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Investigation of Groundwater In-rush Zone using Petrophysical Logs and Short-offset Transient Electromagnetic (SOTEM) Data

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ABSTRACT

The water burst from the Ordovician limestone underlain by the Permo-Carboniferous coal seams have potential to trigger coalmine hazards in Northern China. Therefore, it is crucial to identify and accurately map the water enrichment zones and delineate coal seams using an integrated approach based on surface TEM and subsurface wireline log information to avoid water-inrush hazard and ensure safe production of coal. We inverted surface based TEM data using 1-D Occam inversion to identify the conductive anomaly and then further quantified the zone of interest by gamma and resistivity logs. 1-D Occam inversion results show conductive zone around 370 m while higher resistivity and lower gamma ray log signatures were observed against coal seams. Groundwater inrush zone falls within the mid-range gamma ray and resistivity interval as shown on the petrophysical logs. The distinct log signatures (low gamma-ray and high resistivity values) clearly indicated coal seams at depth of 410 and 470 m and subsequently the log trends were used to distinguish between coal units and more permeable sands. The magnitude and the variability of these parameters in the borehole are attributed to the subsurface stratigraphic heterogeneity. They can be key clues for interpretation of depositional facies of coal-bearing sequence and may also be used as a constraint in characterization of groundwater enrichment zone.

INTRODUCTION

Groundwater inrush into coal-bearing strata pose a serious threat to safe production of coal. The water burst from the Ordovician limestone underlain by the Permo-Carboniferous coal seams is the most common contributor to the coalmine hazards in Northern China, threatening 61.7 % of total coal reserves in Hancheng coal field (Peng and Zhang, 2007). To avoid such type of hazards in coal mines, it is crucial to identify and accurately map the water enrichment zones using an integrated approach based on ground-based geophysical techniques and subsurface wireline logs.

Ground-based geophysical techniques have successfully been applied to identify local conductive zones in coal mines which may result in human and economic loss. Recently, TEM techniques have gained much attention to investigate the groundwater enrichment zone in coal mines (Khan *et al.,* 2018). The SOTEM method is one of the TEM configuration which operates in short-offset mode, proved its efficiency in hydrogeophysical investigations to address the coal-mine hazard related to groundwater within the depth of 2000 m (Chen *et al.,* 2015).

These techniques are non-invasive, cheap and can be performed with a high spatial sampling. However, direct measurements (such as core sampling, and logging) are of great importance for sampling subsurface for system properties and interpreting stratigraphic facies. Petrophysical logs are continuous records of a geophysical parameter along a borehole. These tools are of various kinds, widely used since 1927, aimed at recording the instruments response as function of depth by lowering them into the borehole (Johnson and Pile, 2002). Geophysical log analysis constitutes a standard approach for inferring lithology in petroleum exploration wells. Well logs (gamma-ray, density and resistivity) are of basic importance in identifying hydrocarbons in reservoir geophysics. These tools with similar basic operating procedure are applied in mining geophysics to delineate the coal seams. The wireline logging tools are sensitive to coal due to their internal structure *i.e.*, organic and inorganic (*e.g.*, ash) composition, which is responsible to generate measurable log responses (Scholes and Johnston, 1993). It is common practice to use

