



Time-lapse monitoring of coal fire using self-potential, magnetic, and electrical resistivity imaging over a part of East Basuria Colliery

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Keywords

Coal Fire, RTP, ERI, Resistivity 2.5D Inversion, Time-lapse.

Abstract

Jharia coalfield is one of India's largest and most productive coal fields, home of the oldest-burning coal seam fires in the world. The paper highlights the time lapse combined study comprising Self-Potential (SP), Magnetic, and Electrical Resistivity Imaging (ERI) methods for delineation and mapping of coal fires their depths, extension, and propagation direction. Time lapse studies in 2013 and 2015 over East Basuria colliery were carried out using magnetic, self-potential (SP), and electrical resistivity imaging (ERI). Two SP, magnetic, and ERI profiles data were collected across the expected site in 2013 and 2015. Prominent negative SP and negative magnetic anomalies have been delineated with similar low resistivity anomaly in all profiles conforming to the active coal fire in different seams. In the year 2013, five prominent active/partial coal fire zones have been delineated in coal seams VIIIA/VIIIB/VII based on the combined analysis of SP, magnetic, and ERI are associated. Whereas, two prominent active fire zones and four prominent baked/burned out/fractured rock-mass zones have been identified, in the year of 2015. It is observed that coal-fire front is moving outward from central open coal mine pit; however, a prominent active fire-front is moving towards the north-west part of the study area.

Introduction

The coal fire was initially observed in the V/ VI coal seams in the quarry of East Basuria Colliery in 1976. Subsequently, in 1995 the fire was well developed by then the coal fire quickly spread to other seams, namely VII, VIII, and VIIIA that were resulted in many parallel cracks, fractures, subsidence, potholes, and many of them were observed at the surface as

well. During the years 1997-98, Bharat Cooking Coal Limited (BCCL) started cutting trenches to prevent the spread of coal fire against an eastward advancement. However, the fire spread rapidly due to availability of oxygen supply that acted as a catalyst through the dug (Central Mine Planning and Design Institute (CMPDI) 2003; Coal International 2003; World Bank Group 2003). The position of the area under this investigation is shown in Fig 1(a). Lithology showing different coal seams varying with depths collected from borehole data, SBJ-6 is shown in Fig 1(b) (BCCL 2009). Local seams are very thin and are not preferred for mining, but it has enormous potential in spreading the fire. The slope of coal seams varies from 6.7 to 11.3 degrees and dipped NE 050 SW to NE 150 SW. Previously some researchers have used limited geophysical methods of surveying, which are mainly magnetic methods and SP to detect coal fire (Srivardhan et al., 2016; Pal et al., 2016). Srivardhan et al., (2015) have studied some parts of this area using SP profiles and has interpreted them through PSO (Particle Swarm Optimization) technique to estimate the depth and shape of the coal fire. Vaish and Pal (2015), have also studied the area in greater detail using the only magnetic method. They have successfully detected coal fire and estimated the approximate depth of their propagation. The magnetic data has been processed and interpreted using multiple approaches like a downward continuation, tilt derivative, and vertical derivative techniques for investigation of fire in the East Basuria area. However, only time-lapse magnetic data over the East Basuria region was analyzed which revealed that coal fire extends to the deeper depth with time and the upper seams are burnt/cooled (Vaish and Pal, 2015; Pal et al., 2016). For the first time in India in this study, a combined time-lapse study has been performed over a part of the East

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Basuria region using magnetic, self-potential, and electrical resistivity imaging (ERI) for better understanding the dynamic propagation of coal fires. The East Basuria Colliery is characterized by highly rugged and undulated topography due to a combined effect of the violent coal-fire activities and old mining practices. This subsequently caused several cracks and fissures, land subsidence, and potholes that necessitated dumping of overburden materials. This has hampered data acquisition, and therefore only two profiles were selected for analysis using SP, magnetic, and ERI over the study area in the years of 2013 and 2015 (Fig 1.1(a)).

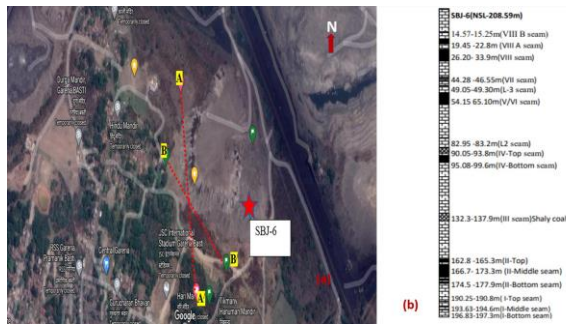


Figure 1 (a) Schematic location plan (prepared using Google earth) shows survey lines in the study area, East Basuria Colliery, Jharia Coal field, India. (b): Borehole lithology showing different coal seams at different depths with their physical status (BCCL 2009). The location of this borehole is shown in Figure 1(a).

