

## GEOL 384.3 and GEOL 334.3

### Lab #6: Induced polarization (IP) in modelling tank

In this lab, you will analyse IP data collected in table-top modeling tank in Rm. 265 Geology (the same as used in lab #5).

In Induced Polarization, a large current is injected into the ground by electrodes denoted A and B, and it electrically polarizes mineral grains that conduct electronically, like a metal or a semiconductor. The effect of this polarization is measured on two receiving electrodes called M and N. Polarization of this kind occurs at the fluid-solid contacts and is caused by the transition from ionic conduction in the pore fluid to electronic conduction in the mineral grain. Photo in Figure 1 shows how small IP surveys look like in our field schools.



Figure 1. Small IP survey during Geophysics field school 2012. White ceramic tubes are the nonpolarizable electrodes

Polarization of the material is ultimately caused by the electrical field  $\mathbf{E}$ , which, by virtue of Ohm's law  $\mathbf{j} = \mathbf{E}\sigma$ , is present everywhere the current density  $\mathbf{j}$  passes through the medium (that is, the current  $\mathbf{j}$  is also caused by field  $\mathbf{E}$ ). Wherever current passes from pore fluid to electronically conducting grains, a polarization will be induced. Any material that conducts electronically, or even as a semiconductor, and is reasonably conductive will polarize to some degree. All metals are polarizable, as well as minerals like magnetite,

graphite, pyrrhotite and some sulphides. Metals might be the target in an environmental survey and sulphides in a mineral exploration survey. IP is used in Gold exploration, and even in petroleum exploration, but it is the associated sulphides that typically produce the signal. Clays are polarizable as well, but by a different mechanism.

In IP, the measured quantity is the chargeability (also see lectures). Chargeability is defined as the ratio of the secondary voltage to the primary one (see Figure 2). The primary voltage (often simply called “the primary”) is the potential difference measured on the receiving electrodes, MN, when a steady current is on at the injection electrodes, AB. The primary may be several V depending on the injection potential, resistivity of the ground and the electrode spacing. The secondary voltage (“the secondary”) is typically much smaller than the primary, and so the convention is to measure the primary in V and the secondary in mV. Thus, the units for chargeability are mV/V.

The primary might vary slightly during the injection as a result of polarization of the injection electrodes as well as polarization of target minerals, electromagnetic induction and instrumental issues, but for technical reasons we would like to define a constant primary. To define a constant primary, we delay the measurement of the primary for a short time until it (hopefully) stabilizes, and then average over the remainder of the injection. The time delay before measuring is denoted  $V_{\text{delay}}$ . This can be anywhere from a quarter of a second (250 ms) to more than a second depending on the conditions. This delay is chosen by the operator based on observation of the stability of the primary.

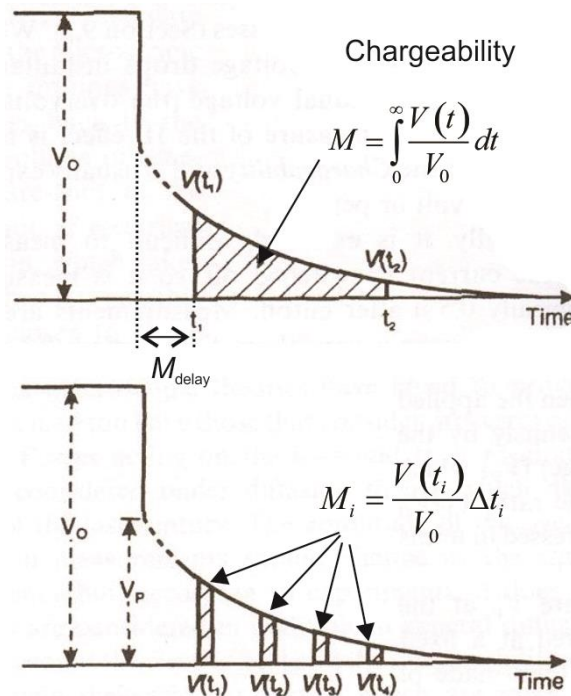


Figure 2. Variation of secondary voltage with time and its measurement within a time interval or time gates.

