Application of electromagnetic transient method for Zn–Pb exploration at the Cho Dien–Cho Don District, Bac Can Province, North Vietnam

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Abstract

Effectiveness of transient electromagnetic method (TEM) used for the localization of Pb–Zn ore bodies at the Cho Don deposit, province Bac Can, North Vietnam is appraised based on the modelling processes results. Conductive Pb–Zn ore bodies hosted in high-resistive limestone are in good conditions for the application of the TEM. The modelling process relays on the calculation of the voltage decay in time domain formed from the induced magnetic field diffusing into the study medium, when a pulse current with a given frequency is flowing in a transmitting loop coil. The model results show that the power current of 1 A transmitted from the coils with 100 or 400 m of size is effective for localization of the Zn–Pb ore bodies. However, the resolution and penetration depth of the TEM with a coil of $L = 100$ m is better and shorter in comparison with those in the case using the coil $L = 400$ m.

Keywords Transient electromagnetic method · Parameters of TEM array system · Resistivity · Pb–Zn ore · Limestone

Introduction

From the geological point of view, zinc deposits can be formed in the carbonate rocks, volcano-sediments and weathered zones with the skarn, hydrothermal and metamorphic processes. In zinc deposits, there are common metals such as lead (Pb) and minor elements like silver (Ag), cadmium (Cd), indium (In), gallium (Ga) and germanium

(Ge). They are often accompanying as sulfide minerals (Sangameshwar and Barnes 1983).

Vietnam has good zinc–lead potential. Most of the Zn–Pb deposits occur in the Northern part of Vietnam. One of the greatest Zn–Pb deposits is the Cho Dien deposit, situated about 40 km in the north of the Bac Can province, 200 km from Hanoi (Fig. 1). This deposit has been exploited by French since the thirties years of the Twentieth Century. In 1960, about 425,000 tons of zinc and 87,000 tons of lead and several hundred kilograms of silver, cadmium and indium were obtained from the oxide and sulfide ores (Kušnir 2000).

Most of the Zn–Pb ores are hosted by the Devonian limestone and limestone formations with thin sandstone beds. The Zn–Pb ore deposits in North-East Vietnam were formed due to magmatic and volcano activities (Tran et al. 2011; Nguyen and Nguyen 2018). The Zn–Pb ore in the study deposit occurs as two forms oxidized and sulfided. The oxidized ores often are occurring near to a surface, but the sulfide ore in the ground at the depth of several tens to a few hundred meters (Kušnir 2000). The localization of the underground ore bodies was the principal task for geological surveys.

Generally in the prospection of Zn–Pb deposit, some different geophysical methods can be used such as: gravimetric, magnetic and electromagnetic, but in this case, due to

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Fig. 1 Localization of Cho Don deposit with North Vietnam as background

the morphology of the studied region and conductivity of the formations, the most effective method in our opinion should be the electromagnetic transient method (TEM). The method was firstly developed in Russia, in the sixties of the twentieth century for studying deep structures (Telford et al. 1990; Meju 1994). It found the wide application in many geological and environmental fields and today represents a very interesting method for investigating some electrical parameters of the subsoil (Ranieri 2000).

In the paper, we attempted to use the mentioned method for the prospecting of the zinc–lead ore bodies occurring in the thick and very low conductive sedimentary formations. Our attempt was to present the signals on the receiver coil as a calculated voltage from the transient process when the

electromagnetic wave is transmitting into the high resistivity half-space containing a conductive body. The signals will be calculated for some selected emitting coils and the current powers as well as for the ore body with different thicknesses.

Regional geology

The zinc–lead Cho Dien deposit is located in the North-Eastern part of Vietnam (Fig. 1). This region belongs to the South China block, separated from the Indochina block by the Red River fault system (Allen et al. 1984). The Red River Fault or Song Hong Fault is a major fault in Yunnan, China, and Vietnam which accommodates continental

China's (Yangtze Plate) southward movement. It is coupled with that of the Sagaing Fault in Burma, which accommodates the Indian plate's northward movement, with the land (Indochina) between faulted and twisted clockwise (Le Dain et al. 1984). It was responsible for the 1970 Tonghai earthquake (Allen et al. 1984). Due to the mentioned tectonics from time to time, the seismic activity is occurring in the South China and North Vietnam (Tan et al. 2016).