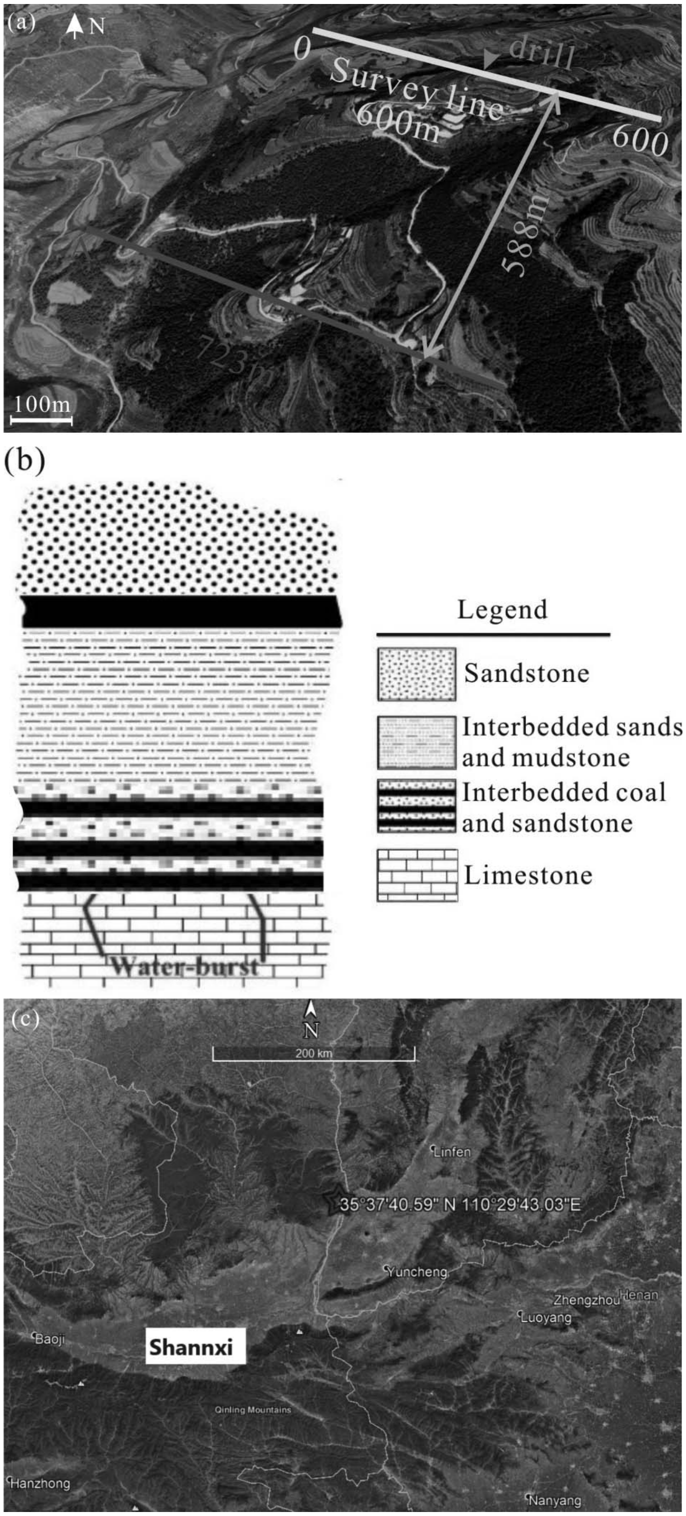

Figure 1 Survey layout of SOTEM soundings: a) Survey layout of SOTEM soundings; b) conceptual model; and c) location map.

borehole log data alone for delineation of depositional environment such as that of Eocene carbonates (Khan *et al.,* 2013). However, in coal bearing strata due to inherent complexity of the signals, classification and characterization of the lithology is not straightforward. Therefore, it is important to utilize geophysical logs integrated with ground-based TEM measurements. Geophysical prospecting allows one to interpolate the results derived from drill holes in order to obtain more comprehensive subsurface images for detailed and improved characterization. Thus, surface-based geophysics has an enormous potential for supplementing the data obtained by invasive approaches *e.g.*, downhole geophysical logs. Integrating information derived from ground-based and borehole geophysical methods has proved to be a powerful combination for different purposes including hydrogeological investigations, mapping contaminated sites and geological modeling (Tsai *et al.*, 2019, Revil *et al.*, 2013), yet the integration strategies are equally valid for water related issues in coal mines.

FIELD DATA ACQUISITION AND GEOLOGICAL SETTING OF STUDY AREA

A short-offset transient electromagnetic (SOTEM) survey was conducted in a coalfield located in Shaanxi province, China (Fig. 1). The geological column spans over Quaternary, Triassic, Permian, Carboniferous, Ordovician and Cambrian. Main aim of the study was to address water-burst problem, and a simplified conceptual model is shown in Fig. 1. A bipolar step current of 16 A was introduced into subsurface with a base frequency of 2.5 Hz using 723 m long grounded-wire as a source to acquire the data at an offset of 588 m along profile of length 600 m. Compared to other loop TEM, two main advantages of Short offset TEM technique are its ease to use and time efficient. It is important to record the exact positions of both transmitter and receivers in field because it is important for subsequent inversion process.