The secondary voltage is also variable in time (see Figure 2). It is at its largest just after the current is turned off and decays with time. The decay is initially rapid and slows as time goes on. Recovery (to 0 V or

some stable level) can take from less than a second to as much as a few minutes, but a few seconds is typical. As with the primary, it is standard practice to delay the start of measuring the secondary voltage for a short time. This time delay called  $M_{\text{delay}}$ .  $M_{\text{delay}}$  can be as small as 50 ms and as large as a few hundred ms. The purpose of this delay is to allow any electromagnetic (EM) induction transient currents to decay before measurement of the IP decay starts.

The magnitude of the chargeability is related to how much polarizable material is present and the current density through mineral surfaces. The shape of the decay curve is related in a complicated way to the nature of the pore ions and the surface of the mineral. To characterize the shape of the decay, we typically measure the chargeability by averaging the instantaneous chargeability over a number of windows or gates (Figure 2). Because the initial decay rate is rapid and slows with time, the first gates are typically shorter than the last gates.

It is important in IP that the measuring electrodes do not polarize. A constant polarization is no problem as it can be measured before injection begins and subtracted. Suppose the potential difference in the ground between the two measuring electrodes is 1V and the input impedance of the meter is 10 MΩ. A leakage current of  $10^{-7}$ A will flow through the measuring electrodes and the meter. Depending on the contact area of these electrodes, they could polarize and create an instrumental IP response. With no metal target in the tank, we usually try measuring sequences with various metal electrodes (*Cu, Fe, Pb, Au, or Pt*) and then non-polarizing Ag – AgCl electrodes (we will not perform this test though).

We will use a gradient array, which would be rarely used in field IP, but since we are not concerned with induction on this small scale, we can use it. The gradient array is useful here because the average current density  $j$  is easy to calculate:

$$j = \frac{I}{wh}, \quad (1)$$

where  $I$  is the measured current,  $w$  is the width of the tank, and  $h$  is the water depth. The current density in the core may not be the same as the current density calculated for the tank, but we can ignore this difference.

As in the preceding labs, the apparent resistivity is  $\rho_a = Rk$ , where  $R$  is the measured resistance, and  $k$  is the geometry factor. With near-constant current density  $j$  (eq. (1)), the geometry factor is similar to the one in lab 4:

$$k = \frac{A}{L} = \frac{wh}{L}, \quad (2)$$

where  $w$  is the width of the tank,  $h$  is the depth of water in it,  $A = wh$  is the cross-sectional area, and  $L = MN$  is the spacing between potential electrodes. The tank is 0.4 m wide and if the water depth is 0.16 m (we may have a different depth, see [worksheet](#)) and the MN electrodes are  $L = 0.01$  m apart, and so the geometry ( $k$ ) factor for the gradient array is 6.4 m. In a Wenner geometry, the same  $k$  factor of 6.4 m is given by 'a' spacing of 1.02 m. Therefore, if we program a “Wenner” array with spacing of 1.02 m into the SYSCAL meter, it will report the correct apparent resistivity for our gradient array.

As a polarizable target, we will place a mineralized rock in the center of the modeling tank (Figure 3).



Figure 3. Mineralized rock used as target in IP tests.

## Assignments

- 1) **Set up the modeling tank** with current electrodes A and B near its ends. Use copper sheets on the ends of the tank and measure on potential electrodes at 1 cm apart. For a gradient array, the array center (pseudo-position of measurement) is located at the middle between the potential electrodes M and N.

On the SYSCAL resistivity/IP meter (see photo in lab #5), make the following settings:

- Set a programmable time of 2000 ms. This means a “square wave” in which the current is on for 2 s in one direction, off for 2 s, and then on for 2 s in the opposite direction.
- Set the  $V_{\text{delay}} = 250$  ms.
- Set recording time gates of the potential at the MN electrodes (the secondary) while the source current is off. Set this up for a delay of 50 ms before the first reading, followed by gate widths of 100 ms, 250 ms, 500 ms and 800 ms.

