Geophysical Investigation of Wuda Coal Mining Area, Inner Mongolia: Electromagnetics and Magnetics for Coal Fire Detection

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Abstract

As part of the Sino-German Coal Fire Research Initiative "Innovative Technologies for Exploration, Extinction, and Monitoring of Coal Fires in North China," the China Aero Geophysical Survey and Remote Sensing Center for Land and Resources (AGRS), assisted by the German Federal Institute for Geosciences and Natural Resources (BGR), carried out in 2004 an airborne electromagnetic and magnetic survey of the Wuda Coal Mining Area (Inner Mongolia Autonomous Region, P.R. China). In the following year, ground geophysical surveys were conducted in selected parts of the area, using transient electromagnetics (BGR) and magnetics (AGRS and Deutsche Montan Technologie GmbH, DMT). The objective of these geophysical surveys was to detect and delineate coal fire areas through physical parameters obtained over burning and burned coal seams. The electromagnetic surveys served to reveal areas of high electrical conductivity, the magnetic surveys those with clearly pronounced magnetic field intensity.

摘要

本研究是中德研究项目“中国北方煤火探测、灭火与监测新技术”的一部分。2004 年，中国国土资源航空物探与遥感中心（AGRS）在德国联邦地球科学和自然资源研究所（BGR）的协助下在内蒙乌达矿区进行了航空电磁和航空磁法测量工作。2005 年，选择该矿区部分地段分别由 BGR 采用瞬变电磁方法与 AGRS 和 DMT 采用磁法进行了地面地球物理测量工作。其探测目的是基于正在燃烧和烧过的煤层上获得的物理参数探测和圈定火区。电磁探测方法旨在揭示低电阻率区，而磁法测量用于圈定具有显著磁场强度区。

1 Introduction

Within the framework of the Sino-German Coal Fire Research Initiative “Innovative Technologies for Exploration, Extinction, and Monitoring of Coal Fires in North China” – a project launched in 2002 and funded by the German Federal Ministry of Education and Research (BMBF) – several Chinese and German research teams from various geo-scientific backgrounds have been investigating Wuda Coal Mining Area in the Chinese autonomous region of Inner Mongolia (Figure 1). In 2004, the German Federal Institute for Geosciences and Natural Resources (BGR) assisted the China Aero Geophysical Survey and Remote Sensing Center for Land and Resources (AGRS) in conducting a helicopter survey of the area. This first survey was followed by several ground geo-physical surveys in 2005. Wuda Coal Mining Area is covered mainly by sandstones, under which 18 mined coal seams extend to greater depths varying from a few meters to several hundreds of meters below surface.

Figure 1: Location of Wuda (Inner Mongolia Autonomous Region, P.R. China)

Coal combustion under electromagnetic and magnetic aspects has been researched for decades. In his 1977 and 1983 studies, Duba described the changes in electrical conductivity (or resistivity for that matter, its reciprocal) of coal samples and their pyrolysis products he had observed in laboratory experiments. The heating of water-saturated coal samples increased their conductivity from an initial value of 10^{-3} Sm^{-1} (resistivity = 1,000 Ohm*m) at 24 °C to 100 Sm^{-1} (0.01 Ohm*m) when recovered as char from pyrolysis at temperatures of 800 °C. After a strong decrease owing to water loss from drying in the temperature range from 24 to 110 °C, the conductivity curve flattened while temperatures rose continually. At 300 °C, it began to rise too, first slowly, and then rapidly after 515 °C. This large increase in conductivity was attributed to the higher carbon content of char. Based on his experiments, Duba (1977) suggested to use electrical conductivity of coal and its pyrolysis products as a means of locating and identifying areas of different physical properties underground. Because pyrolysis induces enormous changes in coal conductivity, and is in fact one of the main processes in coal fires, Duba reasoned, it should be possible to explore underground reaction zones by measuring conductivities off the surface.

Powell and Schofield (1939) investigated electrical conductivity of carbon and graphite at high temperatures. They found that electrical conductivity increased with thermal conductivity and that graphitization had the same effect.

Bartel (1982) described CSAMT (Controlled Source AudioMagnetoTelluric) measurements over coal fires in abandoned mines. In all surveys, resistivity anomalies were observed which could clearly be associated with fires. In laboratory experiments, Bartel was able to show that coal undergoes drastic electrical resistivity changes during combustion. Given these changes, Bartel argued, electrical and electromagnetic techniques were suitable for coal fire mapping and monitoring.

King (1987) performed electromagnetic measurements over burned coal seams in Australia. He found significantly lower resistivities for coal heated to 800 °C and more, and inferred that burned coal seams must be detectable by resistivity lows on the sounding curves.

Hooper (1987) investigated magnetic properties of baked rock in Wyoming. As these proved quite distinct from those of surrounding sedimentary rock, he suggested magnetic surveys be used to locate baked rock. Hooper reported that baked siltstone had a higher magnetic susceptibility than baked sandstone and shale of similar iron oxide content and thermal alteration history. While being generally low, magnetic susceptibility in the baked rock samples showed a rather wide range of values. In most rocks, magnetic susceptibility is proportional to magnetite content, i.e. high magnetic susceptibility can be correlated with high magnetite content. Except for some iron oxides already present before baking, most of the hematites and magnetites in baked rock were derived from thermal alteration of sedimentary minerals (Hooper 1987).