SOTEM has gained large attention as an effective tool in hydrogeophysical studies conducted in China due to its sensitivity to conductive targets, slower signal attenuation and similar resolution when compared to loop TEM (Chen *et al.,* 2017). So, the electric source TEM proved to be a successful technique to detect less resistive water-inrush areas but unable to resolve the non-aquifer units' depth accurately *e.g.*, coal beds. Thus, invasive methods *e.g.*, borehole logs are helpful not only to identify permeable units but also provide control in constraining depth information of ground-based TEM technique especially when buried depth is large. Therefore, it is important to supplement the TEM results by borehole logging information for improved understanding of the ground-water enrichment in the study area.

SOTEM Data Inversion

Occam inversion aims at determining the smooth resistivity model of the subsurface (Constable *et al.*, 1987). The objective function for the inversion is:

Table 1 Parameters for Occam inversion of multilayer synthetic data.

Models	ρ_1 (ohm-m)	d_1 (m)	ρ_2 (ohm-m)	d_2 (m)	ρ_3 (ohm-m)	d_3 (m)	ρ_4 (ohm-m)
Three-layer	100	500	10	600	100	-	-
Four-layer	10	100	100	500	5	600	100

$$\min\left\{\left\|\mathbf{WF}\left(\mathbf{m}^k\right)+\mathbf{WJ}\left(\mathbf{m}^k\right)\Delta\mathbf{m}-\mathbf{Wd}\right\|_2^2-\chi_0^2\right\} + \alpha^2\left\|\mathbf{L}\left(\mathbf{m}^k+\Delta\mathbf{m}\right\|_2^2, \quad (1)$$

where $\mathbf{F}$ denotes the forward operator, $\mathbf{J}$ represents the Jacobian, matrix, $\mathbf{d}$ is the data vector, χ is the target misfit value, and α is the Lagrange multiplier for balancing the misfit and the roughness term. $\mathbf{L}$ is the roughness matrix to implement the Tikhonov regularization. $\mathbf{W}$ is the data weighting matrix to incorporate the standard deviations:

$$\mathbf{W} = \mathrm{diag}\left(\sigma_1^{-1}, \sigma_2^{-1}, \ldots\sigma_M^{-1}\right),$$

where the σ is an estimated error. For a given misfit, the smoothest resistivity model can be obtained by minimizing the defined objective function (Eq. 1). Further details on the Occam inversion are given in the literature (Constable *et al.*, 1987; Li *et al.*, 2016; Chen *et al.*, 2017). We consider three and four-layer synthetic models for which conductive target parameters in terms of depth and resistivity are given in the Table 1 and Fig. 1. The target was placed at 600 m in both models but the resistivity varied from 10 to 5 ohm-m in three and four-layer models respectively. The Occam routine is first applied to synthetic models and then field data at two selected sites 320 and 480 along 600 m profile. Low resistivity zone is interpreted at the two sites around 370 m as shown in Fig. 2. The drilled hole is located at site 340. All the individual soundings are inverted and compiled into 2-D resistivity cross-section which clearly resolves low resistive target at a depth of approximately 370m (Fig. 2). The derived inversion models are found consistent with the borehole data. The field measurements revealed the geological structure and anomalous conductive zone associated with water-enrichment in coal mine. It can be seen that different sounding