The above setup makes the gate center times equal 100 ms, 275 ms, 650 ms and 1300 ms. This means that the first gate averages the MN potential from 50 ms to 150 ms, centered on 100 ms. The second gate averages the MN potential from 150 ms to 400 ms, centered on 275 ms. The third gate averages the MN potential from 400 ms to 900 ms, centered on 650 ms. The fourth gate averages the MN potential from 900 ms to 1900 ms, centered on 1300 ms.

- 2) **Perform measurements** with MN array located at positions listed in [Table 1](#) in the [worksheet file](#). Record the center times and widths. Translate the pair of potential electrodes across the tank at 1 cm intervals from 0.02 m to 0.98 m. At each injection, record the SYSCAL record number in Table 1.

During each recording, SYSCAL will save the four partial chargeabilities M1 to M4, apparent resistivities  $\rho_a$ , and self-potential SP. These records will be downloaded at the end of

the lab, and you will have to **transfer these data into Table 1**. Carefully ensure matching record numbers, particularly in cases of erroneous or repeated records.

In the [zipped data file](#) locate file named like `IP_Data_Lab6_*.csv` (“comma-separated values”) and open it with Excel or any text editor. You can also comment out the first line in this file (column headers) with an ‘%’, and then this file can be loaded into Matlab as text (with option ‘`–ascii`’).

- 3) **Evaluate the column of “integral chargeability”  $M$**  in Table 1. This quantity is simply the sum of values  $M_1$  through  $M_4$ . Compare this sum to the values extracted from SYSCAL (column ‘ $M$ ’ in the .csv file)  
  
Note that this quantity  $M$  is only a proxy for the integral chargeability defined in Figure 2 and the lectures. This empirical  $M$  is measured in mV/V (i.e., is dimensionless), whereas the true integral chargeability is measured in units of time. This  $M$  also depends on the selected set of time gates.
- 4) **Graph the four chargeabilities  $M_1$  to  $M_4$**  and also  $M$  vs. the position of the center of the electrode array. The response of polarizable target should be evident.
- 5) **Select the type of chargeability which looks the best** (this will likely be  $M_1$ ) **and graph it** together with the self-potential (SP in the table) in a profile along the tank.
- 6) **Graph the chargeability** (readings  $M_1, M_2, M_3, M_4$ ) vs. centers of the corresponding time gates  $t_i$  at two positions of the array:
  - a. At one position well away from the target (but still responding to the target),
  - b. At the position where the chargeability selected in task 3) is the greatest. You may see that the decay does not go to zero but levels off at some finite value of a few mV/V. Normally, this would be adjusted by the instrument, so that the decay goes to zero.
- 7) **Repeat graphs 6a) and 6b) in log-log and “semilogy”** (logarithmic in Y axis only) forms.
- 8) **Comment on the following questions:**
  - a. What do the three graphs (linear-linear, log-log and semilogy) say about the behaviour of the decay?
  - b. What forms of decay would be given by straight lines in each of these displays?
  - c. Is the decay any different right on the target compared to off-target?

**For bonus points** (I’ll decide how many depending on the mistakes you made in similar tasks in lab 4): from the loglog and semiology plots, **estimate parameters  $\tau$  and  $\beta$**  in the exponential and power-law approximation for time dependencies of chargeabilities:

$$M(t) = M_0 e^{-t/\tau} \quad \text{and} \quad M(t) = M_0 t^{-\beta}.$$



**The remaining tasks are for GEOL334 only:**

**Analyse nonlinear IP and spectral IP measurements.**

At low current densities, the IP effect is linear, which means that doubling the primary potential also doubles the current and the secondary potential, so that the chargeability is constant. At higher current densities, doubling the primary may result in a secondary that does not quite double, so that the chargeability decreases slightly as the primary increases. This is called non-linear IP.

The cut-off between the linear and non-linear regions is called the exchange current density. In the field, the current density is usually less than the exchange current density, except very near the AB electrodes. Therefore, the chargeability is independent of current density and we do not have to pay too much attention to exactly what the current density is. The current density referred to here is actually the current density through each polarized grain. We are only measuring the primary current density - the current density that would exist at the position of the target if the polarizable target was not there, but the difference is minor.

