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The application of electromagnetic methods for polymetallic prospecting in mining conditions

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Abstract: The paper presents selected results of geophysical surveys carried out in the "Polkowice-Sieroszowice" copper mine in Lower Silesia, Poland. The aim of complex geophysical measurements was the analysis of the usefulness of selected electromagnetic methods for locating ore mineralisation zones in mining conditions. The results were obtained from surveys conducted along profiles designed on the side-wall by the roof, in the middle and the floor of the excavation. Electromagnetic Profiling and Ground Penetrating Radar techniques were applied for outlining the mineralisation zones consisting of Cu, Pb and Fe. The variability of geophysical recordings depending on the degree of mineralisation and distribution of fractures induced by mining activity were analysed. The results of geophysical surveys were correlated to petrophysical parameters and laboratory data concerning the percentages of Cu, Pb and Fe in samples taken from the side-wall at the survey site.

Keywords: GPR, Electromagnetic Profiling, petrophysics, copper mine

INTRODUCTION

The aim of this study was the estimation of the applicability of selected electromagnetic methods for location of mineralisation zones (consisting of Cu, Pb and Fe) in the geological and mining conditions of Polish copper mines. To solve this problem, two geophysical techniques that are fast, cheap, non-invasive and contactless were chosen, i.e. Ground Penetrating Radar (GPR) and Electromagnetic Profiling (EMP) methods. There are also other electromagnetic techniques that might be applied for the detection of ore mineralisation zones in the rock mass, but their application in specific conditions of copper mines would be expensive, time-consuming, very difficult or sometimes impossible.

In mining geophysics, selected geophysical methods have been used for years: seismic surveys, seismology and seismometry observations and seismoacoustic measurements. To solve some problems in mines and mining areas, the gravity method was used. The geophysical methods mentioned above were used mainly for investigating geological structures in the mining area, detection and outlining of natural and anthropogenic fractures and voids that might threaten the stability of the surface and excavations as well as for the prediction and analysis of mining tremors. Such measurements were also used for the analysis of earthquakes induced by mining activity and the impact of exploitation on the surface and on structures and buildings.

The application of electrical and electromagnetic techniques for prospecting different metal deposits is by no means a novelty. Such surveys have been conducted mainly from the Earth's

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surface (rarely from boreholes) with the use of electrical resistivity methods (EP, VES, mise-a-al-masse), self-potentials and induced polarisation techniques as well as VLF and TDEM methods. Magnetometry also plays an important role in such surveys. Very seldom the georadar method (Francke & Yelf 2003, Francke 2012) and electromagnetic profiling technique (i.e. conductivity meter) were applied for the detection of metal deposits due to their shallow depth penetration.

Application of electrical and electromagnetic techniques in mining conditions, i.e. for surveys conducted directly from excavations and/or shafts, was presented in mining and geophysical conferences, but relatively seldom in the geophysical literature (Cook 1977, Verma & Bhuin 1978, Goszcz & Marcak 1986, Turner et al. 1989, Kotyrba & Kortas 2001, Vogt et al. 2005, Vogt 2006, Gundelach et al. 2009, Siever & Elsen 2010, Gołębiowski 2012, Antonik 2013, Gyulai et al. 2013, Żogała et al. 2013). Especially rarely in literature is information about the application of electromagnetic surveys conducted in mining excavations for polymetallic prospection. This fact encouraged the authors to undertake the issue.

Geophysical surveys were carried out in the "Polkowice-Sieroszowice" copper mine (Lower Silesia, Poland) in two sites, i.e. in the incline drift A5F and in the descending gallery D2 (Agreement, 2011). In both sites, measurements were conducted along profiles designed on the side-walls by the roof, in the middle and by the floor of the excavations. Due to the limitations of this paper, only selected results from the incline drift A5F (region SR14) will be presented.

Geophysical investigations were performed in two stages: I) rock samples were taken from the side-wall and were analysed in the laboratory; II) GPR and EMP techniques were applied and the correlation of laboratory and geophysical results were carried out in order to obtain a proper and unequivocal interpretation.

In the first stage, from 10 vertical geological profiles designed with step Δx = 10 m the rock samples were taken; in every profile, the samples were taken between floor and roof of the excavation with distance Δz equal to 0.2 m. On the basis of the percentage of Cu + Fe + Pb determined in the samples, the distribution of ore concentration on the side-wall was prepared (Fig. 1).