Fig. 2 Geological map of the Cho Don deposit (Nguyen and Nguyen 2018): (1) siliceous limestone, (2) dark gray bituminous limestone, (3) bituminous white marble thin sericite schist layer, (4) sericite quartz schist contains manganese, iron ore; (5) marble, rhyolite tuff, amphibole schist; (6) pebbles, gravel, sand, clay; (7) faults; (8) primary Pb–Zn ores; (9) oxidized Pb–Zn ores; (10) Pb–Zn mines

From the tectonics point of view, the South China block is composed of the Outer zone, NE Vietnam nappe, the Chay River ophiolitic mélange and Day Nui Con Voi units (Faure et al. 2014). The Outer zone is located in the region near the boundary with China; this zone is built principally from the Devonian limestone series and overthrust by the NE Vietnam nappes. The nappes include the Silurian Song Chay porphyritic monzogranite and Triassic marble, quartzite and metapelite with some biotite. On top of this unit, there are the Paleogene (Tertiary) suits. The Song Chay ophiolitic mélange is a discontinuous unit built of the serpentine, mafic rocks, limestone and sandstone–mudstone matrix (Roger et al. 2000; Yan et al. 2006). This zone is very fractured by the tectonics activities. The Day Nui Con Voi consists of the high-temperature metamorphic rocks. In this unit, there is the presence of gabbro, diorite and granodiorite. The Cho Don deposit occurs within the Song Chay ophiolitic mélange zone (Nguyen and Nguyen 2018).

Deposit geology

The zinc–lead ores are principally distributed in the Devonian terrigenous carbonate formation consisting of shale, bituminous black argillite, limestone and marble (Nguyen and Nguyen 2018). The deposit area is mountainous terrain with some limestone mountains with 750–960 m of high, the lowest place is 220–250 m, and the highest is 1004 m above the sea level (Tang 2015). On the region, there occurs a dense jungle. Such area conditions make many difficulties with geological and geophysical service.

The ore bodies occur as veins filling the fractures in the faults and broken zones (Figs. 2, 3). In the upper part, the ores occur as an oxidized compound and from a few tens meters under surface, there are a massive sulfate Zn–Pb ores. The Zn–Pb ores are principally distributed in the Devonian terrigenous carbonate formation consisting of shale,

Fig. 3 Geological cross section B–B

Table 1 Calculated maximum measurement time (ms) and penetration depth (m) corresponding to the magnetic moment M_t ($A \cdot m^2$) of the transmitter loop and medium resistivity ρ ($\Omega \cdot m$) at noise level $Nm = 0.5 \text{ nV/m}^2$

$M_t = I \times L^2$	Medium resistivity— ρ				
	10	50	100	300	500
1×10^4	10.02 ^a (224) ^b	3.82 (309)	2.52 (355)	1.30 (442)	0.96 (490)
5×10^4	19.08 (309)	7.26 (426)	4.79 (490)	2.48 (610)	1.82 (675)
$1 \times 16 \times 10^4$	30.38 (390)	11.57 (742)	7.63 (852)	3.95 (1062)	2.91 (1176)
$5 \times 16 \times 10^4$	57.83 (538)	22.02 (852)	14.53 (979)	7.51 (1220)	5.53 (1351)

^aMaximum measurement time

^bPenetration depth

bituminous black argillite, limestone and marble (Nguyen and Nguyen 2018).

The average grade of the ore is 10% Zn and 3.5% Pb, where the sphalerite, pyrite and galena are the major minerals. Most of the ore bodies occur conformably with the host limestone formation in the vein or lens of shape with a few tenths of a meter to 2.5 m of width and a few tens to few hundred meters of length.