Thus, although the exchange current density is likely insignificant in the field, it is still useful to measure and know it for the given target. To measure this current density, we will place the MN electrodes over the mineralized core.

- 9) **Perform chargeability measurements** in two gates  $M_1$  and  $M_2$  by using injection voltages of 50V, 100V 200V and 400 V. Place the results in Table 2 in the [worksheet](#).
- 10) Then, **insert the power resistor array** in series in the AB circuit to reduce the current, and measure again. Place results in Table 2.
- 11) **Graph the first-gate chargeability,  $M_1$ , vs. the current density on log-log scale.**

**Estimate the exchange current density** as the value of current density  $j$  at which the chargeability starts decreasing.

Next, set the measuring electrodes up centered over the target.

- 12) **Using the power function generator, measure the Spectral Induced Polarization response.** Transfer the results from the [zipped data file](#) obtained from the Picoscope into Table 3 in the [worksheet](#).

During the measurements, we applied the voltage on potential electrodes (MN) to channel 'A' on the Picoscope, and the voltage drop on a resistor connected in series with the tank was applied to channel 'B'. Therefore, channel 'B' represents the current in our data acquisition.

Look into images in directory `plots_from_Picoscope` showing the sinusoidal signals and correlations between channels 'A' and 'B'. Phase differences are seen by the ellipsoidal shapes appearing in the plots on the right.

From the data file, use file with extension '.dat' (IP\_Spectrum\_\*.dat). This is a simple text file with six columns. According to the connections explained above, use the following columns:

- Take frequencies of measurements from column 'Freq.' (second). This is the precise frequency measured from data. It actually equals the frequency set in the generator (first column).
- Take values from column 'Amplitude B', divide them by the resistance of the resistor, and obtain a column of current  $I$ . **The resistor was  $R = 1 \text{ k}\Omega = 1000 \text{ Ohm}$ .**
- Derive phases from column 'Phase B':  $\phi = -(\text{Phase B})$ . The minus sign is needed here because the program measures the phase of input 'B' relative to input 'A' but we need it the other way around.

- 13) **Calculate the apparent resistivity amplitude** column in Table 3 by using the geometry factor  $k$  in eq. (1).
- 14) **Graph (log-log) the amplitude of apparent resistivity vs. frequency.** You should see a low resistance or resistivity at high frequency and higher values at low frequency.

Depending on which target we used, we may not have been able to get high enough and low enough frequencies to see the amplitude plateau at high and low frequencies. The apparent chargeability is

$$M_a = 1 - \frac{\rho_{\text{high frequency}}}{\rho_{\text{low frequency}}}, \quad (3)$$

where  $\rho$  can be either resistance or resistivity.

- 15) **Estimate the apparent chargeability** by eq. (3). What is the difference between this value and what you got for the four chargeabilities in task 1) when the array center (MN) was over the target?
- 16) **On this graph, also draw a horizontal line** representing the apparent resistivity if just water was in the tank. This is the resistivity off-target in the profile we did in the first part of the lab (Table 1 in the worksheet). Is this value within the range of your spectral IP measurements, lower, or higher?
- 17) **Also graph the phase vs. frequency in (log-log) scales.** The phase is negative, and so change its sign for the log graph. There will be one, or maybe two peaks in phase depending on what we used as a target, and again the actual peaks could be outside our frequency range.
- 18) **Determine the characteristic or critical frequency  $f_c$ ,** (also called relaxation frequency in the lectures), which is the frequency at which the (negative) phase peaks.

An important characteristic of the IP response is the time constant, defined as

$$\tau_c = \frac{1}{2\pi f_c}. \quad (4)$$

- 19) **Calculate the time constant  $\tau_c$ ,** or two constants if you see two peaks. Is this  $\tau_c$  close to  $\tau$  in the “bonus” part of task 5) (if you did it)?

### ***Hand in:***

Brief answers to the questions highlighted in **bold** above with figures embedded in a Word or PowerPoint document by email.