Additionally, from three geological profiles named SR14-2835, SR14-2833 and SR14-2831 (Fig. 1) 16 rock samples were taken for determining the following petrophysical parameters (Agreement, 2011): relative dielectric constant (ε_r), loss tangent (tanδ), relative magnetic permittivity (μ_r), resistivity (ρ) and electrical conductivity (σ) and polarisation factor (η). Because the applied geophysical techniques (i.e. GPR and EMP) are based on changes of ε_r [–] and σ [mS/m] in the examined medium, only these two parameters will be analysed later.

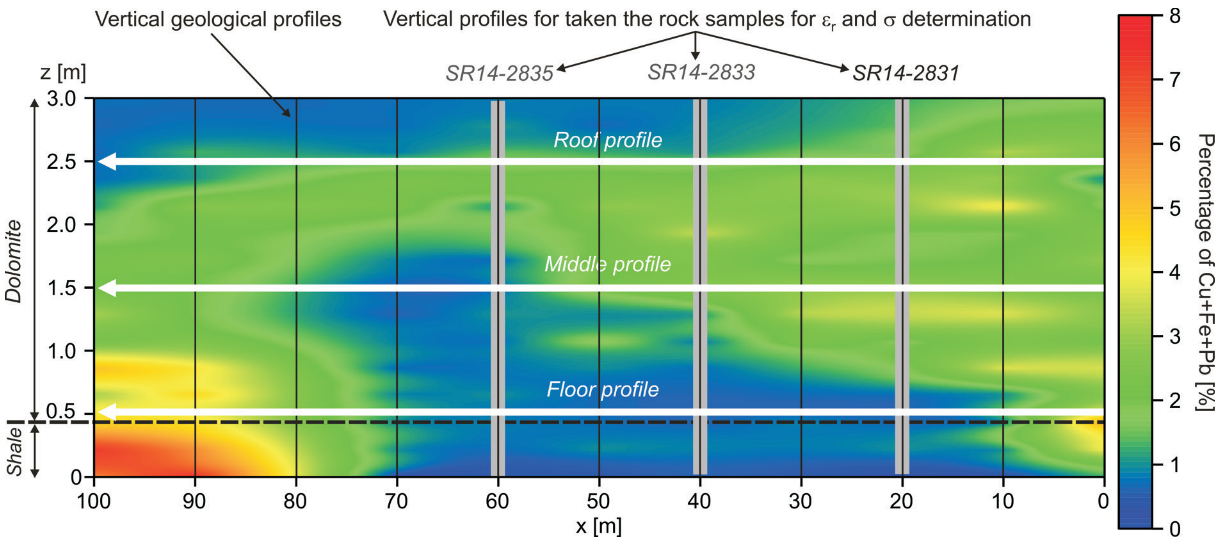

Fig. 1. Distribution of the percentage of Cu + Fe + Pb in the rock samples on the side-wall in the incline drift A5F (region SR14) and projection of the geophysical profiles

The relative dielectric constants ε_r vary in three vertical profiles between 2.5 and 4.3 (Fig. 2A–C); in GPR method it is assumed that the minimum contrast of values of ε_r between two geological media or hosting medium and target should be at least 1 to record in radargram readable reflections.

