diameter at 10 m spacing were made at the line. The holes were filled with water for counteracting the immediate physical changes and to have better contact with electrodes. As the area of study was densely populated, our major task was to measure the spread of fire which is affecting the houses of the village. Some houses have been collapsed due to fire. The next aim was to measure the extent of threat to nearby national railway line connecting the eastern part of the country with rest of the country as well as major railway freight corridor. Managing the available space for carrying out SP survey, second line was chosen approximately parallel and having a length of 70 m within the settlement of people. Finally, the third line which is again 70 m with 10 m spacing along the motor road and it was located close to the railway line. Similar boreholes were made on the second and third lines, and are filled with water before taking the measurement. The base of each station was at the initial point of stations and the gradient approach was carried out to acquire the data for each point in all lines. The readings for each line provided useful information regarding the fire spread.

3.2 *Magnetic susceptibility method*

Combustion of underground coal releases heat which makes the temperature of overlying rock higher than the Curie temperature. This temperature implies the significant changes in magnetic properties (magnetic susceptibility and thermoremanent magnetisation) and thereby results in an observable magnetic anomaly at the surface in the coal fire area.

The magnetic survey was carried out along all the three experimental lines using the proton precession magnetometer (GSM-19) with 0.01 nT resolution. The base station was fixed away from the fire zones and made all possible corrections while processing the magnetic data.

3.3 *Electrical resistivity*

Electrical resistivity of the material is physical properties of soil which depends on soil mineralogy, void and temperature. The resistivity distribution of the soil is determined during the electrical resistivity survey. Artificially generated electric currents are applied to the soil and the resulting potential differences are measured. The potential difference provides information about the subsurface heterogeneities and their electric properties. The electrical resistivity decreases when the temperature of material increases. When the soil layer is uniform, the resistivity is constant and independent of both electrode spacing and surface location. When the subsurface resistivity varies according to the relative position of electrodes, the soil structure is heterogeneous and the resistivity is known as apparent resistivity.

The electric resistivity survey was carried using the Werner configuration of 10 m spacing above each line. The same potential electrodes were used in the electrical resistivity survey and current electrodes were pure stainless steel and salt water solution was used to the current electrodes location to reduce the contact resistance. The reading was observed with the above-mentioned DDR-3 resistivity meter with $50\,\mu\Omega$ resistance resolution. The readings were fluctuating possibly due to the thermoelectric effect. So, results were recorded only after stable reading.

3.4 *Thermography*

The main principle used in this technique is that every object emits certain amount of infrared (IR) energy and the intensity of this IR radiation is a function of temperature. In an electromagnetic spectrum, the IR region varies from 0.8 to 1000 μm wavelength. This wavelength of IR spectrum is more than that of a visible spectrum. The IR energy directly representing the surface temperature can be detected and quantified with the help of IR scanning system. The basic IR system consists of an IR energy detector and a monitor. The scanner is an opto-mechanical device which converts the IR energy received from an object surface to an electrical signal. These signals are further fed into the monitor, where they are processed and presented in many forms like simple digital display to indicate the temperature level and thermal profile (Pandey *et al.* 2013).

An IR thermal imaging camera (Thermo CAM P-65) measures the temperature and gives image of the emitted IR radiation from an object. As we know, radiation is a function of the object surface temperature which makes it possible for the camera to calculate and display this temperature. However, the radiation measured by the camera not only depends on temperature but also a function of emissivity. The radiation also originates and reflects from the surrounding object. The radiation from the object and the reflected radiation will also be influenced by absorption of the atmosphere. To measure the temperature accurately, it is therefore necessary to compensate the effect of a number of different radiation sources. This is accomplished by taking the accurate object parameter in the camera. The following object parameters must be considered for measuring the accurate temperature: emissivity of object, reflected apparent temperature, distance between the object and camera and temperature of the atmosphere.

4. Observation and data analysis

Data collected during the fieldwork in SP measurement, magnetic anomalies, electrical resistivity and thermography along the profile lines 1, 2 and 3 are presented in figures 2–5, respectively.