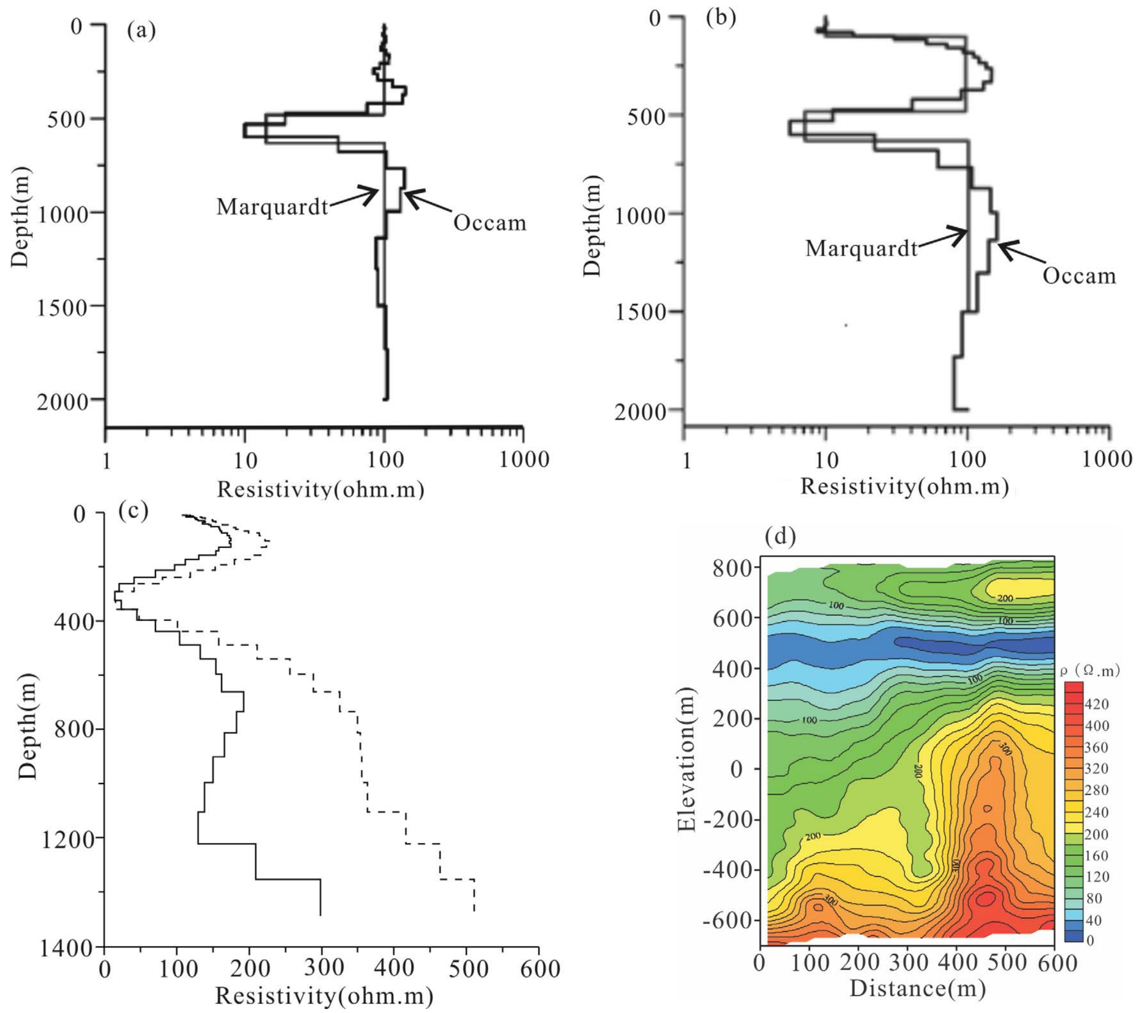

Figure 2 Inversion results of synthetic models and measured data: a) Two different inversion method and result of three layer; b) two different inversion method and result of four layer; c) Occam Inversion results at two survey sites; and d) inversion elevation-resistivity cross section