Background of the electromagnetic transient method

The transient electromagnetic method (TEM) relies on a measurement of the electromagnetic field in a study medium formed as a consequence of the transient process when an electric current in a transmitting loop is abruptly turned out (Kaufman and Keller 1983; Klityński et al. 2014). The TEM is effective for high resistivity medium hosting a good conductive body. Therefore, the TEM method is very useful in prospecting a high conductive metal ore hosted in high resistivity rocks (Keller 1997). The electromagnetic transient method can be draft described as follow: The transmitting cycle is composed of four comparable parts, on the first quarter there is the positive rectangle pulse, then on the second there is no current, on the third quarter there is negative pulse with the same shape and amplitude as positive rectangle pulse and in the last quarter there is no current. When the current in the transmitter loop is abruptly turned out, according to Faraday's Law, the eddy currents are formed and diffuse deeper in the ground and decay periods depend on the resistivity of the geological medium (Oryński et al. 2019). These eddy currents are the source of the secondary magnetic field, and the change with time of the vertical component of this magnetic field is measured in the second part of the cycle (named as time domain) as the voltage drop by the receiver coil. The measurement duration (t) is the interval from t_0 to $t_{\max}$, where t_0 is the moment when the electric current in the transmitting loop is turned out; the $t_{\max}$ is the moment, when the measured voltage is comparable with noise (Kaufman and Keller 1983). Obviously, the duration time ($t_{\max} - t_0$) is shorter than $\frac{1}{4}$ of the current pulse period

(Klityński et al. 2014). Practically, the interval ($t_0 - t_{\max}$) is divided into 20 gates, in which the data are recorded. The width of the gates is logarithmically increased to improve the signal/noise ratio (S/N) with the elapsed time. The mentioned procedure of the transmitting current pulse (I) and the recording voltage signal ($U(t)$) is called as time-domain electromagnetic method (TDEM). The recorded signals correspond to the near zone (induction); in TDEM theory, the near zone refers to the region, in which the distance r between transmitter loop and receiver coil is far shorter than an apparent wavelength λ^* [m] ($r \ll \lambda^*$). The apparent wavelength is usually calculated by the formula (Zhdanov 2010):

$$\lambda^* = \sqrt{2\pi \cdot \rho \cdot t \cdot 10^7} \quad (1.)$$

where:

ρ —medium resistivity [Ωm]; t measurement time [s].

The depth penetration (δ_{TD} [m]) of the TDEM depends on the $t_{\max}$ [s] and resistivity of the medium ρ [Ωm] (Spies 1989) and estimated as follows:

$$\delta_{TD} = \sqrt{\frac{2 \cdot t_{\max} \cdot \rho}{\mu_0}} \quad (2.)$$

where:

μ_0 —the magnetic permeability of vacuum— $4\pi 10^{-7}$ [H/m].

Table 2 Measured voltages within the arranged gates

Time (ms)	U (nV/m ²)	Time (ms)	U (nV/m ²)
0.142	140	0.828	4.57
0.175	96.8	0.957	3.21
0.207	71.6	1.14	2.13
0.239	55.7	1.4	1.41
0.285	41.2	1.66	1.05
0.35	28.9	1.91	0.847
0.414	21.3	2.28	0.658
0.478	16.1	2.8	0.487
0.57	11.1	3.31	0.374
0.699	6.91	3.83	0.296

Fig. 4 Results of simultaneous Occam and LMA inversion of received voltages (a), apparent resistivity (b) and proposed smooth and sharp boundary models (c); all data: results of simultaneous

Occam and LMA inversion of received voltages from (d), apparent resistivity (e) and smooth and sharp boundary models (f) at point (t + 30)

In the case of geological formation, which often is heterogeneous, the resistivity ρ should be regarded as the efficient resistivity of the zone, from which there is the eddy current. The $t_{\max}$ depends on many parameters such as resistivity of the measured medium, the apparatus sensitivity and the noise level (Klityński et al. 2014). So the depth penetration (δ_{TD}) of the TDEM method depends not only on the geoelectrical parameters of the study medium but also on the power current source and the size $[L]$ of the transmitter loop and is expressed by the following formula (Spies 1989):

$$\delta_{TD} \approx 0.55 \cdot \left(\frac{I \cdot S}{\sigma \cdot Nm} \right)^{1/5} \quad (3)$$

where:

I —the current in transmitting loop [A]; S —transmitting loop area, $S = L^2$ [m²]; $\sigma = I/\rho$ —conductivity [S/m] of the

medium; Nm —the noise level, which practically ranges from 0.1 to 1 [nV/m²].