Method

SP method works for coal fire mapping using redox potential generated by oxidation of coal and on Thomson potential caused by temperature gradient. It is observed that low SP anomalies are associated with fire, but high SP anomalies are associated with non-fire areas. The magnetic data provided a map showing the earlier burned, currently burning, and unburned patches based on variation of magnetic properties of the subsurface and changes with temperatures above or below the Curie temperature. Data processing methods such as diurnal correction, reduction to pole (RTP), to delineate the coal fire affected area using magnetic data. It is observed that low magnetic anomalies are associated with fire, but high magnetic anomalies are associated with non-fire areas. Which are well correlated with estimated depth and possible geometry from SP anomaly. The

pyrolysis of coal is one of the main processes in coal fires, which results in very high conductivity. Thus, electrical resistivity imaging (ERI) has been used as a promising technique for the characterization of subsurface coal fire. ERI study using Wenner, Schlumberger, Dipole-Dipole, and Gradient arrays have been carried. Further, combined inversion of filtered data collected by all arrays has been performed using a 2.5D resistivity inversion program, to amalgamate the relative benefits of all the arrays. It is observed that low resistivity anomalies are associated with fire, but high resistivity anomalies are associated with non-fire areas. Most of the features of low and high resistivity anomalies have been delineated well in the ERI sections generated from combined inversion of all arrays.

Result and Discussion

Time-lapse SP data were collected in two profiles, namely along AA/ (North – South), and BB/ (North-West to South-East) years of 2013 and 2015. A total of 260m profile length was covered in each of SP profiles with 5 m station spacing. The amplitude of the observed drift corrected SP anomaly varied from -42.3 to 72.5 mV for the profile AA/, -70.6 to 60.0 mV for profile BB/.

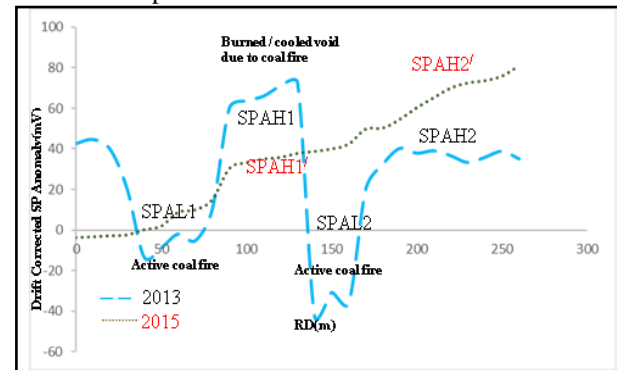


Figure 2 : Figure showing drift corrected SP mV with respect to distance (m) along the profile AA/ for the years 2013 and 2015.

Along with profile AA/ (Fig.2), two prominent negative SP anomalies SPAL1 and SPAL2 have been delineated with ~ -15 mV at around Reduced Distance (RD) 40-75m and with ~ -45 mV at around RD 138-165m respectively and two positive SP anomalies SPA1 and SPA2 have been delineated



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with ~ 75 mV at around RD 75-138m and with ~ 40 mV at around RD 165-260m respectively in 2013. Whereas, in the year 2015, positive SP anomalies; SPAH1/ (~ 40 mV, around RD50-170m) and SPAH2/ (~ 70 mV, around RD170-250m); are dominated almost throughout the profile that starts from RD50m onwards.

Along with profile BB/ (Fig.3), only a prominent low SP anomaly SPBL1 (~ -70 mV) at around RD 130-180m, and two positive SP anomalies SPBH1 (~ 40 mV, RD 0-130m) and SPBH2 (~ 60 mV, RD 180-260m), have been delineated in 2013. Whereas positive SP anomaly (SPBH1/) is dominated almost through the profiles (RD 30-250m) in the year 2015.