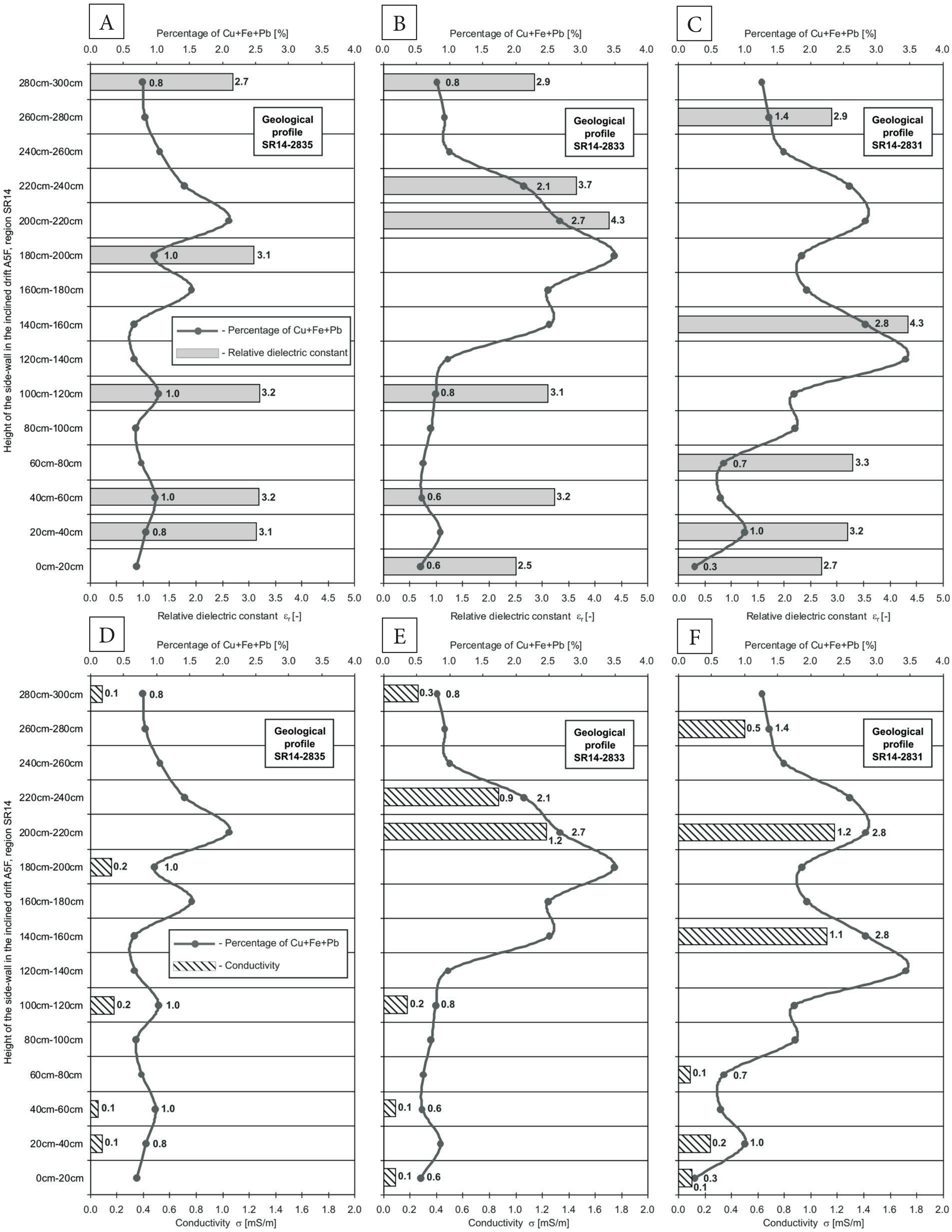

***Fig. 2.** Comparison of changes in relative dielectric constants (A, B, C) and conductivities (D, E, F) with changes of the percentage of Cu + Fe + Pb along vertical geological profiles presented in Figure 1*

An analysis of changes of ε_r versus changes of percentage of Cu + Fe + Pb (Fig. 2A–C) demonstrates that there is no possibility of using the GPR method to outline the mineralisation zones when the concentration of ores in the rock mass is below 1%; in such a situation, values of ε_r are more less constant and fluctuate around 3. When the percentage of Cu + Fe + Pb is c.a. 2% a correlation between the concentration of ores and ε_r appears (Fig. 2A–C). A conclusion might be as follow: the GPR method seems to be a useful electromagnetic technique for outlining the zones of polymetallic mineralisation when the percentage of ores is greater than 2–3% (Fig. 1 – green and first of all yellow, orange and red zones).

The analysis of changes of conductivity σ versus changes of the percentage of Cu + Fe + Pb in rock samples (Fig. 2D–F) shows that no correlation is observed when the concentration of ores in the rock mass is below 1%. A clear correlation appears when in the rock samples c.a. 2% and more of Cu + Fe + Pb was determined. It is obvious that an increase in ore concentration implies an increase of conductivity and zones with concentration of Cu + Fe + Pb higher than 2–3% (Fig. 1 – green and first of all yellow, orange and red zones) should be distinguished with the EMP technique.

In the second stage, GPR and EMP surveys were carried out along three, 100-metre-long profiles designed on the side-wall in dolomite formation located over the shale layer (Fig. 1). Former geophysical investigations carried out on the side-wall at this site using the Resistivity Imaging Technique allowed different distributions of fractures to be distinguished between the floor and roof of the excavation (Żogała et al. 2013); therefore measurements conducted along three profiles should allow us to analyse the influence on the recordings of both the percentage of Cu + Fe + Pb in the geological medium and the degree of fracturing in the rock mass.

The geophysical surveys were carried out to maximum distance (i.e. depth) from the side-wall equal to 1.5m; such a short distance (depth) was assumed in order to correlate the results of geophysical surveys to those of laboratory tests (the rock samples were taken only from surface of the side-wall).

The GPR measurements were performed using a ProEx georadar system (MALA GS, Sweden) with a 500 MHz antenna with a maximum depth of penetration of c.a. 5 m and a mean resolution c.a. 0.05 m; traces were recorded along profiles every 0.025 m. The measurements were performed in constant-offset (offset 0.14 m) reflection profiling mode.