The SP values obtained during the fieldwork have been plotted with distance. Figure 2(a) shows the SP value *vs.* distance plot along the profile line 1 where the non-fire area is indicated by the high SP value of about +80 mV. Subsequently, it has a decreasing trend up to the cracks at a distance about 60–70 m. The SP value found to drop to −60 mV on the coal fire part. However, the low values of −30 mV at around 30 m indicate the deeper coal fire source. Figure 2(b) shows the SP value *vs.* distance plot for profile line 2, where the positive SP value of 30 mV is seen around 50 m, which may be due to the presence of unburnt coal seam. Later, the negative SP value of −50 mV is found at distances of 60 and 70 m, which may be due to the presence of vegetation near those stations. Figure 2(c) shows the SP value *vs.* distance plot for the profile line 3 where a large negative SP value is observed near station no. 4 (at a distance of about 40 m) which may be due to an abandoned well having underground water trace.

The magnetic responses along the three profile lines are shown in figure 3(a–c). Figure 3(a) shows the magnetic anomaly *vs.* distance plot, where it is observed that in the non-fire area the magnetic anomaly is positive having 1000 nT value, later in the location of cracks, at a distance of about 60–70 m, on the coal fire part, the anomaly has suddenly increased further negative to 800 nT. However, the low positive values of 300 nT around 20 m indicate a deeper coal fire source. Figure 3(b) shows the magnetic anomaly *vs.* distance. The results show that there is a sudden peak in magnetic anomaly values in several stations (i.e., station nos. 1, 4 and 6). The stations were on the close proximity of roads and the houses where the power line sources play a predominant role. Figure 3(c) shows the magnetic anomaly *vs.* distance for line 3, where it is seen that there is a sudden peak in the magnetic anomaly value over the station no. 6 and there is no appreciable variation in the anomaly values in other stations. The presence of dyke can be envisaged which may be the main reason for such high magnetic anomaly.

The apparent resistivity for different profile lines has been plotted with distance and are presented in figure 4(a–c). In figure 4(a), the apparent resistivity is found to be high in the non-fire area, later this has been found to be decreasing in the presence of cracks and fire at a distance of about 60–70 m. There is a peak in apparent resistivity value and finally on the coal fire part, the value has suddenly increased slightly which is small enough with respect to the non-fire zone. However, the deeper coal fire zone presence cannot be overruled below 30 m point. In figure 4(b), the apparent resistivity