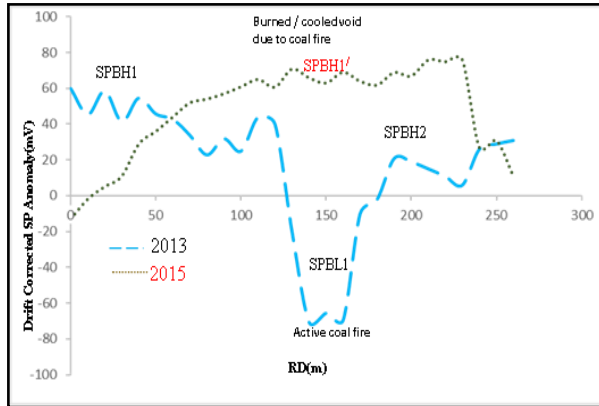


Figure 3: Figure showing drift corrected SP mV with respect to distance (m) along the profile BB/ for the years 2013 and 2015.

Time-lapse magnetic data were collected in two profiles, namely along AA/, and BB/ in the years of 2013 and 2015. Reduction to the pole (RTP) generated from total magnetic intensity (TMI) data along with the profiles AA/, BB/, of the years 2013 and 2015 are shown in Fig.4 and 5 respectively. It is observed from Fig 4 to 5 that in the year 2013, the magnetic RTP anomalies varied from -675 nT to 765 nT in profile AA/, -675 nT to 624 nT in profile BB/, Whereas in year 2015, the RTP anomalies varied from -235 nT to 1337 nT, -122 nT to 1373 nT, along profiles AA/, and BB/ respectively.

Along profile AA/ (Fig.4), two prominent negative RTP anomaly zones RTPAL1 with ~ -190 nT at around RD 40-65m and RTPAL2 with ~ -670 nT at around RD 140-160m, and two positive RTP

anomaly zones RTPAH1 (~ 750 nT) at around RD 65 140m and RTPAH2 (~ 100 nT) at around RD 160-260m, have been delineated in 2013. Whereas, in the year 2015, four positive RTP anomalies RTPAH1/ (~ 750 nT, RD 10-40m), RTPAH2/ (~ 1200 nT, RD50-145m), RTPAH3/ (~ 1100 nT, RD160- 200m), RTPAH4/ (~ 1300 nT, RD230-250m), and a small negative anomaly zone RTPAL1/ (~ -10 nT, RD 145-155m) have been delineated.



Figure 4: Figure showing RTP magnetic field intensity (nT) and with respect to distance along the profile AA/ for the years 2013 and 2015.

Along profile BB/ (Fig.5), a prominent negative RTP anomaly zone RTPBL1 (~ -700 nT, RD 140-180m) and two positive RTP anomaly zones RTPBH1 (~ 600 nT, RD 0-140m) and RTPBH2 (~ 400 nT, RD 180-260m) have been delineated in 2013. Whereas, in the year 2015, two positive RTP anomalies RTPBH1/ (~ 1000 nT, RD 30-100m), RTPBH2/ (~ 1300 nT, RD100-245m) at about have been delineated.

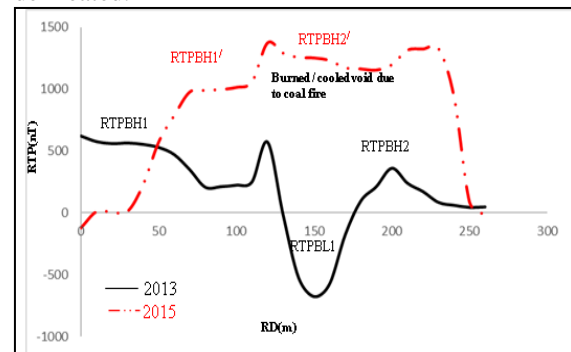
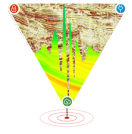


Figure 5 : Figure showing RTP magnetic field intensity (nT) and with respect to distance along the profile BB/ for the years 2013 and 2015



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A Time-lapse ERI study of 2013 and 2015 was carried out to delineate and monitor the coal fire propagation with the time over the East Basuria Colliery region. Two profiles of Electrical resistivity imaging (ERI) data were collected along with the same profiles of SP/Magnetic at 4m electrode spacing with 252m profile length (Fig 6). Quality factor 5 and current thresholds of 100mA were considered for filtering out noisy data using Flash -universals software (Zhe et al. 2007; Bharti et al. 2016a). The filtered combined data sets acquired through Wenner, Dipole-Dipole, Gradient, and Schlumberger arrays in each of the four profiles were inverted jointly in the 2.5D resistivity inversion program (Zhe et al. 2007) for the estimation of the 2D subsurface geoelectric model.