Sternberg and Lippincott (2004) presented magnetic surveys over clinkers and coal seam fires in the United States. They measured enhanced magnetic susceptibility in sedimentary rock above burning coal seams, including clinker formations.

Mainly drawing from insights of previous international research as described above, the BGR/AGRS teams went to investigate the changes in electrical conductivity and local anomalies of magnetic field intensity of areas related to coal seam fires in Wuda. The ground surveys were conducted in selected parts of the airborne survey area. Numerous ground electromagnetic measurements, especially transient electromagnetics (TEM), were carried out by BGR across several fire zones (FZs) and in adjacent unaffected areas. A ground magnetic survey by AGRS covered most of FZ 8; it was later supplemented by the Deutsche Montan Technologie GmbH (DMT). Satellite-supported maps of the burning areas provided by the German Aerospace Center (DLR) were used for completion of the survey (Voigt et al. 2004; Künzer et al. 2005). Further investigations with respect to geological, micropetrographical, thermal, and geochemical aspects of Wuda Coal Mining Area are presented by other authors in this volume (Kus et al. 2007; Schlömer et al. 2007).

2 Geophysical Surveys

The airborne electromagnetic and magnetic surveys of Wuda Coal Mining Area were conducted in August and September 2004. The electromagnetic system, an IMPULSE 2 developed by Aeroquest, Canada, used two coil configurations (coplanar and coaxial) at a coil separation of 6.5 m, each operating at three different frequencies between 870 and 23,250 Hz. The total magnetic field was measured simultaneously using a CS-3 Cesium sensor by Scintrex, Canada. The output sampling rate was 30 Hz for electromagnetic signals and 10 Hz for magnetic signals, resulting in a sampling distance of c. 1.2 m and 3.8 m respectively, at an average flight velocity of 140 km h^{-1}. The size of the survey area was c. 120 km². About 300 survey lines were flown at a line distance of 50 m from east to west and 250 m for north to south.

In May and June 2005, numerous ground electromagnetic measurements followed across the FZs and in adjacent unaffected areas. While TEM was the method of choice; a few survey profiles were measured using other electromagnetic techniques, e.g. Horizontal-Loop (HL) with an Apex MaxMin. The results of these measurements are not presented in this paper.

TEM uses transmitter and receiver coils of different sizes and configurations. Currents are shot off intermittently in the transmitter coil so as to change the corresponding magnetic field. This way, eddy currents are induced in the soil, where they cause a secondary magnetic field, whose change induces a decaying voltage in the receiving coil. This decaying voltage, also called the transient, is recorded and gives information about the resistivity distribution in the ground. The effective exploration depth depends on the local noise level (King 1987; Greinwald & Schaumann 1997).

Compared to HEM, the TEM system offers the advantage of variable coil size and extension of recording time, which allows measurements at greater depths. Near-surface depth resolution is less clear. To investigate subsurface resistivity distribution from near-surface to depths of several hundred meters it is best to combine both methods.

TEM measurements were conducted across FZs and at single locations of a FZ. A number of 65 transient electromagnetic soundings on 12 profile lines were performed using the Geonics PROTEM47 system. Those across the well investigated FZ 8 (Figure 2) – one of the 20 or so FZs in Wuda Coal Mining Area – are discussed in this paper. The spacing of the TEM sites was adapted to the terrain. A loop size of 50 m x 50 m was chosen for most sites in inloop configuration, where the receiver coil is placed in the centre of the transmitter loop. Models for each site were created from the data obtained without *a-priori* information, using an iterative *Marquardt algorithm* (Weidelt 1984) to determine resistivities (Rho) and depths of model layers.

AGRS carried out its ground magnetic survey of FZ 8 in May 2005. It was supplemented by DMT in October of the same year (Elsen 2006). Survey lines in selected parts of the area were narrowed or extended to places of special interest.

3 Investigation Results

Figure 2 shows a satellite image of Wuda Coal Mining Area. The dotted red polygon marks the area of the helicopter survey, the continuous red rectangles mark the FZ study areas; FZ 8 is marked in bold. The FZs are outlined in light to dark blue (colder fires of less than 150 °C) and orange to red to purple (hotter fires of more than 150 °C), depending on surface temperature. These zones had been delineated by several DLR ground surveys with infrared thermometer (Gielisch & Künzer 2003).