The EMP measurements were performed using the conductivity meter EM-38 and EM-31 (Geonics Ltd., Canada) with the vertical orientation of the dipoles. The EM-31 conductivity meter was used for the verification of the results obtained from the EM-38 device, because the EM-31 is less sensitive to the presence of small heterogeneities in the rock mass, like e.g. fractures induced by mining activity. The distances between coils in the EM-38 conductivity meter were equal to 0.5 m and 1.0 m and, consequently, the depth penetrations were equal to 0.75 m and 1.5 m; the distance between coils in the EM-31 conductivity meter was equal to 3.66 m, which allowed a depth penetration of c.a. 6 m. The frequency of the generated electromagnetic field was equal to 14.5 kHz (EM-38) and 9.8 kHz (EM-31). The measurements were carried out in continuous profiling mode.

THEORETICAL BECKROUND OF APPLIED GEOPHSICAL METHODS

The measured apparent conductivity σ_a [mS/m] in EMP techniques is described by the following formula (Sharma 1997):

$$\sigma_a = \frac{4}{i\omega\mu_0 s^2}\frac{(H_s)}{(H_p)} \tag{1}$$

where:

H_p, H_s – respectively values of generated and recorded magnetic fields,
i – imaginary unit,
ω – angular frequency,
μ_0 – magnetic permittivity of a vacuum,
s – distance between coils.

Depth penetration of the EMP technique depends on: angular frequency ω, conductivity σ of medium, distance s between coils, orientation of dipoles (i.e. vertical or horizontal).

Depth penetration z [m] also depends on attenuation of the medium and can be described by the formula (Sharma 1997):

$$z = \sqrt{\frac{2}{\mu_0 \rho \omega}} = 504\sqrt{\frac{\sigma}{f}} \tag{2}$$

where:
ρ – resistivity,
σ – conductivity,
f – frequency.

As mentioned, GPR surveys were carried out in the reflection profiling mode where the reflection coefficient R [–] in loss media is described as follow (Jol 2009):

$$R^* = \frac{\sqrt{\varepsilon^*_{r1}} - \sqrt{\varepsilon^*_{r2}}}{\sqrt{\varepsilon^*_{r1}} + \sqrt{\varepsilon^*_{r2}}} \qquad \varepsilon^*_r = \varepsilon_r - \frac{i\sigma}{\omega\varepsilon_0} \tag{3}$$

where:
$\varepsilon^*_{r1,}\ \varepsilon^*_{r2}$ – relative complex dielectric constants for two geological media or for hosing medium and target,
ε_0 – electrical permittivity of a vacuum.

Depth penetration of the GPR method depends on: frequency f of applied antenna and conductivity σ of the examined medium. The attenuation coefficient α [dB/m] for an electromagnetic wave is described by the following formula (Annan 2001):

$$\alpha = \sqrt{\mu\varepsilon}\cdot\omega\sqrt{\frac{1}{2}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right]} \tag{4}$$

where ε and μ – respectively electrical and magnetic permittivity of the examined media.

Analysis of equations (1)–(4) allows us to draw the following conclusion: an increase of electrical conductivity σ in the regions of the rock mass where a concentration of Cu + Fe + Pb is observed should allow us to outline such regions with the proposed GPR and EMP techniques. An increase of electrical permittivity ε in regions with higher ore mineralisation causes that a sufficient contrast of relative dielectric constant ε_r between such regions and dolomite should appear. An increase of conductivity in polymetallic zones to a maximum value of 1.2 mS/m (Fig. 2D–F) should not influence strongly the depth range of the GPR method; a visible reduction of the depth penetration of electromagnetic waves is observed when conductivity increases above 10 mS/m.

COMPLEX INTERPRETATION OF THE RESULTS

In the surveyed site, the local Cartesian system of coordinates was established where length of profiles is the "x" axis, the position of profiles on the side-wall is the "z" axis and depth is the "y" axis.

The results of laboratory tests and GPR and EMP measurements are shown in the following figures:
– Fig. 3 – floor profile,
– Fig. 4 – middle profile,
– Fig. 5 – roof profile.

The results of EMP surveys were processed in Oasis Montaj software (GeoSoft, USA) and the curves were smoothed by a moving average procedure.

The radargrams were processed using the ReflexW software (SadmeierGeo, Germany). The following procedures were applied (ReflexW Manual 2015): phase correction, amplitude declipping, interpolation in the "x", "y" and "z" directions, dewowing removal, DC shift, gain function, background removal, Butterworth filter, smoothing, stacking. For time-depth conversion of radargrams, a mean velocity equal to 0.1 m/ns was assumed as adequate for dolomite. The radargrams are presented in normalised mode, with normalisation to a maximum amplitude of the Direct Air Wave. Additionally, for outlining the anomalous zones, classic radargrams were substituted with envelopes distribution (which may be identified with signal energy), counted from a Hilbert transform (Yilmaz 1994). One of operations was the muting of recordings for Direct Air and Ground Waves, and zero values of "y" axis were placed directly below the recordings for direct waves.