ERI of Profile AA/

Along with profile AA/, 2D ERI sections of the 9a) year 2013 (Fig.6 (a)) and of the year 2015(Fig.6 (b)), have been generated using combined data collected by Wenner, Schlumberger, Dipole-Dipole, and Gradient arrays with the current threshold of 100mA and quality factor 5%. Six low resistivity anomaly zones; i)AL1 with $\sim 10\Omega m$, $\sim RD10m$, $\sim 10m$ depth; ii)AL2 with $\sim 40\Omega m$, $\sim RD50m$, $\sim 25m$ depth; iii)AL3 with $\sim 2\Omega m$, $\sim RD70m$, $\sim 15m$ depth; iv)AL4 with $\sim 2\Omega m$, $\sim RD150m$, $\sim 10-20m$ depth; and v)AL5 with $\sim 20\Omega m$, $\sim RD240m$, $\sim 10m$ depth; have been delineated from 2D ERI section AA/ in the year 2013. Further, two high resistivity anomaly zones i) AH1 with $\sim 450\Omega m$, $\sim RD125m$, $\sim 10-20m$ depth; & ii) AH2 with $\sim 65\Omega m$, $\sim RD200m$, $\sim 20m$ depth) have been delineated from 2D ERI section AA/ in the year 2013. Whereas, five low resistivity anomaly zones i)AL1/ with $\sim 1\Omega m$, $\sim RD10m$, $\sim 10m$ depth; ii) AL2/ with $\sim 40\Omega m$, $\sim RD40m$, $\sim 20m$ depth; iii) AL3/ with $\sim 6\Omega m$, $\sim RD100m$, $\sim 12m$ depth; iv) AL4/ with $\sim 5\Omega m$, $\sim RD160m$, $\sim 10-18m$ depth; v)AL5/ with $\sim 1\Omega m$ $\sim RD250m$, $\sim 10-30m$) have been delineated from 2D ERI section AA/ in the year 2015. Further, four high resistivity anomaly zones AH1/($\sim 400\Omega m$, $\sim RD25m$, $\sim 10-20m$ depth), AH2/($\sim 500\Omega m$, $\sim RD50-125m$, $\sim 15-50m$ depth), AH3/($\sim 500\Omega m$, $\sim RD125-210m$, $\sim 15-50m$ depth), and AH4/($\sim 400\Omega m$, $\sim RD220-245m$, $\sim 15-50m$ depth), have been delineated from 2D ERI section AA/ in the year 2015.

It is observed from Fig.6c that the prominent low resistivity anomaly AL4, associated with active fire, is well correlated with negative SP anomaly SPAL2

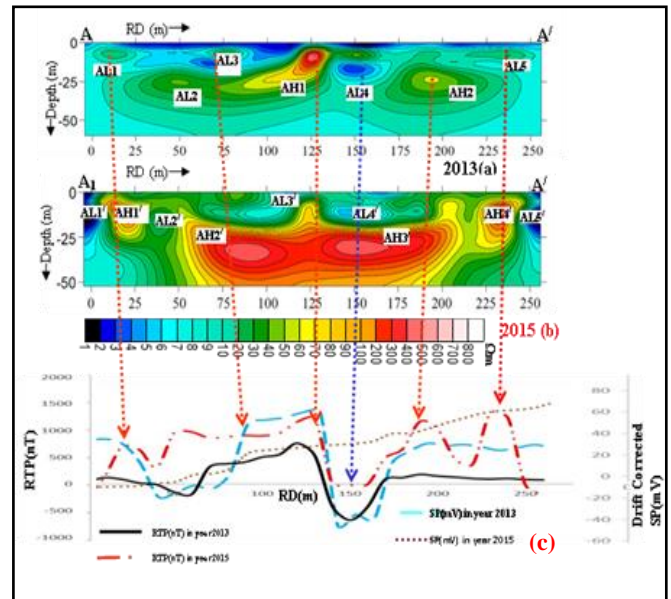


Figure 6 : 2D ERI section along profile AA/ (a) in the year 2013 and (b) in the year 2015, generated by combined inversion using Wenner, Schlumberger, Dipole-Dipole, and Gradient arrays with current threshold of 100mA and quality factor 5%, (c) Combine SP and Magnetic anomaly distribution along profile AA/.

and negative RTP anomaly RTPAL2 and field photograph/ thermal image shown in Fig.8a&e of 2013. Later in 2015, the intensity of fire decreased as delineated by AL4/ that is well correlated very small negative RTP anomaly RTPAL1/ ; however, underneath coal seam totally burned and converted to void/ fractured rock mass/ dry/baked rock mass as delineated by AH3 / that is well correlated with positive SP anomaly SPAH2 / , (Fig.6c) and field photograph (Fig.9a). Similarly, other anomalies of 2013 could be correlated with the respective anomalies of 2015.