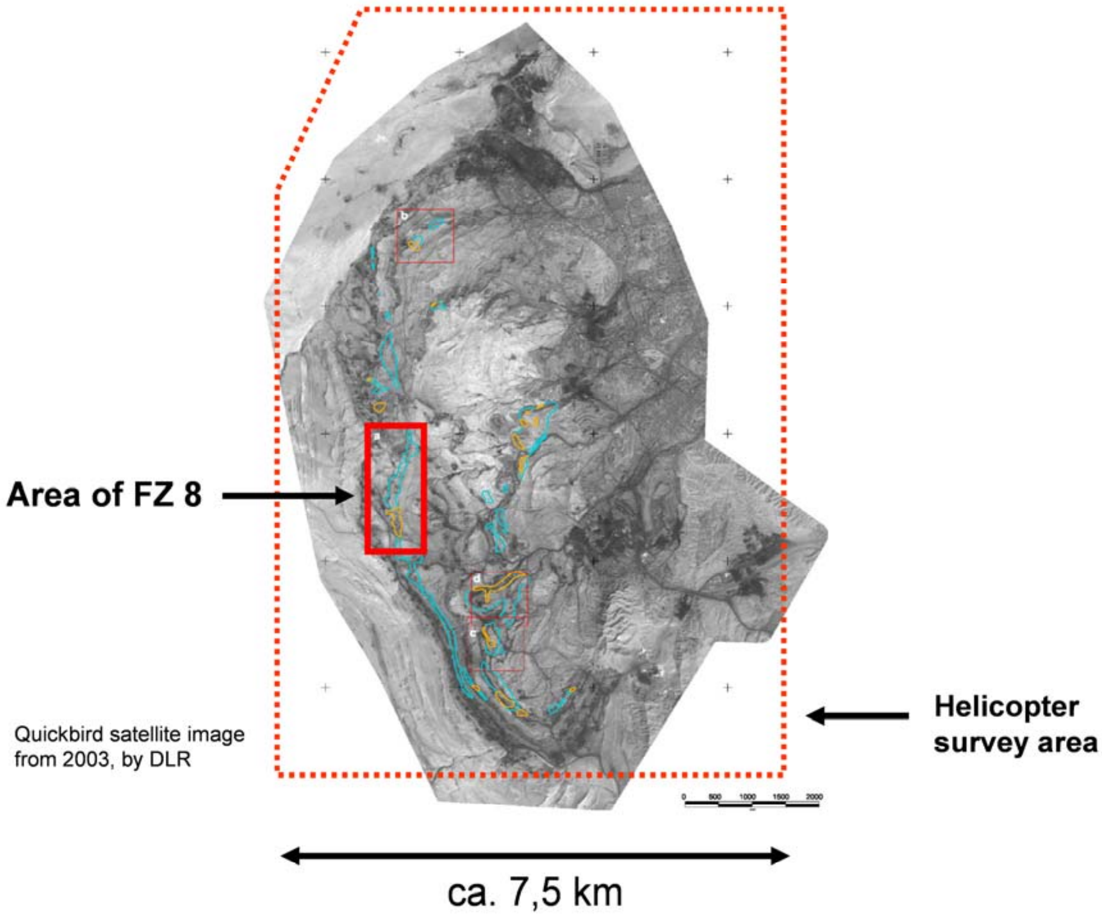

Figure 2: Satellite image of Wuda Coal Mining Area (projection UTM 48S (WGS84))

Data Source: Gielisch & Künzer (2003)

3.1 Airborne electromagnetic survey

An apparent resistivity map at a frequency of 4,650 Hz (horizontal coplanar coil configuration) was drawn after the airborne electromagnetic survey over FZ 8; it is shown in Figure 3. Apparent resistivities (Rhoa) as well as centroid depth values were calculated using a homogeneous half-space model (Siemon 2001). The centroid depth depends on conductivity and varies between 20 and 35 m at the given frequency. Close to the TEM profiles nos. 6 and 7 (see Figure 3 for exact location), the centroid depth ranged from 20 to 26 m. Several resistivity lows obviously caused by ongoing coal removal or mining activities are marked by black circles. The conductive area in the left part of the map might be a result of high iron oxide content in sandstones.