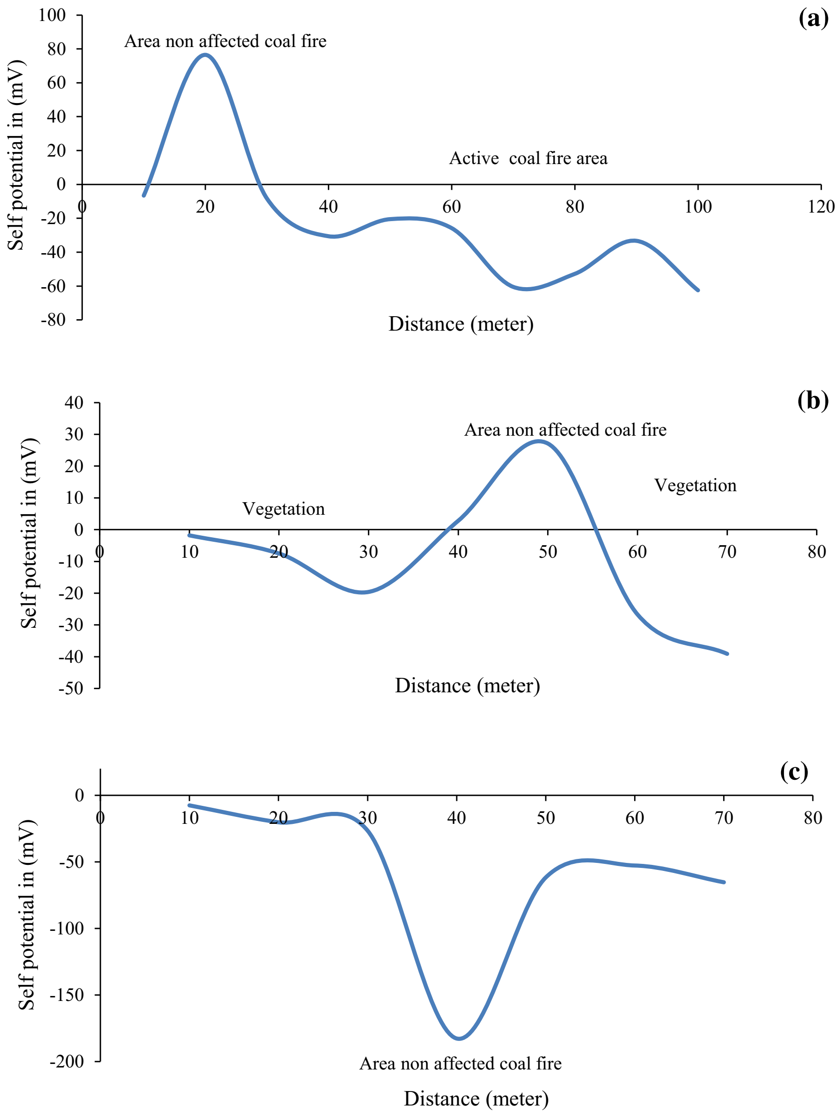

Figure 2. Figure showing SP mV with respect to distance: (**a**) along the profile line 1, (**b**) along the profile line 2 and (**c**) along the profile line 3.

is found to have a sudden peak at a distance of about 35 m, later the value has been found to be in a decreasing trend. The high value indicates the presence of coal seam. In figure 4(c), the apparent resistivity *vs.* distance plot, where the apparent resistivity value is found to be high between the distances 15 and 35 m, later there is a sudden fall in the apparent resistivity value at a distance of about 45 m. On this line, the current penetration was small which may be due to the presence of hard rock cover. However, the low apparent resistivity value may be due to the presence of scanty water in the abandoned well.

Thermal images of profile lines 1, 2 and 3 are shown in figure 5(a–c), respectively. Figure 5(a) suggests the fire along line 1 with the minimum and maximum temperatures of 39.5° and 74.3°C, respectively, whereas figure 5(b) and (c) for lines 2 and 3 shows the absence of fire, where the minimum and maximum temperatures are 33° and 55°C.

5. Results and discussion

The integrated approach of various geophysical techniques provided an overview of coal fire spread across the three profile lines. Initially, figure 2(a) shows the SP value along the first profile line which shows a high negative value of −60 mV in the intense coal fire zones. The physical observation of cracks emitting gas suggests fire at deeper portion (Revil *et al.* 2013). The non-fire area has