Three curves (i.e. to depths of 0.75 m, 1.5 m and 6.0 m) obtained from EMP are very similar in shape (Fig. 3A) and the mean value of the conductivity of dolomite in the central part of the profile might be assumed as 250 mS/m. In all curves, two anomalies with conductivity c.a. 500 mS/m were recorded, which correlate to zones of the rock mass where the percentage of Cu + Fe + Pb is between 3.4–4.8%. This result confirms the conclusion drawn from the results of the petrophysical measurements.

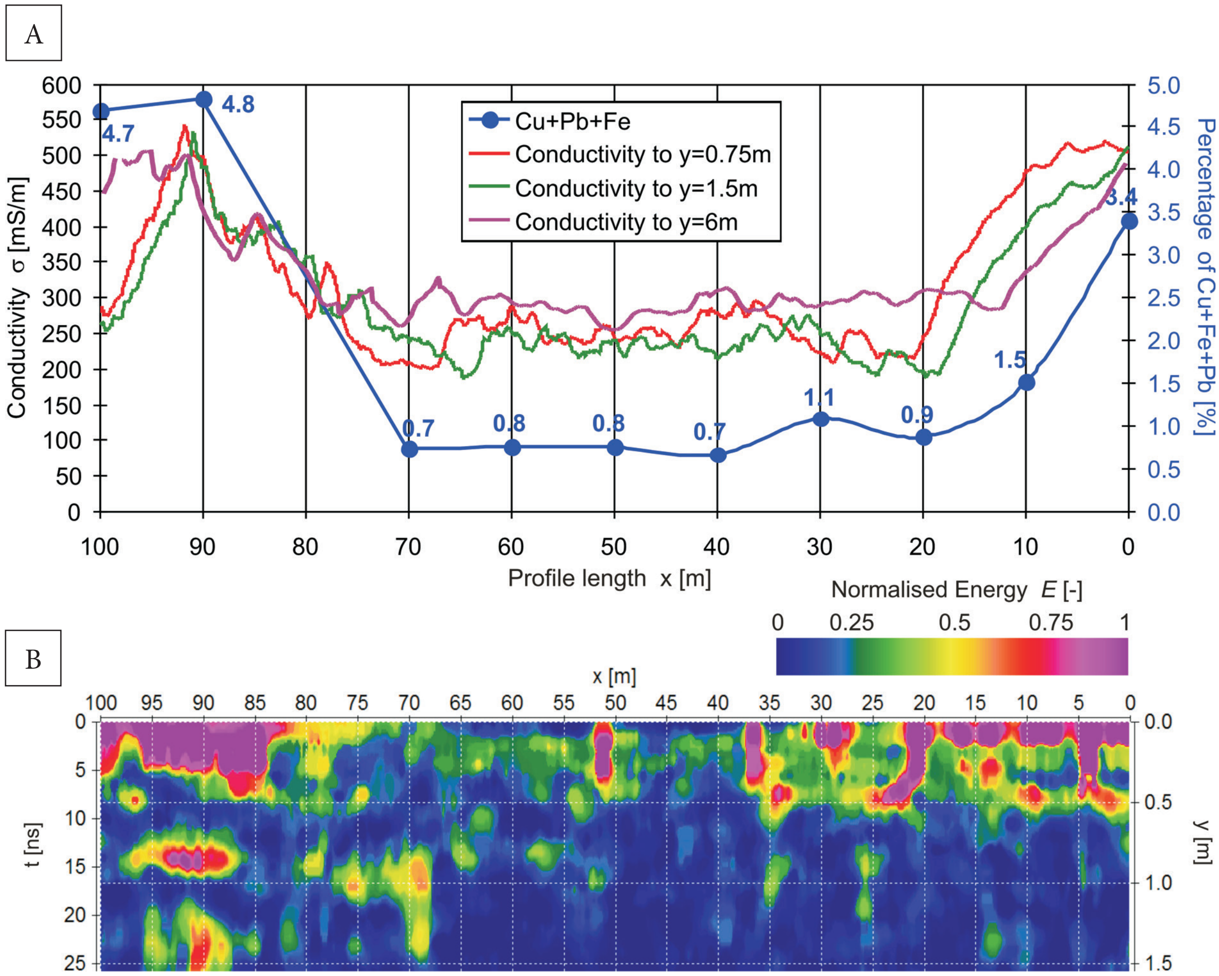

Fig. 3. Results of laboratory tests and EMP surveys (A) and GPR measurements (B) along the floor profile