ERI of Profile BB/

Along profile BB/, 2D ERI section of the year 2013 (Fig.7a) and of the year 2015(Fig.7b), have been generated using joint inversion of combined data collected by Wenner, Schlumberger, Dipole- Dipole, and Gradient arrays with the current threshold of 100mA and quality factor 5%. Two prominent low resistivity anomaly zones BL1($\sim 2\Omega m$, $\sim RD50-100m$,

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~5-12m), BL2(~1Ωm, ~RD130-178m, ~25m) have been delineated from 2D ERI section BB/ of the year 2013. Further, four prominent high resistivity anomaly zones BH1(~400Ωm, ~RD0-80m, ~10-30m), BH2(~80Ωm, ~RD100-125m, ~10-25m), BH3(~70Ωm, ~RD200-220m, ~25-30m), BH4(~60Ωm, ~RD220- 225m, ~10-15m) have been delineated from 2D ERI section BB/ of the year 2013. Whereas, two prominent low resistivity anomaly zones BL1(~3Ωm, ~RD0-25m, ~15-45m), BL2(~5Ωm, ~RD250m, ~20-35m) have been delineated from 2D ERI section BB/ in the year 2015. Further, three prominent high resistivity anomaly zones BH1/ (~50Ωm, ~RD15-25m, ~8-12m), BH2/ (~400Ωm, ~RD60-150m, ~0-20m), BH3/ (~400Ωm, ~RD190-240m, ~8-20m) have been delineated from 2D ERI section BB/ in the year 2015.

It is observed from Fig.7 a,b, c that the prominent low resistivity anomaly BL2 is well correlated with negative SP anomaly SPBL1 and negative RTP anomaly RTPBL1 and field photograph/ thermal image shown in Fig.8 b&f of 2013. Which later in 2015 is converted to void/ fractured rock mass/ dry/baked rock mass delineated by BH2/ that is well correlated with positive SP anomaly SPBH1/, positive RTP anomaly RTPBH2/ (Fig.7c), and field photograph (Fig.9b). Similarly, other anomalies of 2013 could be correlated with the respective anomalies of 2015. The low resistivity anomalies BL1 and BL2 indicate an active fire in coal seam VIII B and VIII A respectively. The high resistivity anomalies BH1, BH2, BH3 indicate burned out/ partially burned / fractured rock mass caused by coal seam VIII A, whereas BH4 is caused by the partial burning of coal seam VIII B. Anomaly pattern of BH2 is indicative of a conduit for oxygen supply to the surrounding coal seam. It is inferred that anomaly zones BH1, BL1/BH2/BL2, and BH3/BH4 of 2013 are lead to BH1/, BH2/, BH3/ in 2015, respectively due to complete / partial burning of coal seam VIII A/VIII B/VII and other local seams. The broad and prominent high resistivity anomalies (BH2/ and BH3/) between RD60-240m are generated in 2015 by the complete combustion of VIII B, VIII A, and VIII seam due to sufficient oxygen supply through fractures (BH2) developed in 2013.

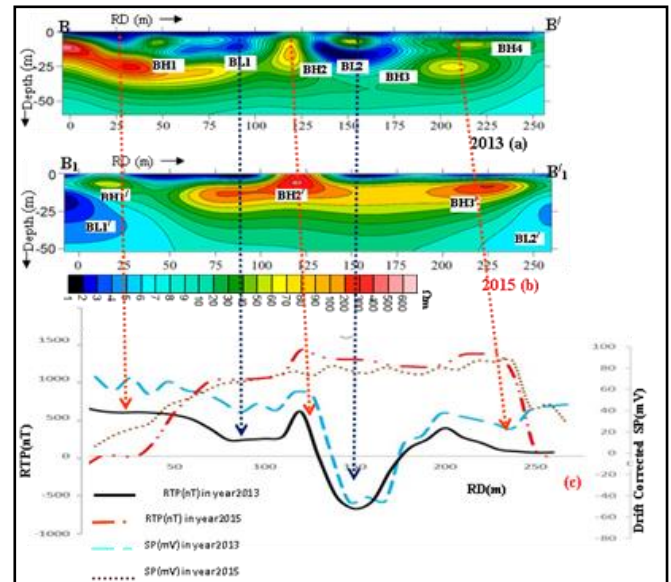


Figure 7 : 2D ERI section along profile BB/ (a) in the year 2013 and (b) in the year 2015, generated by combined inversion of data collected using Wenner, Schlumberger, Dipole-Dipole, and Gradient arrays with current threshold of 100mA and quality factor 5%, (c) Combine SP and Magnetic anomaly distribution along profile BB/

