

Interpretation of EM soundings using polarizable S-plane

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The well-known method of the “floating S-plane” or S-tau method has obtained a new “lease on life” for the interpretation of huge amounts of data obtained during airborne surveys. The method allows identifying segments with high- and low-resistivity rocks in a section. At the same time, induced polarization effects often occur and distort the measured signals. Several commercial software algorithms are available that can perform direct inversions for resistivity and determine also polarization parameters, but it is still a time-consuming process especially for large airborne data sets. However now it is possible to record hundreds or thousands of soundings within several hours or a single day and to satisfy client expectations there is a need for fast (albeit preliminary) conversion of the recorded EM data into a conductivity/resistivity depth image along a flight line. The use of a conductive polarization S-plane model can significantly help in creating an initial geoelectric model, which can serve as the basis (*a priori input*) for one-, two- or three-dimensional modeling using more sophisticated commercial or research version software. Currently, there are algorithms available for calculating the transient EM field propagating through an inhomogeneous medium with dipping polarizable S-planes. The advantage of the models is that the formulas (except for convolution when calculating the polarization) are analytical and therefore provide high accuracy and speedy calculations [Hallbauer-Zadorozhnaya, 2024].

Scientists of the Siberian School of Geosciences of the Irkutsk National Research University are actively developing a method of electromagnetic sounding that includes the induced polarization method (EMS-IP). EMS-IP uses a long grounded electric line AB as a transmitter, and a series of short electric lines MN located parallel to the current line as receivers. This method allows you to record, using a stationary single line AB, several hundred soundings sequentially with a, or several moving MN receivers. Very often survey sites are located over highly resistive geological structures as in Eastern Siberia, the Far East and Kazakhstan, where a significant portion of the recorded signals are overloaded by induced polarization effects.

The potential difference $\Delta U(t)$ for an array with grounded electrical wire AB and receiver dipole MN for a single horizontal S-plane is equal to:

$$\Delta U = U_M - U_N = \frac{Iab}{2\pi Sr_0} \left(\frac{1}{2\tilde{m}_M} \frac{\cos_M^2 \varphi}{[1 + 4\tilde{m}_M^2]^{1/2}} - \frac{1}{2\tilde{m}_N} \frac{\cos_N^2 \varphi}{[1 + 4\tilde{m}_N^2]^{1/2}} \right). \quad (1)$$

where U_M and U_N are potential difference between electrodes M and N, I is the electrical current, r_0 is the minimal distance between MN and line AB, ab is a section of line AB, $\cos_M \varphi$ and $\cos_N \varphi$ are the cosines of angles between r_0 and lines connecting M and N, (r_M and r_N) and ab ,

$$\tilde{m}_M = \frac{h}{r_M} + \frac{t}{\mu Sr_M}, \quad \tilde{m}_N = \frac{h}{r_N} + \frac{t}{\mu Sr_N},$$

– parameters of S-planes with conductance S and depth h and t is a particular time interval.

As is known, the polarization processes that occurs in rocks is usually described by the Cole-Cole formula. This formula (at $c = 1$) quite satisfactorily describes polarization processes of the electrokinetic type. In the frequency and time domains the Cole-Cole formula has the following form:

$$\sigma(\omega) = \frac{\sigma_\chi}{1 + \frac{1}{i\omega\tau + 1}}, \quad \sigma(t) = \frac{\sigma_\chi}{1 + \eta} \left[1 - \eta \exp\left(-\frac{1 + \eta}{\tau} t\right) \right], \quad (2)$$

where η is a chargeability, τ is a decay constant (in s), σ_χ is a specific conductivity of the pore fluid (in S/m).

The potential difference $\Delta U(t)$ arising in a polarizing medium can be written as:

$$\Delta U(t) = \int_0^t \Delta U_{tr_field}(t - \tau) * g_\lambda(\tau) d\tau, \quad (3)$$

where $g_\lambda(\tau) = \sigma_\chi[\delta(t) + p(t)]$, where $\delta(t)$ is a Dirac function, ΔU_{tr_field} is the potential difference in the non-polarizable medium (eq. 1).

$$p(t) = \frac{\partial \sigma_\chi}{\partial t} = -\frac{\eta}{\tau} \exp\left(-\frac{1 + \eta}{\tau} t\right).$$

For polarizable S-planes:

$$S(t) = \lim_{\substack{\Delta h \rightarrow 0 \\ \Delta h \sigma_\lambda \rightarrow S_0}} [g_\lambda(t) \Delta h] = S_0 \delta(t) + S(t).$$

where

$$S(t) = -S_0 \frac{\eta}{\tau} \exp\left(-\frac{1 + \eta}{\tau} t\right).$$

S_0 is a longitudinal conductance of the non -polarizable S-plane.

Substituting $g_\lambda(t)$ into (3) we obtain:

$$\Delta U(t) = \Delta U(t) + S_0 \int_0^t \Delta U(t - \tau) * p(\tau) d\tau, \quad (5)$$

where $\Delta U(t)$ for our array is determined by eq. 1.

