11th SAGA Biennial Technical Meeting and Exhibition
Swaziland, 16 - 18 September 2009, pages 206 - 211

Interpretation of laboratory measured data: New information on pore structure and anisotropy using relating to the IP effect

V. Zadorozhnaya[1]**,** L.P. Maré[2]

1. Council for Geoscience, South Africa, valeriya@geoscience.org.za
2. Council for Geoscience, South Africa, leoniem@geoscience.org.za

ABSTRACT

Membrane polarization is a fundamental phenomenon of geophysical methods such as induced polarization (IP) method and frequency domain induced polarization method (FD IP). Determination of the characteristic parameters of induced polarization is required for studying physical properties of rocks. Mathematical modeling of a little known model of IP referred to as “induced polarization caused by constrictivity of pores” was conducted. Diffusion equations with specified boundary conditions that are different for current on- and off-times were used in the model. It was shown that membrane polarization occurs in all types of rocks if surface areas and transfer numbers are different for connected pores. During the polarization process all contacts between pores of different transfer numbers will be blocked and the electrical current will flow through the remaining canals. The new algorithm was tested on laboratory measurements. Several samples were selected: shale, mudstone, tillite, hematite, lava and manganese ore. Each theoretical model includes pores of more than 40 sizes sporadically distributed in the sample. The output of this stage of work is the pore size distribution in the sample, anisotropy and the relative amount of pores able to transport ions. It was shown that the size (pore radii) of pores can be different even when the porosity of samples is the same. The prevalent radii of investigated samples varied from 10 μm up to 1 μm. Laboratory data showed good agreement with theory and provided new information on the pore structure of rocks. Mathematical modeling provides reliable information of pores space of rocks, their dynamic porosity and permeability and transportation, especially of contaminant compounds

Key words: membrane polarization, modeling, pore, anisotropy

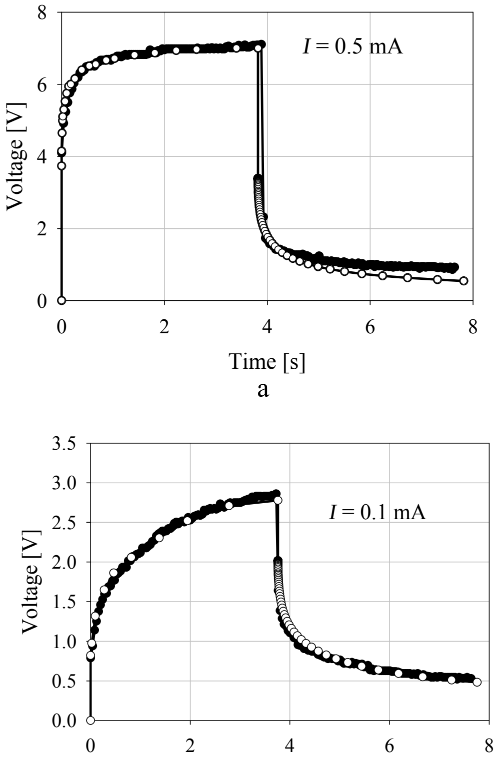
INTRODUCTION

The phenomenon of membrane polarization is fundamental to geophysical methods such as the time domain induced polarization (IP) method and frequency domain induced polarization method. Determination of the characteristic parameters of induced polarization is required for studying physical properties of rocks. The model of membrane induced polarization (diffusion coupling) caused by constrictivity of pores was proposed by D.J. Marshal and T.R. Madden (1959). Anderson and Keller (1964) were the first to use the applied diffusion (heat) equation to explain the phenomenon of membrane polarization in rocks. It was found that the diffusion of ions through the pores of rocks was presented as diffusion through a half limited capillary tube. This simplifies the equation to a homogeneous diffusion equation, following current switch-off. We can also refer to Schön, (1996), Pipe et al., (1987), and Titov et al., (2002) who brought some contributions to the theory of membrane polarization caused by constrictivity of pores.