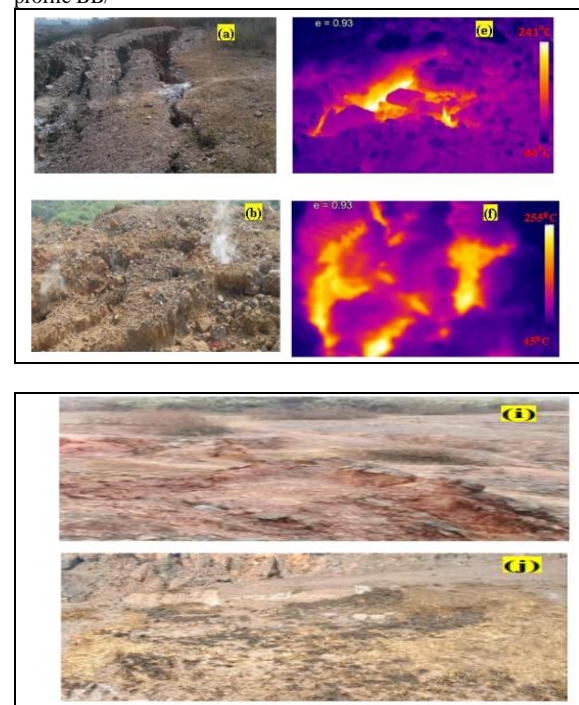


Figure 8: (a), (b) are the field photographs of 2013 over active fires through fissures, cracks, near the negative SP anomalies

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SPAL2, SPBL1 in the year 2013 of profiles AA/ , BB/ respectively. (e), (f) are the respective thermal images. (i), (j) are the field photographs of 2013 over backed and cooled surface near positive SP anomalies SPAH1, SPBH1 of profiles AA/ , BB/ respectively.



Figure 9: (a), (b), are the field photograph of the year 2015 showing secondary fracture, cracks, fissures/fire etc corresponding to SP anomalies SPAH1/ , SPBH1/ , corresponding to Fig. 8 a.b of profiles AA/ , BB/ respectively.

Conclusions

The fire zone around the East Basuria Colliery in Jharia Coalfield was investigated using a time lapse approach by combining multiple geophysical surveys, comprising of magnetic, self-potential (SP) and electrical resistivity imaging (ERI) methods. In the year of 2013, two five prominent active fire zones; i) SPAL1/RTPAL1/AL2/AL3, ii) SPAL2/RTPAL2/AL4, iii) SPBL1/RTPBL1 /BL2, have been delineated based on the combined observations of SP, magnetic, and ERI; are possibly associated with active/partial coal fire in coal seam VIIIA/VIIIB/VII. In the year of 2015, four prominent active fire zones; i) RTPL1/ , AL4/, has been identified that are associated with active/partial coal fire in coal seam VIIIA/VIIIB/VII. Further, four prominent baked/burned out / fractured rock-mass zones i) SPAH1//RTPAH2//AH2/, ii) SPAH2//RTPAH3//AH3/, iii) SPBH1//RTPBH1//BH2/, iv) SPBH1//RTPBH2//BH3/, have been identified, in the year of 2015, based on the combined analysis of SP, magnetic and ERI.

The broad and prominent high resistivity anomalies (AH2/ and AH3/) between RD50-210m are generated in 2015 by the complete combustion of VIII seam due to sufficient oxygen supply through fractures (AH2) developed in 2013. The broad and prominent high resistivity anomalies (BH2/ and BH3/) between RD60-240m are generated in 2015 by

the complete combustion of VIIIB, VIIIA, and VIII seam due to sufficient oxygen supply through fractures (BH2) developed in 2013.

The time-lapse study using self-potential (SP), magnetic and electrical resistivity imaging (ERI) techniques is found to be very effective to delineate the location, depth, extension, and condition of the coal fire activity in the subsurface formations. It can also help in understanding and monitoring the fire so that suitable rehabilitation measures can be taken.

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