According to the formula (3), the depth penetration δ_{TD} is proportional to $\sigma^{-1/5}$, and for $L > 500$ m the depth penetration can reach 1000 m or greater (Klityński et al. 2014).

According to Kaufman and Keller (1983), the measured voltage $U(t)$ is a function of both the medium resistivity and the magnetic moment of the transmitter loop. In half-space and for the near zone, the voltage $U(t)$ is expressed by formula (Klityński et al. 2014):

$$\frac{U(t)}{S_r} = \frac{\mu_0 \cdot M_t}{5 \cdot t} \cdot \left(\frac{\mu_0}{4 \cdot \pi \cdot t \cdot \rho} \right)^{3/2} \quad (4.)$$

Table 3 Proposed geoelectric models I and II on site S-0 (Fig. 3)

Rock	Model I		Model II	
	ρ (Ωm)	H (m)	ρ (Ωm)	H (m)
Limestones, sandstones	1000	65	500	65
Ore body	10	2.5	10	2.5
Limestones, sandstones	300	115	150	115
Pb–Zn ore zone	10	2.5	10	2.5
Limestones, sandstones	300	120	150	120
Limestones, sandstones	1000	–	500	–

Fig. 5 Calculated results for the geoelectric model I with the loop size $L = 100$ m; **a** synthetic and calculated data; **b** apparent resistivity curves and **c** geoelectric and smooth models

where:

S_r —the effective surface of the receiver coil [m²]; M_t —the magnetic moment $M_t = IS$; t —measurement time [s].

Formula (4) shows that the $U(t)$ is proportional to $t^{-5/2}$ and its decay is slower in a medium with better conductivity. So the longer measurement time the resistivity of deeper formation can be observed. While the vertical resolution is better when the measurement time (t) is shorter (Formulas 1 and 4), this rule also is true even in the case of a thin layer with high conductivity hosted in the relatively

Fig. 6 Calculated results for the geoelectric models; **a** apparent resistivity with loop size $L = 100$ m for model II; **b** geoelectric and smooth models $L = 100$ m for model II; **c** apparent resistivity with loop size $L = 400$ m for model I; **d** geoelectric and smooth models $L = 400$ m model I; **e** apparent resistivity with loop size $L = 400$ m for model II; **f** geoelectric and smooth models $L = 400$ m model II

high resistivity formation. Obviously, the depth penetration and measurement time can be raised by the using of larger transmitter loop (L) and/or greater power current (I), but the enlarging of the parameters often deteriorates the

Fig. 7 Resistivity cross sections; **a** for $L = 100$ m with resistivities proposed in the model I; **b** for $L = 100$ m and with resistivities proposed in model II

resolution of the TDEM, especially in a poor conductive medium (Krivochieva and Chouteau 2003). The TDEM method is sensitive to the variation in the conductivity since the voltage $U(t)$ is proportional to $\sigma^{3/2}$ (Formula 4). In the TDEM, the recorded voltage is a function of both the measurement time (t) and apparent resistivity (ρ_a), which is calculated by the formula.

$$\rho_a = \frac{\mu_0}{4\pi} \cdot \left(\frac{2 \cdot \mu_0 \cdot M_t}{5 \cdot U(t)/S_r} \right)^{2/3} \cdot t^{-5/3} \quad (5)$$

The transmitter loop is usually in the square form with a side L of length and a receiver coil (Krivochieva and Chouteau 2001). Both the transmitter loop and receiver coil are placed on the ground. There are various geometry configurations, but in this case, we use the central loop and MulTEM. The central loop configuration is the system, in which the receiver coil is placed inside on the center of the transmitting loop, while in the MulTEM the receiver coils are located within the transmitting loop (Phoenix Geophysics 2006). The measurement is taken from one point to the other by moving the used configuration along the profile.