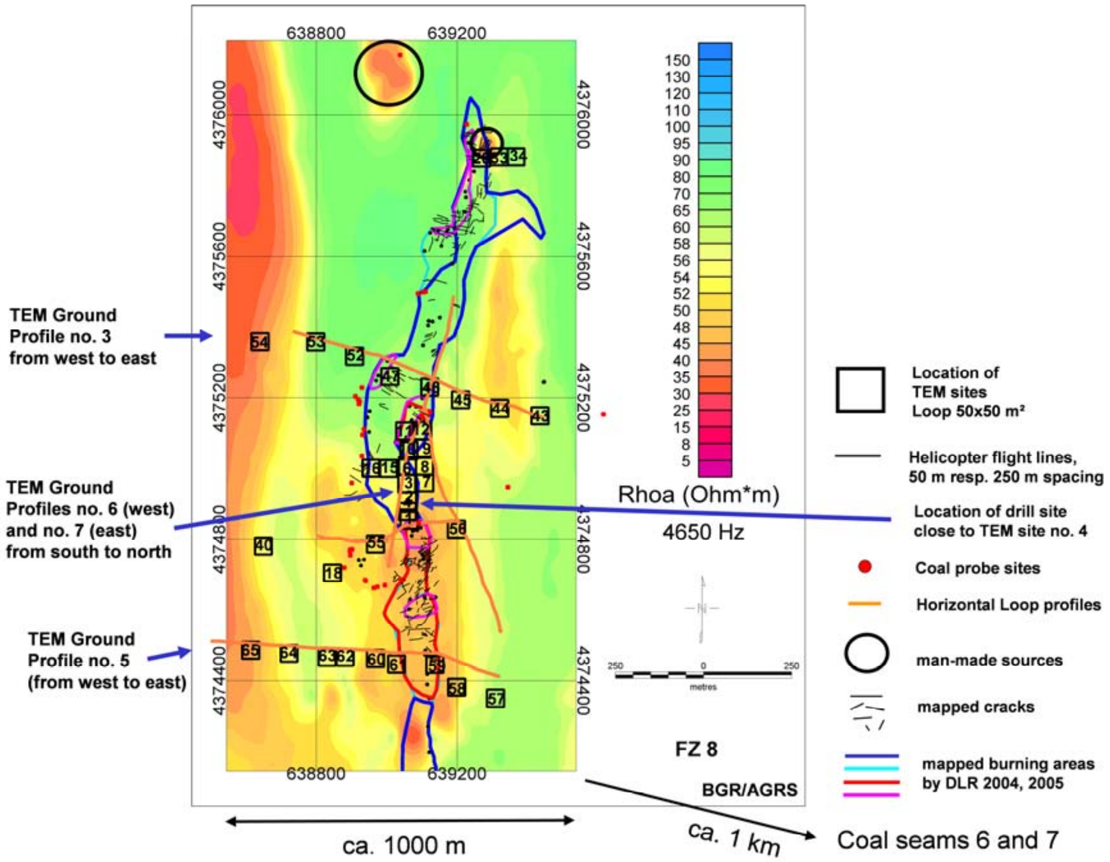

Figure 3: Map of apparent resistivity Rhoa (Ohm*m) at a frequency of 4,650 Hz, derived from airborne survey over FZ 8. The locations of TEM sites crossing the active parts of the FZ are marked by black squares, including a drilling site close to TEM site no. 4 (see Chapter 3.2).

3.2 Ground electromagnetic survey

Several TEM ground profiles crossed FZ 8. TEM profile no. 3 ran from west to east in the northern part of the FZ, profile no. 5 in the southern part. Profiles nos. 6 and 7 ran from south to north, starting directly north of the inaccessible part of the area.

The areas of low apparent resistivity (Rhoa below 50 Ohm*m) determined by the helicopter survey coincide with areas showing low resistive layers (Rho below 30 Ohm*m) in the ground TEM survey, i.e. the eastern part of profile no. 3 (Figure 4), the southern part of profile no. 6 (Figure 5), and the central part of profile no. 5 (Figure 7). Low resistive layers were found at sites 47, 45, and 44 of profile no. 3 (from west to east), at sites 1, 4, 2, 3, and 6 of profiles no. 6 (from south to north), and at sites 62 to 57 of profile no. 5 (from west to east). Site 47 of profile no. 3 shows a low resistive layer (Rho about 26 Ohm*m) below 30 m depth. This location coincides with a burning coal seam and an anomaly found in the ground magnetic survey (Figure 9). Sites 46 to 44 display a conductive layer close to the surface. These locations coincide with a low resistive area found in the helicopter survey (Figure 3) and with an anomaly of the total magnetic field intensity discovered in the airborne magnetic survey (Figure 10). The TEM resistivity-depth section of profile no. 6 displays a northwards dipping conductor (Figure 5) at a depth of 23 m (site 1) down to about 50 m (site 6). The southern part of FZ 8 was not accessible on ground due to numerous cracks passing the area. No data could be obtained here. At a drilling site about 50 m north of site 1 of profile no. 6, close to TEM site no. 4, the top coal seam was localized at 20 m below surface. With increasing distance from the cracks (in northerly direction), the depth of this conductor increases, and so does its resistivity (from 10 to 23 Ohm*m). In the northern part of profile no. 6 (sites 10 and 11), the resistivity structure underground is more complicated and one-dimensional modeling may not be sufficient for adequate explanation of data.

Investigations of gas temperatures at FZ 8 point toward a fire front movement in northeasterly direction (Schlömer et al. 2007 in this volume). This corresponds to the continuation of the northwards dipping conductor of TEM profile no. 6 to profile no. 7 (Figure 6), situated 50 m to the east of the former profile (see Figure 3).

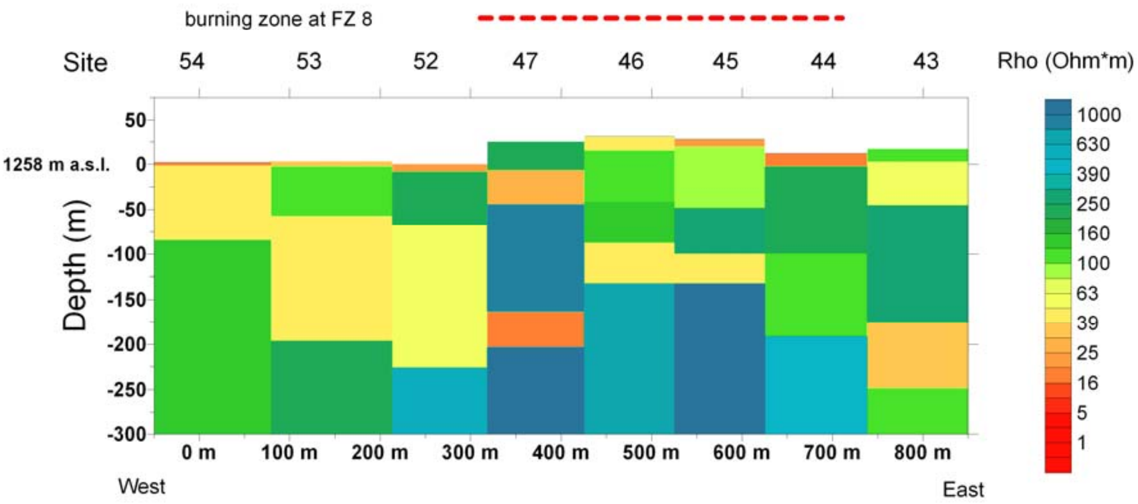

Figure 4: Resistivity-depth section from one-dimensional inversion of TEM data along profile no. 3 from west to east. The burning zone is marked by a dashed red line.