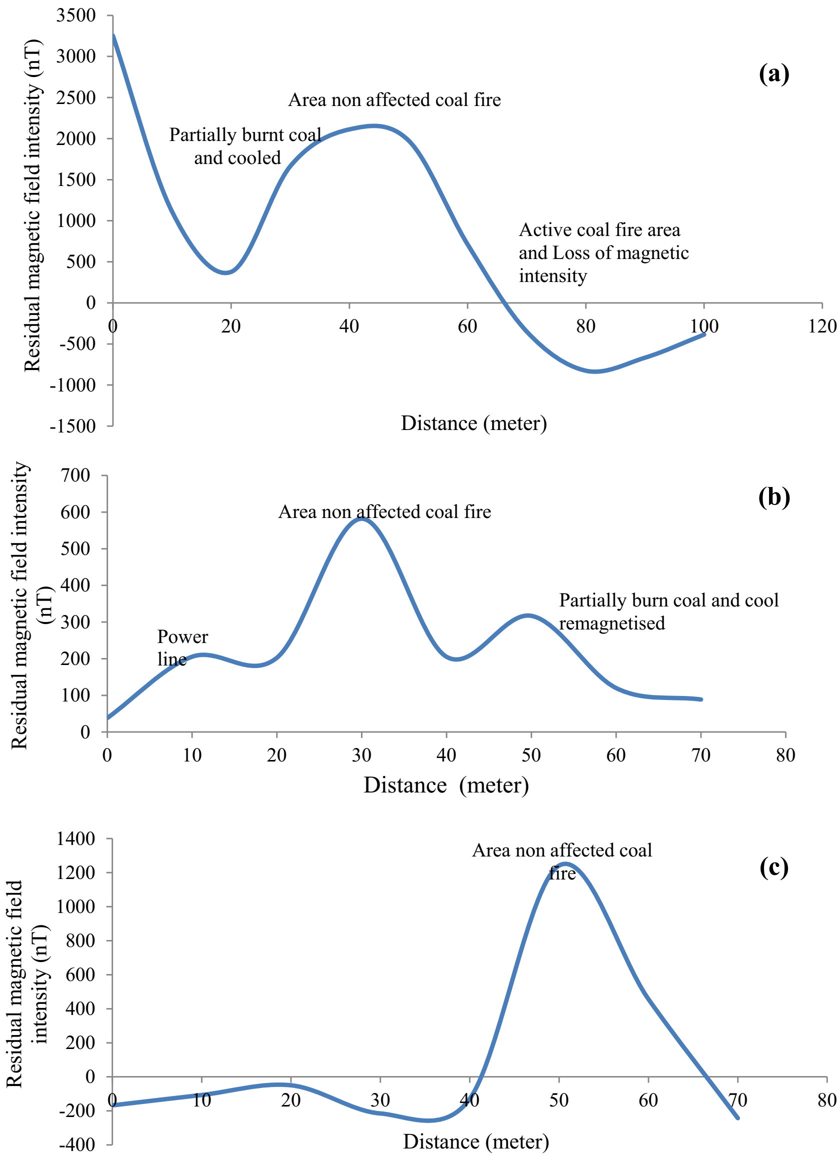

Figure 3. Figure showing residual magnetic field intensity (nT) with respect to distance: (**a**) along the profile line 1, (**b**) along the profile line 2 and (**c**) along the profile line 3.

positive SP values of 80 mV which suggests the possibility of coal at depth. The second line, which was away from the exposed coal fire zone without any observed subsidence, shows a negative SP value of −50 mV (figure 2b), which is possibly due to the intense vegetation or a tree seen in the close proximity of the second line. Another point, i.e., 30 m from base, a negative value of −20 mV is observed which corresponds to the existence of vegetation. A positive SP value of 30 mV near 50 m point suggests the deep seated coal seam. The observation at third line shown in figure 2(c) shows the abnormal negative SP value of −180 mV. This abnormal observation can be explained with the abandoned portable water well, which is approximately 20 m deep. This well is found to be wet inside, but without any water saturations. Similar observation was reported by Karaoulis *et al.* (2014), where the SP value ranging from +70 to −50 mV was observed for non-fire to fire area while delineating a shallow depth fire of Colorado mine, USA. Here, the absence of any positive SP values overrules the presence of coal seam at this location. Thus, the SP results show that the fire is well contended in close proximity of line 1 having surface fire exposed zones.

Magnetic susceptibility study was carried out to make inferences less ambiguous. Figure 3(a) shows a trend of drop in magnetic value which starts at deep seated coal fire cracked zones and reaches to