The maximum measurement times and penetration depths calculated for a medium with various resistivities using transmitter loops with 100 m and 400 m size and power current 1 A and 5 A at noise level = 0.5 nV/m² are presented in Table 1.

For the medium with lower resistivity, the penetration depth is shallower, but the measurement time interval is longer (Table 1), in consequence, the resolution is better.

Modeling results and interpretation

The data obtained from the TDEM sounding carried out at the point ($t + 30$) on the study area (Fig. 3) using a loop with $L = 100$ m, transmitting pulses of 50 Hz and 1 A of current, are presented in Table 2 and Fig. 4a. Using the mentioned data (Fig. 4a), the apparent resistivity was calculated and shown in Fig. 4b. In the central loop or MulTEM systems, the effects of 2D and 3D are ignored, and therefore, the interpretation is referred to the 1D model (Klityński et al. 2014). The geoelectrical models were built using the Occam's and LMA algorithms. Both of the algorithms are based on the least squares inversion and iterative processes.

Fig. 8 Resistivity cross sections; **a** for $L=400$ m with resistivities proposed in the model I; **b** for $L=400$ m with resistivities proposed in model II

The LMA algorithms are used for the layered model, while the Occam's for the model, where the resistivity function is to be piecewise perfectly smooth with discontinuous fixed microlayers (smooth model) (Constable et al. 1987). The software IX1D (Interpex, Ltd 2008) for 1D TDEM modeling and inversion of TDEM data were used. Based on the sounding curves and the Occam's and LMA algorithms, the smooth and equivalent sharp boundary models are proposed and shown in Fig. 4c. The equivalent sharp boundary models are result of the ambiguous quantitative interpretation of the TDEM data, since the ratio of the interpreted thickness h of the studied bed to its corresponding resistivity ρ (h/ρ) should be stable. The obtained model at the point ($t+30$) is treated as the typical geological and geoelectrical structure of the studied area.

In our case, for the smooth model, the starting resistivity was arbitrary appointed to $100 \Omega \text{ m}$ and the maximum depth, to which the model is constrained is about 600 m (Fig. 4c).

The curves at the time more than 1 ms (Fig. 4d, e) show an extreme change of the measured voltages and apparent resistivity, which could be related to an unexpected layer of either extremely low resistivity ($< 1 \Omega \text{ m}$), or very great

thickness (Fig. 4f). Such suggestion is impossible for the study area from the geological point of view.

Based on the geological structure of the study area (Fig. 3) and the interpreted results from the mentioned data (Fig. 4c), taking into account of limestone resistivity ($\sim 10^5 \Omega \text{ m}$) and limestone with ore (from 1 to $100 \Omega \text{ m}$) (Kobranova 1989), geoelectric models concerning with this area are proposed. The parameters of the models are constructed for every point on the geological cross section B–B (Fig. 3) and Table 3 presents, for example, the parameters at the point S-0.

For the model, the synthetic¹ and calculated² voltages for the receiver coil corresponding to the transmitting loop $L=100$ m and current pulse 1 A with frequency 25, 50, 100 and 500 Hz are presented in Fig. 5a.

¹ The synthetic voltages are as the calculated ones for the assumed geoelectric models (cf. Table 3) within the correspondent arrange gates.

² The voltage was calculated for the 1D smooth model using Occam inversion of the synthetic curve (Constable et al. 1987).

The apparent resistivity sounding curve from the mentioned voltages and the view of the proposed geoelectric model I as well as the interpreted smooth model are shown in Fig. 5b, c, respectively. On the calculated voltage curve, the effects of the low resistivity layers (ore body) are seen at the points, where the voltage decay is slower (arrow). The high conductivity layers are visible at the low-value interval on the apparent resistivity curve (Fig. 5b). The smooth model (Fig. 5c) is as a result of the fluent change of the interpreted resistivity.

Though the boundary of the conductive bed's is not clearly reflected on the smooth curve, the lowest points are corresponding to the localization of the ore zones (Fig. 5c) and the depth sections with differently interpreted resistivity are obtained from the smooth model.