The results obtained in the inclined drift A5F (region SR14) from the Resistivity Imaging Technique (Żogała et al. 2013) allow us to draw the main conclusion that fractures developed up to the distance (depth) of a few metres from the side-wall should be filled with air; such filling should change the reflection coefficient in the GPR method to less than the presence of ore mineralisation, especially when the percentage of Cu + Pb + Fe is above 2–3%; therefore, high-energy zones (i.e. violet and red colours) in Figures 3B, 4B and 5B might be correlated with the presence of ore mineralisation zones, and middle-energy zones (i.e. green colour) rather with fractured zones.

In the radargram (Fig. 3B), high-energy anomalies are located by the surface of the side-wall, at the beginning and end of the radargram. Such a location of anomalies correlates well with the results of the EMP surveys (Fig. 3A – violet, red and green lines) and the results of the laboratory tests (Fig. 3A – blue line). In the central part of profile, fractured dolomite with low polymetallic mineralisation occurs and consequently recordings with low energies (i.e. green colour) are observed in the radargram (Fig. 3B).

Along the middle profile, the average value of conductivity of dolomite is around 150 mS/m (Fig. 4A – red and green lines and partly violet line); a lower value of mean conductivity of the rock mass in the middle of the side-wall compared to the floor profile (Fig. 3A) is caused by the fact that the middle profile is located in dolomite but the floor profile is located on the boundary between dolomite and shale (Fig. 1). In shale, the mean conductivity is higher due to the presence of clay minerals. Both curves obtained from EM-38 conductivity meter are similar in shape (Fig. 4A – red and green lines) and depict more or less constant conductivity along the profile; such shapes of curves were probably caused by the appearance of a higher fractured rock mass in the middle of the side-wall. In Figure 4A, only one anomaly might be distinguished from red and green lines, i.e. an increase of conductivity to 200 mS/m between $x = 70$ m and $x = 100$ m; this anomaly correlates with increasing ore mineralisation (Cu + Fe + Pb = 2.3%) at the end of the profile (Fig. 4A – blue line). The result obtained from EM-31 device (Fig. 4A – violet line) correlates well with the distribution of the percentage of Cu + Fe + Pb along the profile (Fig. 4A – blue line). The divergence between results obtained from EM-38 and EM-31 conductivity meters confirms the assumption about the sensitivity of these devices presented in the Introduction.

In Figure 4B, the satisfied correlation between the percentage of Cu + Fe + Pb and the distribution of high-energy zones in the radargram is visible. The appearance of fractures in the rock mass is observed in the radargram by the slight increase of energies (Fig. 4B – green colour). The radargrams presented in Figures 3B and 4B allow us to draw the conclusion that ore mineralisation zones (with a percentage of Cu + Fe + Pb above 2–3%) extend in the rock mass mainly to the depth from the side-wall equal to 0.5 m, and in some sub-regions to 1.0 m.