A calculation algorithm has been created for the interpretation of EMS-IP data and the main building blocks of this algorithm is as follows.

1. The EM measurements are transformed into curves of apparent longitudinal conductance $S(H)$, where $H(t)$ is the location depth of the “floating S-plane”. The $S(H)$ function allows quite reliably to determine the depth of a surface of a conductive object and evaluates the change in longitudinal conductance with depth. However, visualization of the results is not satisfying to the clients as a S-Plane is an infinitely thin sheet.

2. For visualization of the conductor in the section, it is necessary to calculate the derivative of the apparent longitudinal conductance $S(H)$ with respect of depth H, which determines the apparent electrical conductivity function $\sigma_k(H) = \Delta S(t) / \Delta H$. It is obvious that with an increase in longitudinal conductivity, the value of $\sigma_k(H)$ increases. However at $S(H) \approx const$ then $\sigma_k(H) \rightarrow 0$. Moreover, when the effect of induced polarization (which, as is known, has a negative sign) is superimposed on the signal, a so-called “slope” is observed on the $S(H)$ curves, that is, a decrease in longitudinal conductance with depth. Therefore, the apparent electrical conductivity $\sigma_k(H)$ will be negative.

3. The IP effects and the induction part of the signal are separated.

4. At each time t , the amplitude of the separated IP signal is compared with the polarization part of the theoretical S-plane curve for fixed or increasing value of S of the “floating” plane, and then the apparent polarizability $\eta_k(t)$ is determined. The value of the decay constant τ is determined for each reading.

5. Separately, the $\sigma_k(H)$ and $\eta_k(H)$ arrays are displayed and geoelectric sections are constructed.

As an example of the application of the described method of interpretation of field data ‘contaminated’ by overlapping induced polarization processes, the geoelectric profile of one site in Kazakhstan is presented. The work was carried out using the EMS-IP method. Typical $\Delta U(t)$ curves are shown in Fig. 1. At times greater than 0.1 s throughout the entire area, a change in sign occurs on all $\Delta U(t)$ curves. Note, the decay constant τ on all curves exceeds 0.1 s, which is not typical for the electrokinetic type of polarization. It is possible that rock types with membrane polarization may be present in the section. Currently, also the effect of a migration polarization that may occur in isolated pores and mineral grains has been considered and is being studied.

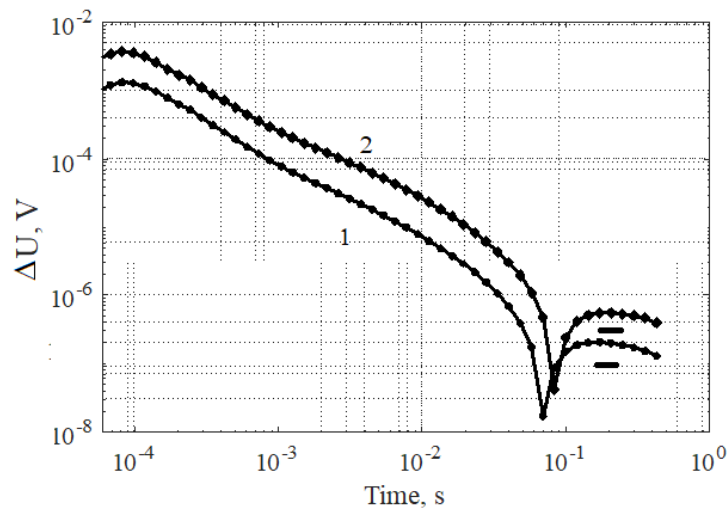


Fig. 1. Typical $\Delta U(t)$ readings collected within the survey area.

The geology of the site is relatively simple. The basement of the section consists of granitoids of the Middle Carboniferous age, cutting through Early-Middle Carboniferous tuffs of various compositions. Granitoids emerge on the surface in the eastern and southeastern parts of the site and tuffs are present throughout the rest of the area. The thickness of the tuffs can reach 500 meters. Quaternary sediments (0.5 - 6 m and up to 70 m) are partially covered by the tuff and metamorphic rocks of basement. Faults of a sub-meridional direction dip to the east at an angle of 75°-80°.

Almost throughout the entire mass of granitoids, disseminated sulfide mineralization of pyrite and chalcopryrite is widespread. Ore zones, represented predominantly by chalcopryrite and malachite, and, less commonly, molybdenite, gravitate toward linear zones of brecciated rocks and sub-meridional fracturing.

A geoelectrical section is presented in Fig.2. In the western part of the section, at an interval of 750–950 m, there is a discontinuity in the electrical conductivity field, accompanied by a region with a polarizability gradient extending in depth. Here we can assume the presence of a steeply dipping fault (about 70 degrees to the east).

The maximum values of apparent electrical conductivity are presumably observed in the subsurface aquifer at depths of up to 80 m and in the range of 850 – 1150 m along the profile. Also, the maximum values of electrical conductivity, decreasing with depth, trace three

zones, presumably zones of copper ore mineralization, possibly associated with feathering faults accompanied with broad fractures into the side walls.