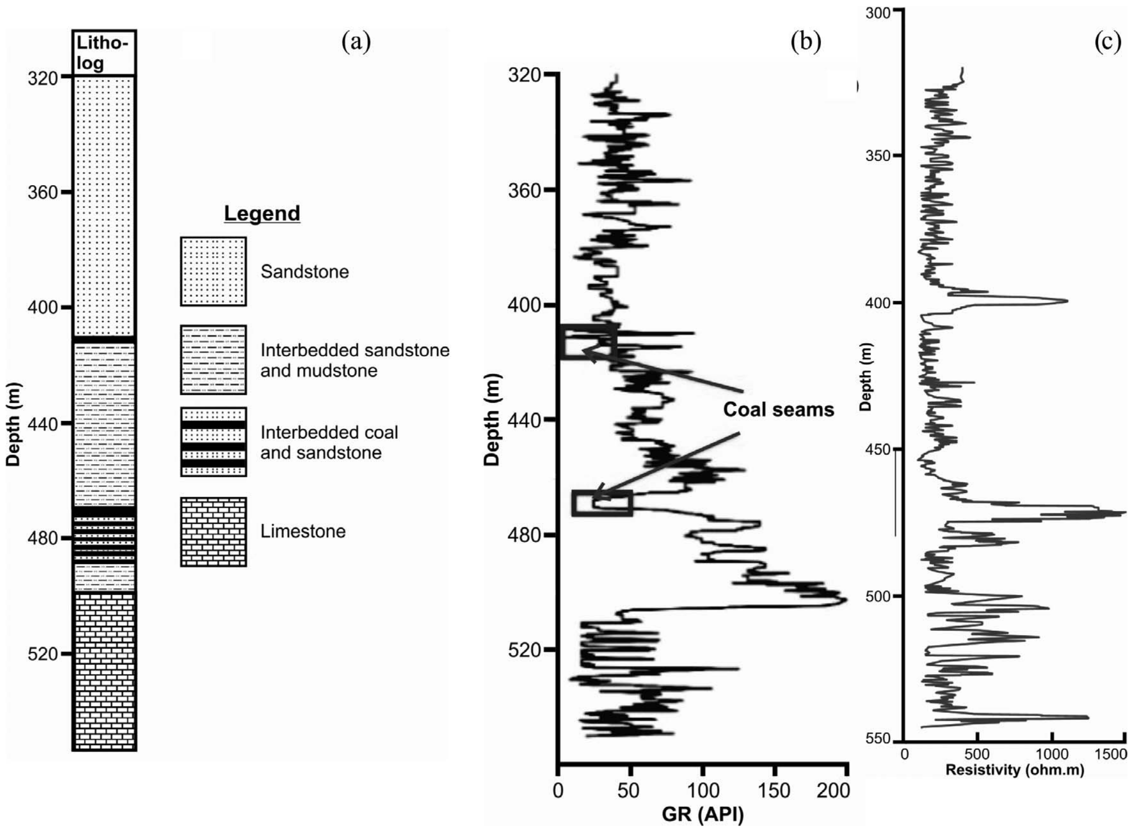

Figure 3 a) Geological log; b) gamma-ray; and c) resistivity log.

points demarcate an undulating low resistivity zone along TEM profile. Resistivity cross section indicated different ranges for resistivity to interpret the subsurface layers of the study area. Some of the geoelectric layers have very close range showing the overlapping characteristics which results in speculation and uncertainty while interpreting ground-based TEM data. In this situation, lithological information derived from subsurface resistivity distribution using SOTEM measurements may not provide details on permeable formations capable of storing water as well as other stratigraphic units (coal beds) which are main targets in coal mines. On the other hand, invasive subsurface geophysical tools (borehole logging) can provide accurate data to characterize the coal bearing strata in terms of individual depositional facies and their burial depths. However, such type of data lacks in high spatial sampling. Thus, use of SOTEM soundings in conjunction with borehole logs is important for obtaining meaningful hydrogeological results.