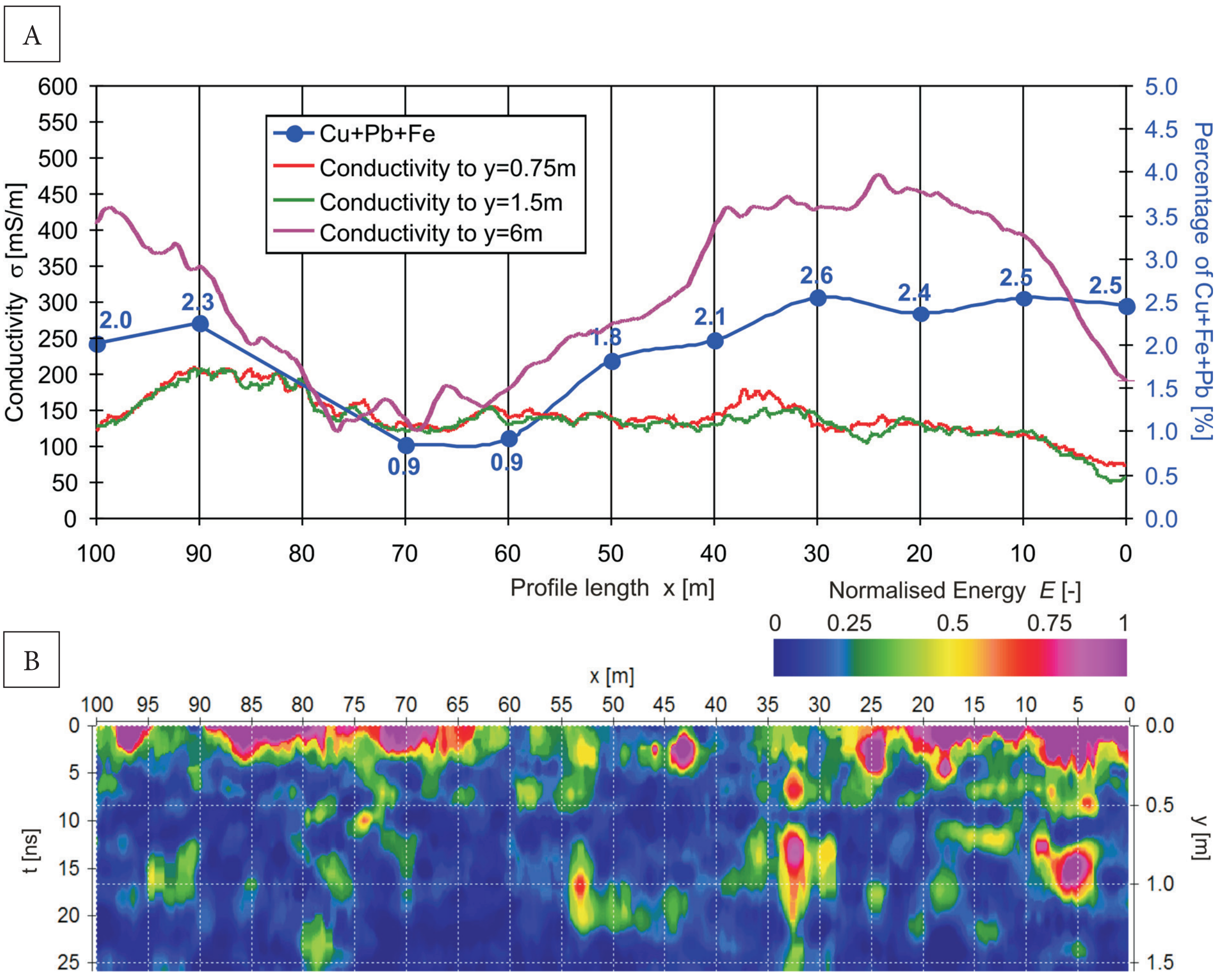

Fig. 4. Results of laboratory tests and EMP surveys (A) and GPR measurements (B) along the middle profile

In Figure 5A, no correlation between results obtained from the EM-38 conductivity meter and laboratory data is observed. This is caused by the presence of highly fractured zones in the rock mass by the roof of the excavation which was discussed in Żogała et al. (2013). The continuous decrease of mean conductivities recorded by the EM-38 device between the floor and roof of the excavation, i.e. 250 mS/m (Fig. 3A), 150 mS/m (Fig. 4A) and 50 mS/m (Fig. 5A) confirms that the fractures were filled with air, which might be treated as an isolator. The shape of the violet curve in Figure 5A more or less correlates with the distribution of ore concentration (blue curve).

The effects caused by the presence of fractures, i.e. the appearance of higher energy zones (green colour) in Figure 5B, are clearly visible during a comparison of Figures 3B and 4B with 5B.

Laboratory data (Fig. 5B – blue line) and the distribution of anomalies (i.e. high-energy zones) in the beginning of the radargram (Fig. 5B) correlate well. A strange effect is observed in Figure 5B from x = 55 m to x = 100 m, i.e. high-energy anomalies were recorded, which were confirmed partly by the increase of conductivity from x = 80 m to x = 100 m (Fig. 5A – violet line), but the percentage of Cu + Fe + Pb in this region decreases from 1.4% to 0.7%. It is difficult to explain such a divergence between laboratory and measured data without additional surveys; it was probably caused by a lack of a rock sample from x = 80 m and limited probing of the sidewall for petrophysical analysis (i.e. every 10 m), compared to the geophysical probing, i.e. every 0.025 m in the GPR method and 0.2 m in the EMP technique.