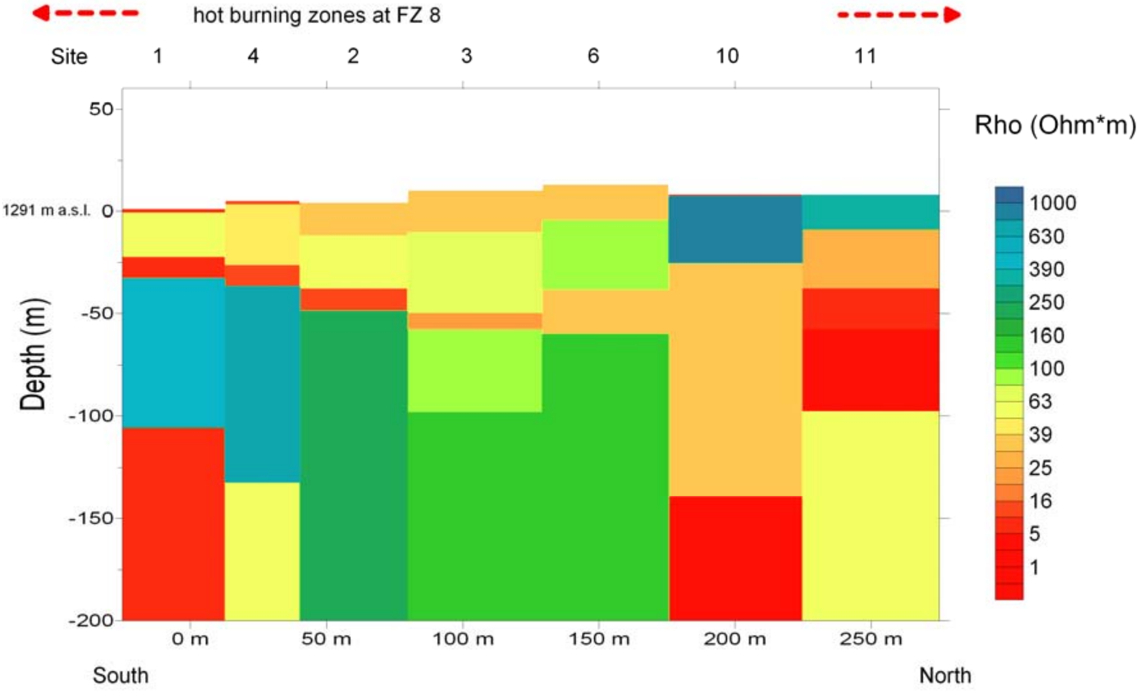

Figure 5: Resistivity-depth section from one-dimensional inversion of TEM data along profile no. 6 from south to north. The burning zone is marked by a dashed red line. The conductor is dipping northwards from about 25 m down to 50 m depth.

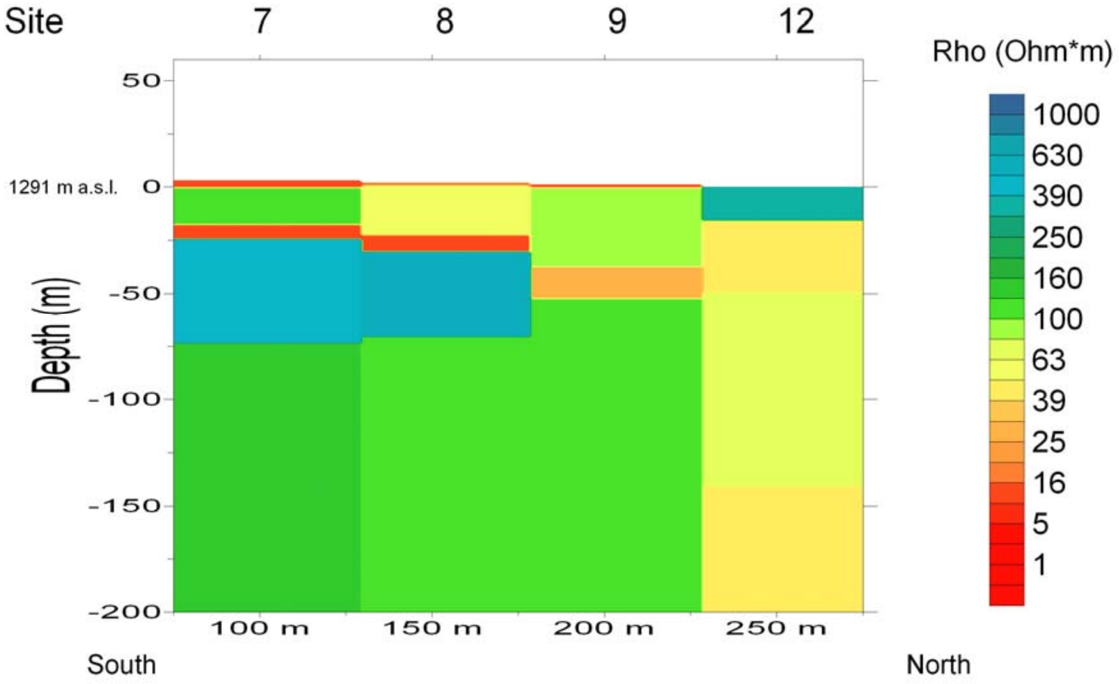

Figure 6: Resistivity-depth section derived from one-dimensional inversion of TEM data along profile no. 7 from south to north