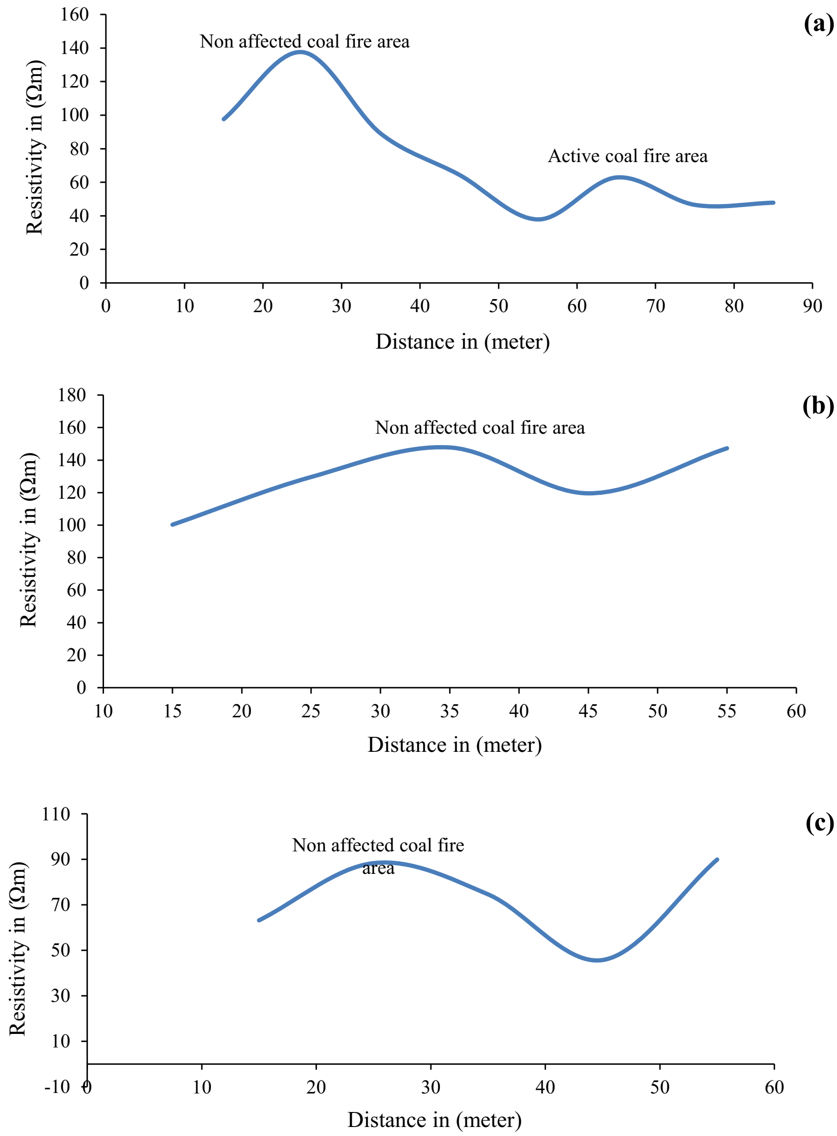

Figure 4. Figure showing the resistivity of the soil with distance: (**a**) along the profile line 1, (**b**) along the profile line 2 and (**c**) along the profile line 3.

high negative values of −900 nT at surface exposed fire zones in line 1. These interesting values may be explained due to observed temperature exceeding the Curie temperature (Shao *et al.* 2014). The low magnetic value of 350 nT may be due to the presence of unburnt coal seam. The second line was again seen with the mixed pattern of low and high values in figure 3(b). As there was an overhead domestic 50 Hz time varying (AC) power line along the second line of observation, the meaningful interpretation of observation may not be possible. However, figure 3(c) presents the magnetic reading for third line, which shows negative values of −200 to −350 nT and shoots up to 1200 nT. Such an abnormal value may be contributed due to the presence of dyke intrusion near the well. The low and negative values of residual magnetic anomalies have also been reported by Vaish and Pal (2015) and Pal *et al.* (2016) for a fire delineation study at East Basuria Colliery of Jharia Coal Fields, India. The possible reason for drying up of the well can be linked to hindrance created by dyke on recharge of water from the surroundings. The second and third lines do not show any extension of fire in the subsurface.

Electrical resistivity profile was conducted to further reduce the ambiguity of result. Figure 4(a) shows that there is a tendency of reduction in the apparent resistivity as it approaches towards the coal fire from the non-coal fire zone. The reason for low apparent resistivity of ∼40 Ωm is due to the increased conductivity contributed by the