The thickness of these faults is about 50 m, the angle of incidence is from 45 to 80 degrees to the west. One of these zones was confirmed by a prospecting well. In addition, starting from a depth of 400–200 m, an area of almost continuous increased polarization exists throughout the entire section (with the exception of the interval 850 - 1150 m, which is “screened” by highly conductive aquifers). The nature of this area is currently unclear.

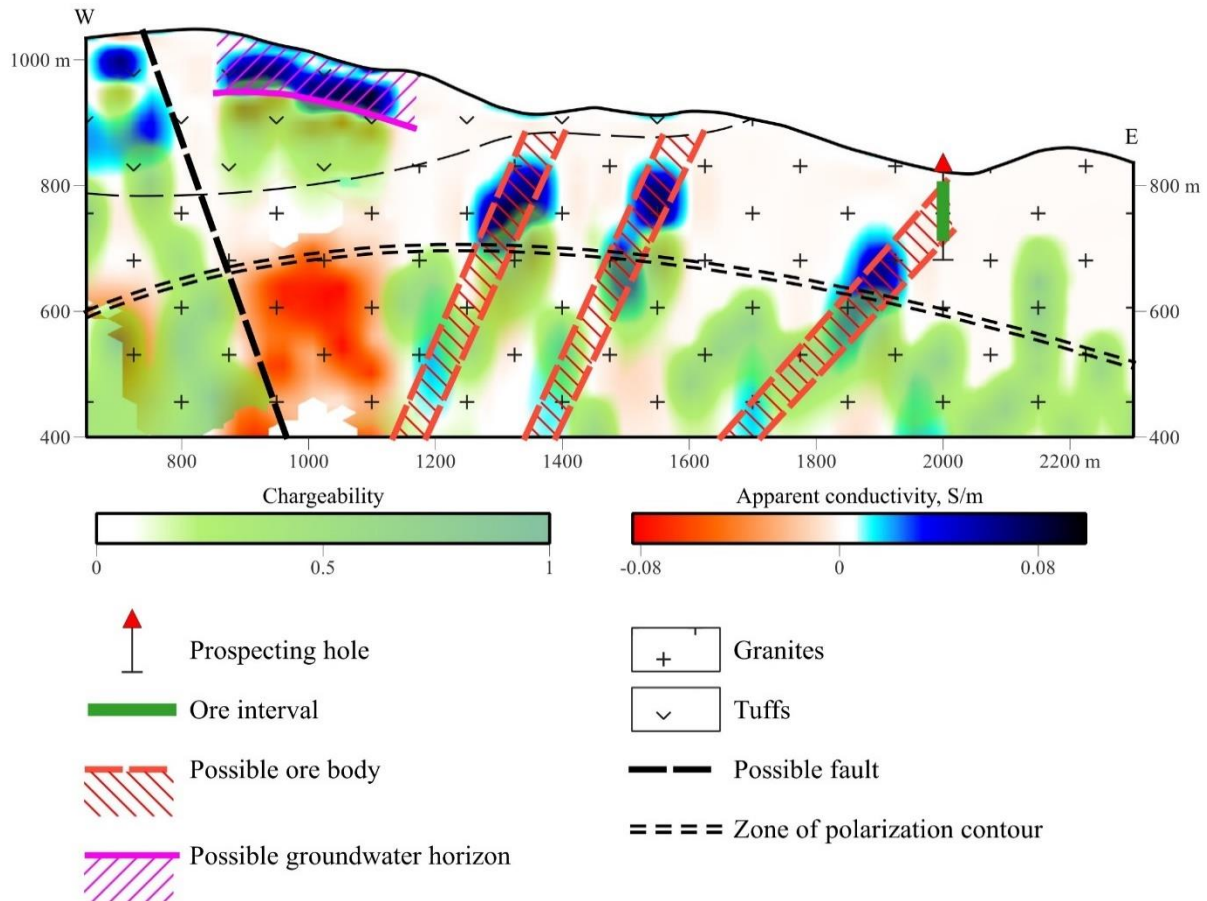


Fig. 2. Geological and geoelectrical section.

Abstract

The well-known method of the “floating S-plane” or S-tau method has obtained a new “lease on life” for the interpretation of huge amounts of data obtained during airborne surveys. At the same time, induced polarization effects often occur and distort the measured signals. The use of a conductive polarization S-plane model can significantly help in creating an initial geoelectric model, which can serve as the basis (*a priori input*) for one-, two- or three-dimensional modeling using more sophisticated commercial or research version software. As an example of the application of the S-plane method of interpretation of field data ‘contaminated’ by overlapping induced polarization processes, the geoelectric profile of one site in Kazakhstan is presented. The work was carried out using the EMS-IP method. The results obtained make it possible to detail the geoelectric structure of the study area, to identify zones of different resistivity, intervals of rocks where polarization processes occur, and to quantify the amplitude of the IP effect.