The resistivity-depth section along profile no. 5 (Figure 7) displays a sufficient spatial correlation between shallow conductor and burning zone. The eastwards dipping conductive layer coincides with the thermally affected coal seam at sites 60 to 58. The area of low apparent resistivities in the airborne electromagnetic survey (Figure 3) corresponds to the location of the thermally affected coal seam.

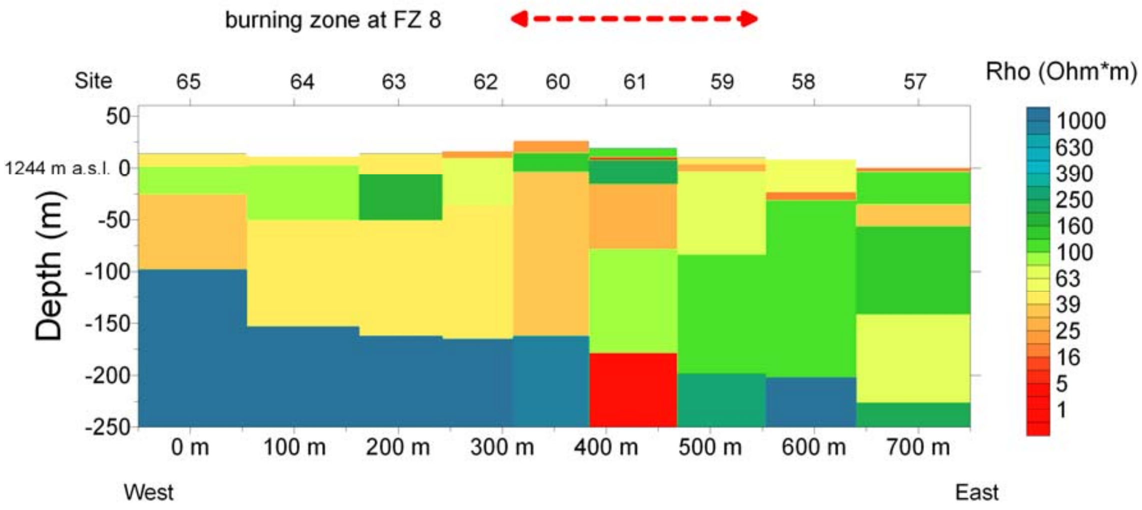

Figure 7: Resistivity-depth section derived from one-dimensional inversion of TEM data along profile no. 5 from west to east. The burning zone is marked by a dashed red line and correlates with the eastwards dipping shallow conductor.

TEM soundings at sites 35 and 36 were performed over two unaffected coal seams (seams nos. 6 and 7), about 1 km southeast of FZ 8. The one-dimensional modeling results did not reveal conductive layers at coal seam depth. Figure 8 shows an example derived from TEM data; at the depth of coal seams nos. 6 and 7 no resistivity low was observed.