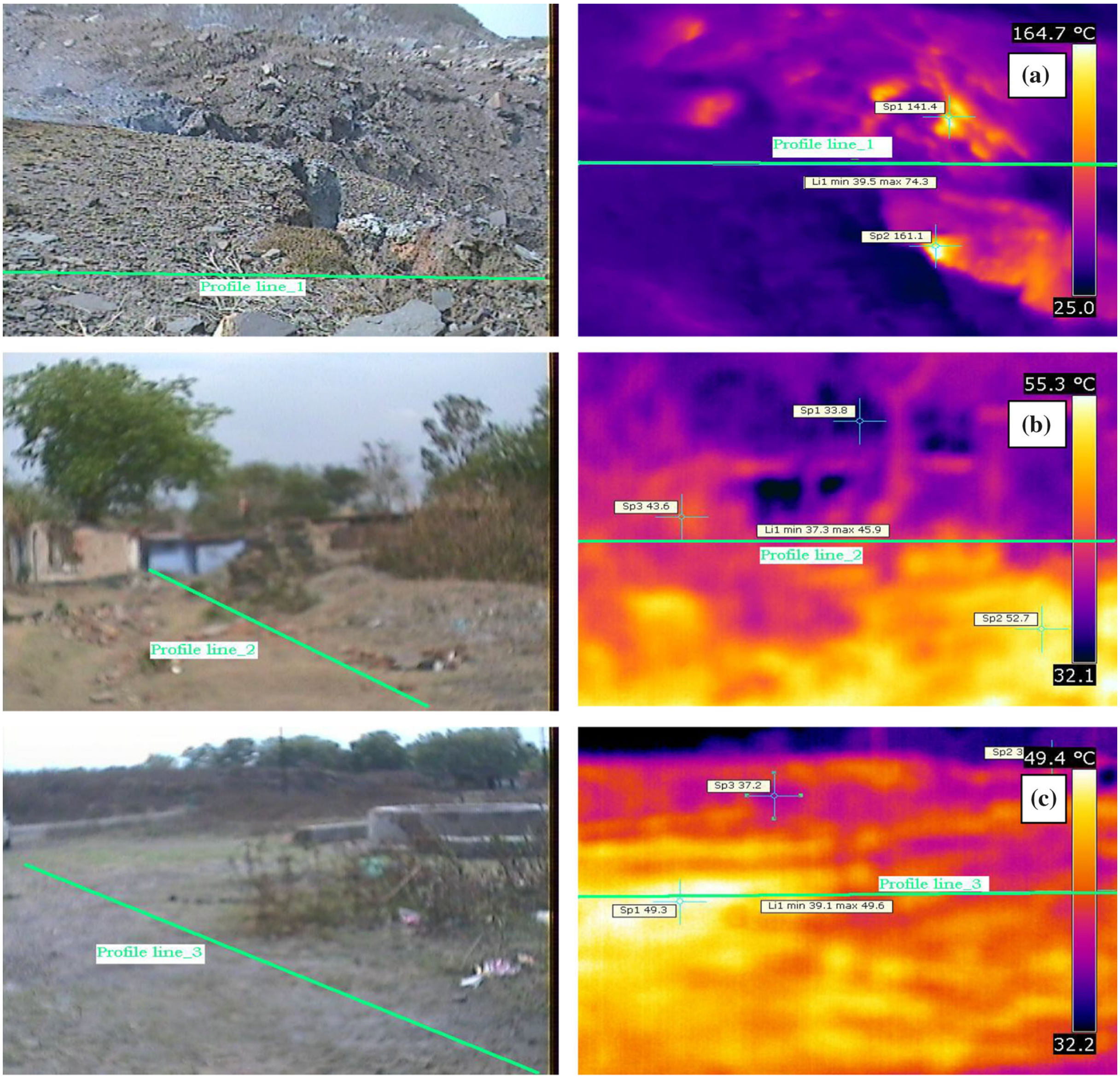

Figure 5. Visual and the respective thermal images: (**a**) along the profile line 1, (**b**) along the profile line 2 and (**c**) along the profile line 3.

temperature gradient, thus increase in the mobility of ions contributes to the easy passage of DC current (Revil *et al.* 2013). Line 2, as shown in figure 4(b), has the same tendency of low apparent resistivity near vegetation, i.e., the presence of water saturation zones and hence the low resistivity of 100–115 Ωm as in the case of a SP method. A high resistivity value of 150 Ωm at 30–35 m along the profile line 2 indicates the presence of coal seam. Line 3 responses shown in figure 4(c), corroborate with the earlier results of SP, i.e., the low resistivity of 45 Ωm contributed due to the abandoned well. The high value near both sides of the well corroborates with the earlier discussed magnetic reading of possible dyke intrusion. A high resistivity value for non-fire affected coal seams and low resistivity values for fire affected seams have also been reported by many authors (Singh *et al.* 2004; Karaoulis *et al.* 2014; Bharti *et al.* 2016).

Thermography observation along the profile line 1, shown by optical and thermal image for the surface and subsurface coal mine fire, reveals the minimum and maximum temperatures of 39.5° and 74°C, respectively. Temperature of cracks is 161°C, which is shown in figure 5(a). The gases emitted through cracks suggest sub-surface fire. The observations presented in figure 5(b and c) along the borehole, which is in the direction of railway line and road, do not indicate any temperature anomaly. Even thermography shows the trend of normal temperature at the surface for profile lines 2 and 3. The fire is not found to have any propagating tendency from the seam quarry location towards the Gondudih village near the bore hole and railway line. All the results of the SP, magnetic resistivity and thermography indicate the absence of fire zone along the railway road direction, near the Gondudih village. The complexity of interpretation in line 2 remained, where the low SP found was preliminarily justified with vegetation or trees present. However, the other supporting methods of magnetic susceptibility reading were affected by the presence of AC power line. Similarly, a relatively low apparent resistivity (not as low as coal fire zones) may be due to the presence of water associated with the roots of the tree. Thus, ambiguity remains about the presence of coal fire in the zone around line 2. However, the presence of borehole along this line and the thermography study along with the other observations clearly support the non-coal fire zones, but the anomaly dominated by the vegetation and water associated with the soil.