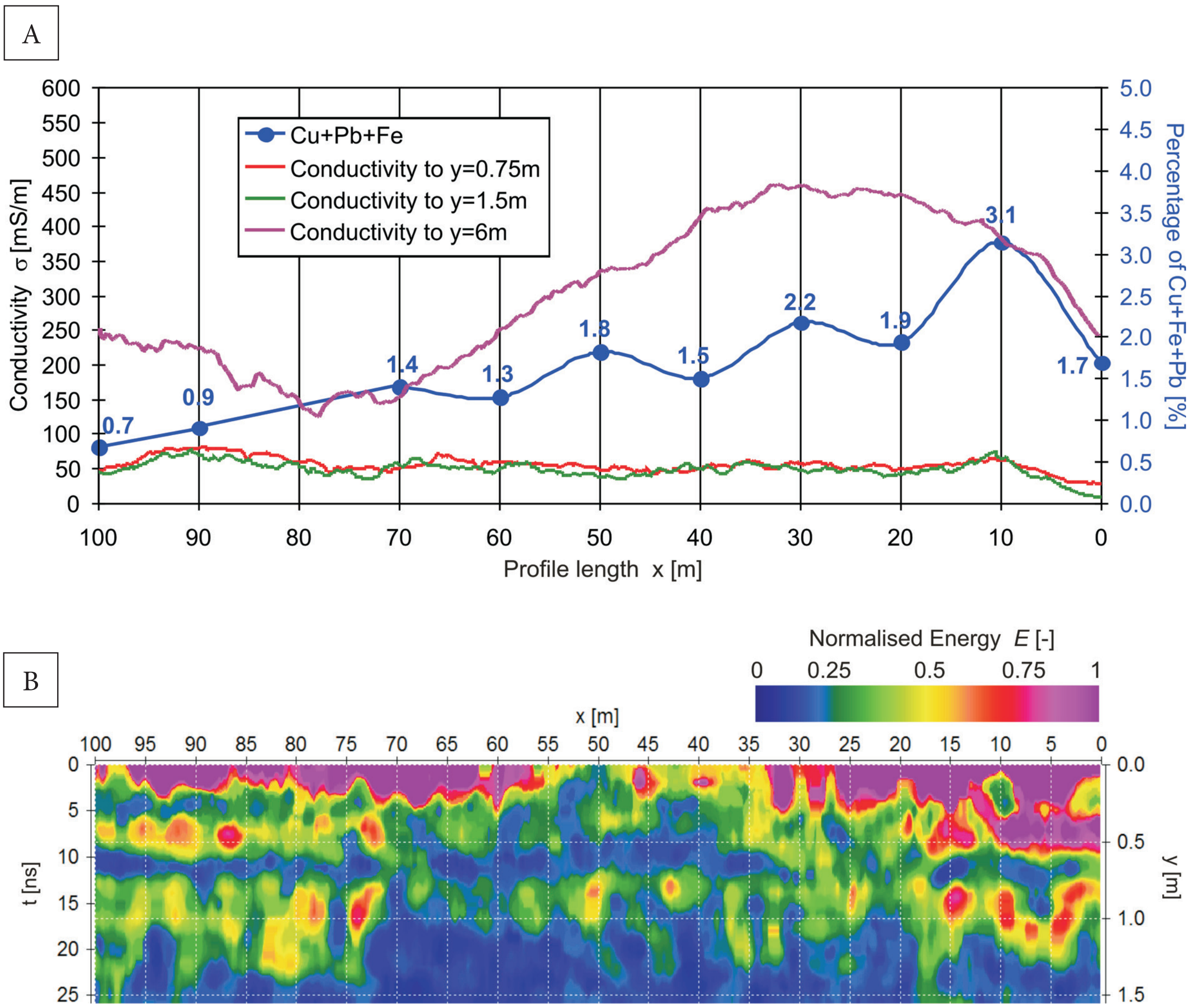

Fig. 5. Results of laboratory tests and EMP surveys (A) and GPR measurements (B) along the roof profile

CONCLUSIONS

The results of petrophysical analysis showed that a clear correlation between the values of conductivity and the relative dielectric constant versus the percentage of Cu + Fe + Pb in rock samples appeared when ore mineralisation was above 2–3%. The development of fractures towards the roof of the excavation enabled the analysis of conductivity curves obtained from the EM-38 conductivity meter; the results delivered by the EM-31 device correlated well to those obtained from the GPR method and laboratory tests. The results obtained from EMP surveys and former Electrical Resistivity Tomography (presented in another paper) allowed us to determine that the fractures in the surveyed site were filled with air; such information allowed the differentiation of the origin of GPR anomalies from both fractures and polymetallic zones. Laboratory and in-situ tests allowed us to draw the conclusion that increases in the percentage of Cu + Fe + Pb in the rock samples equal to 1% caused an increase in conductivity of c.a. 100 mS/m. The high resolution of the GPR method and positive results of surveys allow us to state that this geophysical technique, aided by EMP surveys with a EM-31 conductivity meter, should be the basic electromagnetic method used for outlining ore mineralisation zones in Polish copper mines, but with the limitation that polymetallic mineralisation must be higher than 2–3%.

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