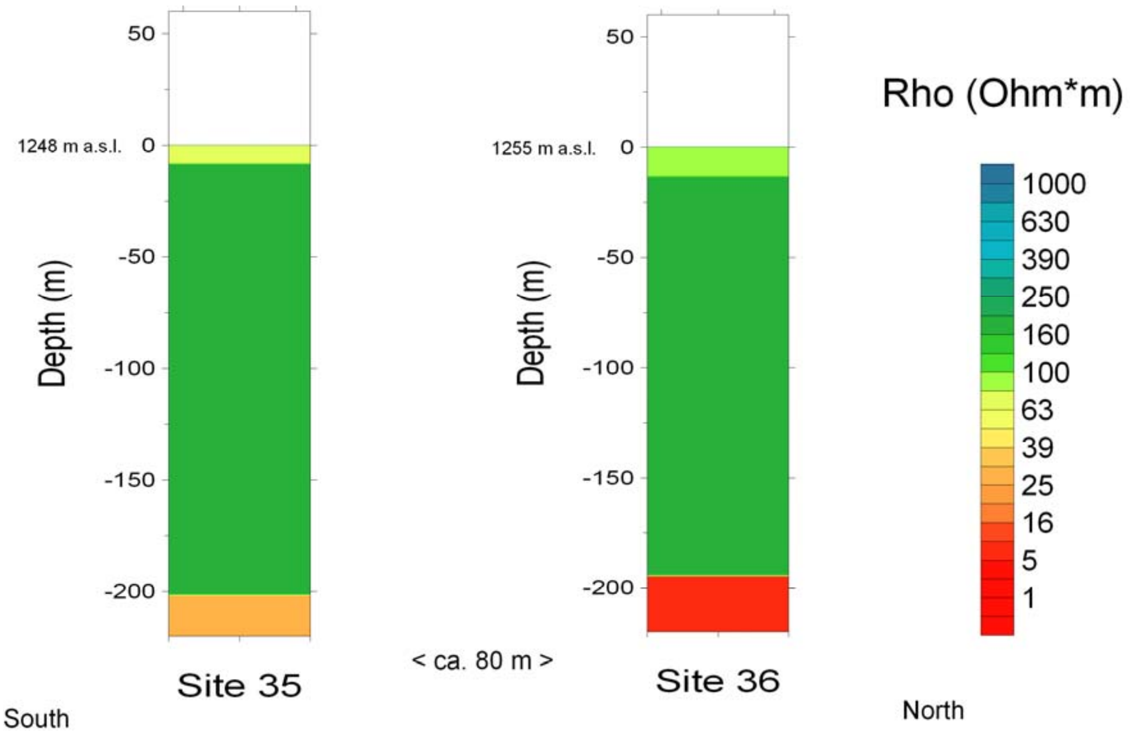

Figure 8: One-dimensional inversion models derived from TEM data outside FZ 8's burning zones over not-burning coal seams nos. 6 and 7 about 1 km south-east of FZ 8

3.3 Airborne and ground magnetic surveys

The ground magnetic survey performed by AGRS was carried out with a HC-95 ground helium optically-pumped magnetometer. The line direction was mainly east to west, and the nominal line spacing and sampling distance was 10 m for most of the measurements. The second ground magnetic survey, carried out by DMT, used GSM-19, a system manufactured by GEM, Canada (Elsen 2006). The results of both surveys did not differ significantly, but the latter shows more details due to increased density of survey sites. Both data sets were merged. The map of anomalies of magnetic field intensity of FZ 8 presented in Figure 9 shows pronounced positive amplitudes over burning and burned coal seams. The burning zones (purple, red, and blue polygon lines) were derived from temperature and satellite data (Gielisch & Künzer 2003; Künzer et al. 2007 in this volume).

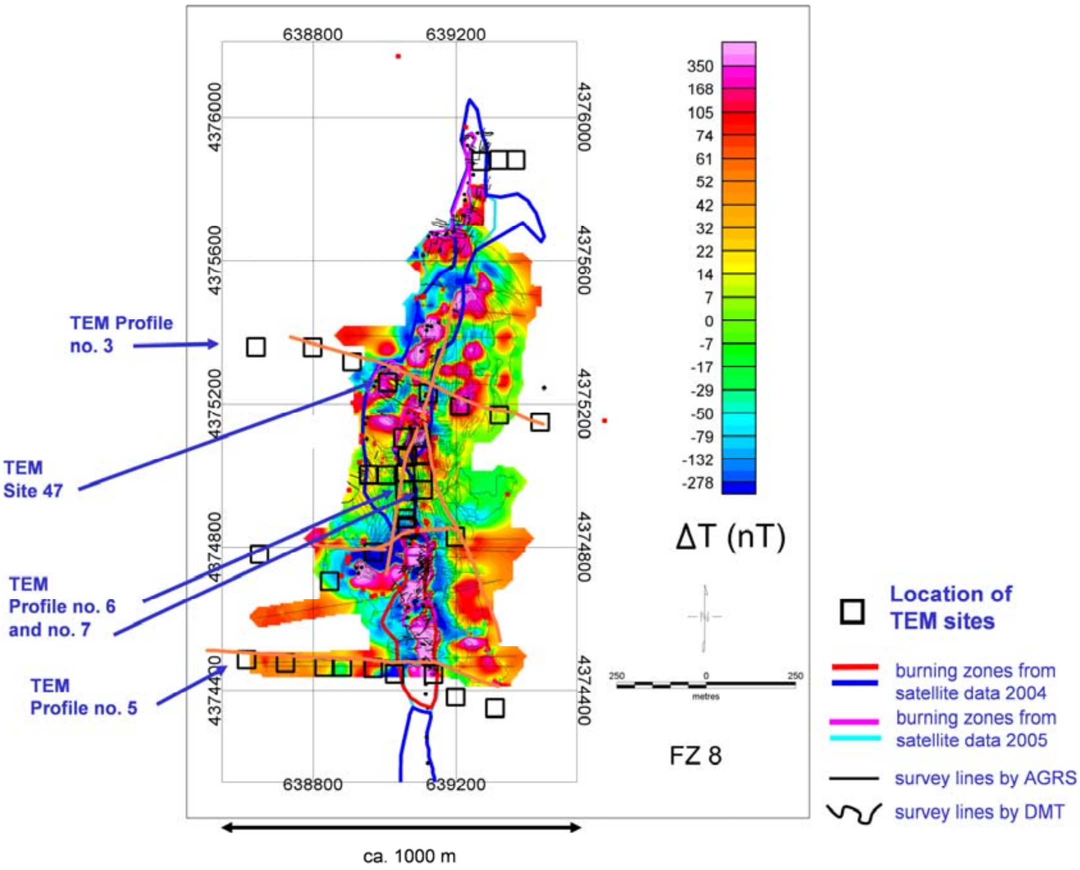

Figure 9: Anomalies of magnetic field intensity Δ*T*, derived from ground magnetic surveys conducted by AGRS and DMT in 2005. Dark or light blue and purple or red lines outline areas of colder and hotter coal fires.