Due to the possible coal seam extension found in line 2, the presence of habitat is a serious concern. Hence, careful monitoring is required at repeated intervals as well as suitable measures are to be adopted for taming the coal fire spread in this crucial area of concern.

Thermography limitation was overcome with the conventional geophysical methods for the mapping of fire extent depthwise. However, thermography gave basis of surface and near surface coal fire spread more reliably.

6. Conclusions

The following conclusions can be inferred from with the detection and delineation study of coal mine fire conducted in the Gondudih colliery of Jharia coal fields using SP, magnetic susceptibility, resistivity and thermography study.

- The integrated approaches of SP, magnetic susceptibility, electrical apparent resistivity and thermography unambiguously indicate that the fire is well contended along the profile line 1. The fire is initially at depth and later exposed at the surface. The profile line 2 does not have any indication of fire spread but suggests the presence of coal seam. The profile line 3 has no effect of coal fire but the presence of water and possible dyke is indicated with the help of apparent resistivity and magnetic susceptibility.
- Since the interpretation of various geophysical techniques is suggestive in nature, the conclusion about coal seam, geological discontinuities, state of coal fire and its boundaries from any one technique is never unambiguous. In the present study, four geophysical methods have been used along the three profile lines 1, 2 and 3 and all the four methods suggest similar observation and interpretation confirming the findings of the study including the status of coal fire in the study area.
- Although the coal fire is well contended in line 1, proper routine monitoring is a must in this area to ensure that fire is not spreading towards the village and railway line through the extended coal seam. A detailed strategy for controlling or extinguishing the fire is needed for keeping the people or habitat safe and to avoid threat to the important national railway track.

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References

Bartel L C 1982 Evaluation of the CSAMT geophysics technique to map abandoned coal mine fires: Department of energy contract DE-AC04-76DP00789, Sandia National Labs; Presented at the 52nd annual international SEG meeting, Dallas.

Bharti A K, Pal S K, Priyam P, Kumar S, Srivastava S and Yadav P K 2016 Subsurface cavity detection over Patherdih colliery, Jharia Coalfield, India using electrical resistivity tomography; *Environ. Earth Sci.* **75**(**5**) 1–17.

Chatterjee R S 2006 Coal fire mapping from satellite thermal IR data – A case example in Jharia coalfield, Jharkhand, India; *ISPRS J. Photogr. Rem. Sens.* **60**(**2**) 113–128.

Chatterjee R S, Wahiduzzaman M, Ankit S, Raju E V R, Lakhera R C and Dadhwal V K 2007 Dynamics of coal fire in Jharia coalfield, Jharkhand, India during the 1990s as observed from space; *Curr. Sci.* **92**(**1**) 61–68.

Corwin R F and Hoover D B 1979 The self-potential method in geothermal exploration; *Geophysics* **44** 226–245.

Dai S, Ren D, Tang Y, Shao L Y and Li S S 2002 Distribution isotopic variation and origin of sulfur in coals in the Wuda coalfield, Inner Mongolia, China; *Int. J. Coal Geol.* **51**(**4**) 273–250.

Gangopadhyay P K 2003 Coalfire detection and monitoring in Wuda North China – A multi-spectral and multi-sensor TIR approach; MSc (Geo-information) Thesis, Int. Inst. Geo-infor. Sci. Earth Observation Enschede, Netherlands, 19p.

Hatherly P 2013 Overview on the application of geophysics in coal mining; *Int. J. Coal Geol.* **114** 74–84.

Ide T S, Crook N and Orr F M Jr 2011 Magnetometer measurement to characterize a subsurface coal fire; *Int. J. Coal Geol.* **87** 190–196.

Karaoulis M, Revil A and Mao D 2014 Localization of coal seam fire using combined self-potential and resistivity data; *Int. J. Coal Geol.* **129** 109–118.

King A 1987 Cindered coal detection using transient electromagnetic methods; *Geoexploration* **24** 367–379.

Kuenzer C and Stracher G B 2012 Geomorphology of coal seam fires; *Geomorphology* **138**(**1**) 209–222.

Kuenzer C, Hecker C, Zhang J, Wessling S and Wagner W 2008 The potential of multidiurnal MODIS thermal bands data for coal fire detection; *Int. J. Rem. Sens.* **29**(**3**) 923–944.