In the case of the geoelectric model II, the apparent resistivity curve and smooth model for the loop $L = 100$ m and current pulse 1 A are presented on Fig. 6a, b, respectively. The interpreted resistivity for the model II is lower than that for the model I, but the vertical resolution is similar for both geoelectric model's (cf. Figs. 5b, c, 6a, b).

The apparent resistivity curves and smooth model for the loop size $L = 400$ m with current pulse 1 A and frequency 25, 50, 100 and 500 Hz for geoelectric models I and II are presented in Fig. 6c–f, respectively.

Generally, the results calculated for both loop size $L = 100$ m and $L = 400$ m are similar; however, due to the higher penetration depth, the deeper ore body is clearly visible for the bigger loop— $L = 400$ m (cf. Fig. 6d, f).

Taking into account the resistivities proposed in the model I and model II (site S-0), the modeling processes were carried out for every point with the step of 100 m along with the profile B–B 3000 m long, using the loops with $L = 100$ m and $L = 400$ m. In the results, there are four different combinations: 1. model I with 100 m of loop size; 2. model II with 100 m loop size; 3. model I with 400 m loop size; and 4. model II with 400 m loop size. The 1D Occam inversion of the synthetic data for every combination was performed, and the vertical resistivity distribution at each point was obtained. The geoelectrical cross sections were built by the connection of the vertical resistivity distributions for all points in the profile. Figure 7a, b presents the geoelectrical cross sections corresponding to the loop size with 100 m and geoelectrical model I and model II, respectively. Similarly, Fig. 8a, b presents the geoelectrical cross sections corresponding to the loop size with 400 m and geoelectrical model I and model II, respectively.

The geological boundaries from Fig. 3 are clearly observed on the geoelectrical cross sections (Figs. 7a, b, 8a, b), suggesting the effectiveness of the TDEM method in the Zn–Pb ore localization.

Generally, there are similar influences of the resistivities assumed in the model I and II on the geoelectrical cross

sections obtained for the loop $L = 100$ m (cf Fig. 7a, b). This effect is also observed for the bigger loop— $L = 400$ m (cf Fig. 8a, b). However, the vertical resolution for the smaller loop with $L = 100$ m is better than that for the bigger one with $L = 400$ m, especially for the shallow medium (cf. Figs. 7a, 8a or 7b and 8b).

On the geoelectrical cross section, the artifacts can be noted at the places, where the ore body is broken into upper and lower parts (cf. Figs. 7a, b, 8a, b). The discontinuous ore bodies could probably indicate a fault occurrence.

Conclusions

First of all, the most important outcomes of our study are that the time-domain electromagnetic methods are efficient for routine identification of the ore minerals and mineral exploration. Due to the stratified characteristics of the formations in the studied region, the interpretation of TDEM data referred to the 1D is justified. In our case, the Occam inversion is more objective since the boundaries of the ore bodies with the surrounding rocks are unknown. For the precise interpretation, the additional information such as bore-hole data especially the data concerning with the electrical parameters as well as geological structure of the study region are needed (Ślęzak et al. 2018).

The influences of the relatively high resistivity of the formations containing a good conductive ore body on both tested loop sizes: smaller 100 m and bigger 400 m are similar. On the other hand, the penetration depth of the TDEM is strongly limited by noise, and therefore, it is necessary to use transmitting loop with large size and stronger power, but in the dense jungle, there is difficulty to transport a big and heavy current generator producing more than 2A. So it is better to use the larger loop size, which is also satisfied with the economic point of view. For such a difficult, mountainous area, a MulTEM technique should be a good solution, where more receiver coils can be placed within the transmitting loop (Tasci and Zordan 2009; Klityński and Targosz 2011).

In the study region, the ore bodies can occur as vertical lenses, in order to locate them, we should make additionally some plots of the apparent resistivity or/and voltage along with the profile in the time cross section. The plots will indicate the behavior of the anomaly at different time. Based on the plots, we can estimate the ore body at different depth levels (Tasci and Zordan 2009; Spies 1980). The above suggested mentioned above work should be made in the future.

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