The map of anomalies of the magnetic field intensity Δ*T* derived from the airborne magnetic survey of FZ 8 is shown in Figure 10. Although the regional magnetic field has not yet been deducted, the airborne magnetic anomalies correspond to those measured on ground. Due to cubic amplitude reduction of magnetic field intensity with increasing distance from the magnetic source, i.e. the soil, the amplitudes obtained at a relatively high flight altitude (about 60 m) are smaller and the anomalies broader than in the ground magnetic surveys. Nonetheless, anomalies with pronounced positive amplitudes coincide with areas of burning and burned coal underground.

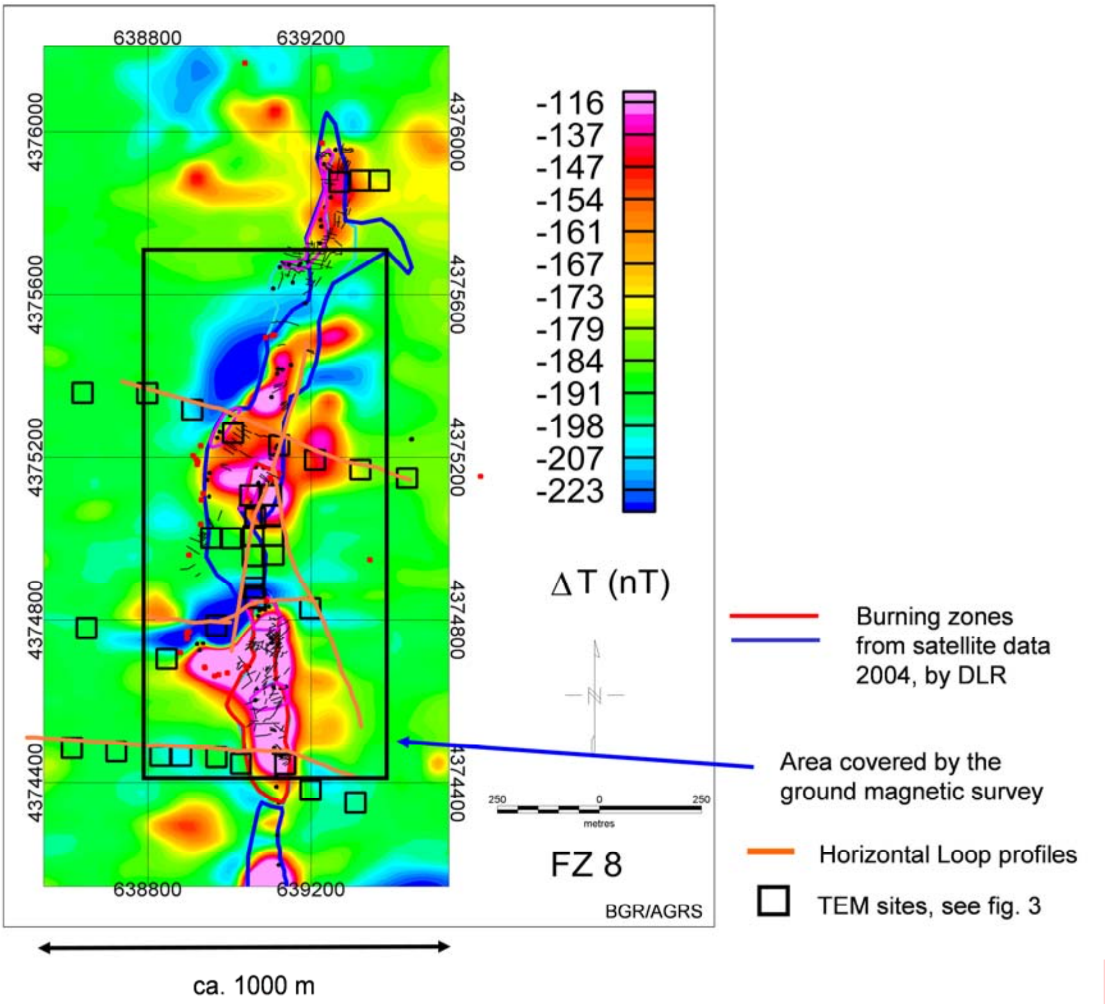

Figure 10: Anomalies of magnetic field intensity ΔT over FZ 8, derived from magnetic airborne survey at an average flight altitude of 60 m and a line separation of about 50 m. Blue and red lines mark areas of colder and hotter coal seam fires.

4 Conclusions

The objective of the geophysical surveys in Wuda Coal Mining Area was to detect and delineate coal fire areas by means of physical parameters, such as electrical conductivity and magnetic field intensity. Both parameters can point to coal fires – electromagnetic surveys highlight areas of lower resistivity, and magnetic surveys higher amplitudes of magnetic field intensity. The investigations presented in this study clearly prove that both methods can be used effectively as a tool for detection and exploration of burning and burned coal seams.

As the variance of geophysical parameters over coal fires compared to unaffected areas is rather small, ground geophysical surveys are the more reliable tool in coal fire detection and exploration; they allow for higher data sensitivity than airborne surveys. However, coal fire areas are not always accessible on ground, and airborne surveys are an alternative in these cases. Because of the weak parameter variance, high-resolution and high-quality data are imperative in geophysical investigations. It is essential for obtaining meaningful results to: (i) survey at low flight altitude, (ii) cover the investigated area by narrow survey lines, and (iii) use high-precision measuring devices, as well as (iv) sophisticated processing and interpretation tools.

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