STRATIGRAPHY AND BOREHOLE LOGS ANALYSIS

Petrophysical logs are used to characterize the lithological units (facies) in subsurface, which has a set of distinct lithological and paleontological characteristics. The facies determined from geophysical logs are known as electro-facies characterized by clear physical and genetic association with neighboring sequences. Therefore, determination of stratigraphic facies associations is essential for reasonable characterization of borehole logs. Resistivity and gamma ray logs are used in this study. The resistivity log can represent the lithological characteristics with depth in which resistivity fluctuations reflect on facies variations while gamma ray log is an excellent tool for subsurface lithological identification through the general form $V_{shale} = f(GR)$ where V_{shale} denotes volume of shale and f is a linear factor (Kennedy, 2015) in sedimentary depositional environment. The available log data met with varying degrees of success within the context of local hydrostratigraphic characteristics. Consequently, examination of these geophysical logs such as natural gamma and resistivity logs in drill hole BH-01 indicate four principal facies-types including sandstone, interbedded argillaceous sandstone with mudstone, coal interbedded with mudstone and limestone. Of particular interest in the log composite shown in Fig. 3 are the relative magnitudes of both natural gamma and resistivity curves. In zones (410 and 470 m) where they indicate opposite trends were used to distinguish between coal units and more permeable sands. Areas of interest in the natural gamma log were characterized by <25 API emissions, showing coal beds. Similarly, larger fluctuations (~ 50 API) reflected at boundaries separating coal seams from other sequences. A log of resistivity recorded in BH-01 is shown in Fig. 3 alongside the corresponding gamma log also confirms distinctive log signatures (>400 ohm-m), tending to mimic each other and clearly differentiate the main coal beds from sandstones and limestone penetrated by BH-01. Within lowermost section, a higher response of both logs can be observed in the depth interval ~500-535 m. However, very clear peaks (<25 API and >1000 ohm-m) were noted against coal seams in this depth range.

Based on 1-D Occam inversion of SOTEM soundings, Fig. 2(d) shows the low resistivity (~40 ohm-m) around 370 m which is interpreted as water-inrush zone in sandstone. The interpreted ground water enrichment in sandstone is underlain by top coal seam in the interval 400~455 m. This zone of resistivity log was characterized by curve changes around 150 ohm-m against sandstone and >400 ohm-m against coal bed at 410 m. This zone of interbedded sandstone with more than 40 m thickness was used to distinguish between coal seam at 410 m and more permeable sands where water-inrush is occurring due to thick fractured limestone aquifer with sufficient water supply. Inversion of SOTEM measurements resolved the anomalous low resistivity (~40 ohm-m) as a ground inrush zone while it falls within mid-range gamma ray and resistivity interval of petrophysical logs. Thus, the interpretation of the subsurface logs in conjunction with inverted surface-based measurements were used to differentiate permeable sands holding inrush water from coal beds.

Besides the detection capability of conductive anomalous area, the lithological information extracted from the inverted SOTEM soundings could not reflect on the subtle stratigraphic units (coal seams at 410 and 470 m). The coal beds at different depths have a great impact on the internal dynamics of the water enrichment zone. Therefore, taking advantage of the merits offered by individual geophysical tools, the correlation of the resistivity trends (inversion and log based) led to the detection of coal beds and delineation of potential hazardous zone in the coal bearing strata. We conclude that integration of both data sets revealed that surface TEM data inversion mapped the gross subsurface structure and identified the conductive target while petrophysical logs further quantified the zone of interest by locating the coal seams, helped in differentiating permeable sands from non-aquifer units and thereby add to geological interpretation of SOTEM soundings.

CONCLUSIONS

We have integrated the inverted short-offset TEM data with the geophysical logs in order to reduce interpretational ambiguities, common in single technique and improve the interpretational methodology. 1-D Occam inversion of ground-based SOTEM data delineated the groundwater enrichment zone and overall subsurface resistivity structure. Furthermore, the coal beds encountered in borehole were interpreted based on gamma-ray and resistivity logs. 1-D Occam inversion results resolved low resistive zone in terms of resistivity whereas petrophysical log signatures quantified depth interval of interest in terms of low gamma-ray and high resistivity values in relation to neighboring formations. The synthetic results followed by field example attest the applicability of proposed methodology.

The study demonstrated mapping of coal bearing sequences enclosing aquifers. Thus, detection of coal seams as well as accurate mapping of water-inrush zone in coal bearing strata reduces the hazard risk related to coalmine water which is very common in this region. Occurrence of issues associated with coalmine water have seriously impacted the Permian coal exploration in the study area. Our findings have implications for improved understanding of distribution of potential hazardous zones common in Northern China due to groundwater inrush in Permian coal systems.

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