Mishra R K, Bahuguna P P and Singh V K 2011 Detection of coal mine fire in Jharia coal field using Landsat-7 ETM+ data; *Int. J. Coal Geol.* **86** 73–78.

Mishra R K, Pandey J, Chaudhary S K, Khalkho A and Singh V K 2012 Estimation of air pollution concentration over Jharia coalfield based on satellite imagery of atmospheric aerosol; *Int. J. Geoma. Geosci.* **2**(**3**) 723–729.

Mishra R K, Roy P N S, Pandey J, Khalkho A and Singh V K 2014 Study of coal fire dynamics of Jharia coal field using satellite data; *Int. J. Geoma. Geosci.* **4**(**3**) 477–484.

Pal S K, Vaish J, Kumar S and Bharti A K 2016 Coal fire mapping of East Basuria colliery, Jharia coalfield using vertical derivatives technique of magnetic data; *J. Earth Syst. Sci.* **125**(**1**) 165–178.

Pandey J, Kumar D, Mishra R K, Mohalik N K, Khalkho A and Singh V K 2013 Application of thermography technique for assessment and monitoring of coal mine fire: A special reference to Jharia coalfield, Jharkhand, India; *Int. J. Adv. Rem. Sens. GIS* **2**(**1**) 138–147.

Pandey J, Kumar D, Singh V K and Mohalik N K 2016 Environment and socio-economic impacts of fire in Jharia coalfield, Jharkhand, India: An appraisal; *Curr. Sci.* **110**(**9**) 1639–1650.

Prakash A and Gupta R P 1999 Surface fire in Jharia coalfield, India – Their distribution and estimation of area and temperature from TM data; *Int. J. Rem. Sens.* **20**(**10**) 1935–1946.

Prakash A, Gupta R P and Saraf A K 1997 A Landsat TM based comparative study of surface and subsurface fire in the Jharia coalfield, India; *Int. J. Rem. Sens.* **18**(**11**) 2463–2469.

Revil A, Karaoulis M, Srivastava S and Byrdina S 2013 Thermoelectric self-potential and resistivity data localize the burning front of underground coal fires; *Geophysics* **78**(**3**) 259–273.

Rodriguez B D 1983 A self-potential investigation of a coal mine fire; MS Thesis, Colorado School of Mines, 132p.

Schaumann G, Siemon B and Changchun Y 2005 Geophysical Investigation of Wuda coal mining area, Inner Mongolia, electromagnetic and magnetic for coal fire detection; In: *International conference on spontaneous coal seam fires*: *Mitigating a global disaster*, ERSEC Ecological Book Series – 4, Beijing, PR China, pp. 336–350.

Shao Z, Wang D, Wang Y and Zhong X 2014 Theory and application of magnetic and self potential method in the detection of Heshituluogai coal fire, China; *J. Appl. Geophys.* **104** 64–74.

Singh K K K, Singh K B, Lokhande R D and Prakash A 2004 Multielectrode resistivity imaging technique for the study of coal seam; *J. Sci. Ind. Res.* **63** 927–930.

Sinha A and Singh V K 2005 Spontaneous coal seam fires: A global phenomenon; In: *International conference on spontaneous coal seam fires*: *Mitigating a global disaster*, ERSEC Ecological Book Series – 4, Beijing, PR China, pp. 42–65.

Sternberg R and Lippincott C 2004 Magnetic surveys over clinkers and coal seam fires in Western North Dakota; In: *Denver annual meeting of the Geological Society of America* **15**(**9**).

Vaish J and Pal S K 2015 Subsurface coal fire mapping using magnetic survey at East Basuria colliery, Jharkhand; *J. Geol. Soci. India* **86**(**4**) 438–444.

Xin M, Zhu H, Xiang M, Zhang Y and Liu D 2015 Application of transient electromagnetic method in coal mine fire detection; *Metallurg. Min. Indus.* **6** 321–326.

Zhang J, Zhongdan H, Mei, Wang and Yaling X 2005 3D Detection and visualization of underground coal fires; In: *International conference on spontaneous coal seam fires*: *Mitigating a global disaster*, ERSEC Ecological Book Series – 4, Beijing, PR China, pp. 410–425.

Corresponding editor: N V Chalapathi Rao