Models of a half limited capillary tube as well as equivalent electrical circuit models have been widely used to describe electrode polarization parameters. It is also assumed by many geophysicists that the IP processes at current switch-on (time-on) and switch-off (time-off) are the same and that there is a linear dependence between the applied electrical current and the IP amplitude. Practically all existing instruments register transient decay during time-off. However, the results of laboratory measurements very often show the opposite (Zadorozhnaya, 2008). It was shown that there is no linear dependence between the applied electrical current and the IP amplitude. Laboratory measurements also show that IP processes at time-on and time-off are different. This research intends to develop the model of polarization by constrictivity of pores by giving a mathematical consideration of the process and discusses the physical phenomena occurring during time-on and time-off of applied electrical current. Diffusion equations with specified boundary conditions different for time-on and time-off have been used to develop the base of this model (Zadorozhnaya and Hauger, 2007). Our aim is also to provide modeling of pore structure and obtain information of pore size distribution and anisotropy of rocks.

METHOD AND RESULTS

The theoretical consideration of this new model of induced polarization caused by constrictivity of pores is discussed by Zadorozhnaya and Hauger (2007) and Zadorozhnaya (2008). The diffusion equations with specified boundary conditions have been used for mathematical modelling of IP effect. To describe the processes of IP at time-on, a homogenous equation has been applied; however, for the time-off case, additional sources of ions may occur at the boundary of connected pores with surrounded capillaries. That is why an inhomogeneous equation is used to describe this phenomenon. Figure 1 demonstrates an example of the comparison of mathematical modeling to laboratory data.



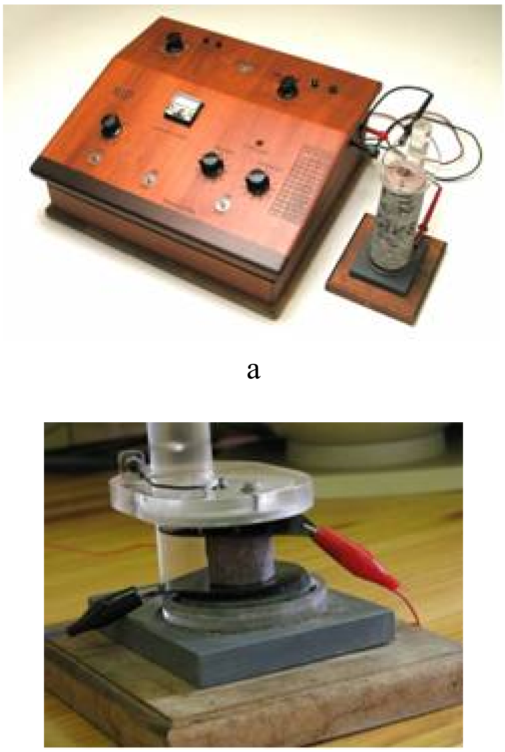
a

b

Figure 1. Mathematical model of membrane polarization of a sample of sandstone (bold dots) and experimental data (circles)

A model of pore spaces distribution for a sample can only be accepted if theoretical and laboratory data fit at least for three applied currents Let us note that in this case model of pore space of the hole sample is not equivalent of model containing three connecting capillary. So let us introduce the word "cell" for the simplest combination of three capillaries, each cell are characterized by different size. Usually 35-45 cells are used to describe a model of pore spaces for each sample; computing time of any model takes 2-3 seconds.

Physical modeling have been performed at the CGS for several years using the instrument RIP built by M.E. Hauger (Figure 2a). The instrument contains a holder with two silicon electrodes (Figure 2b). The sample of rock is located between the electrodes. At time on both electrodes serve as transmitter electrodes, at time off – as receiver electrodes.



a

b

Figure 2. (a) RIP instrument for measurements of IP effect and (b) holder containing a sample of rock and silicone electrodes

In order to prove our theory we must first of all determine whether the conductive silicon pads used by the Council for Geoscience for electrodes on their RIP resistivity-induced polarization instrument is subject to any self induced polarization, several tests were conducted:

-To eliminate the possibility that the water might have an influence on the results, the test was to place two dry aluminium discs (2 mm thick each) between the silicon pads. The conduction was determined by measuring the volts at different applied currents;

-The next step was to add a 6 mm thick non-conductive perspex block between the aluminium discs. The aluminium discs were connected with an electric wire and the measurements repeated.

-To simulate rock samples of different resistance, while not adding the influence of porosity and mineralization, resistors of varying magnitude (558 Ωm; 38 kΩm; 68 kΩm; and 8.8 MΩm) was connected between the aluminium discs and the measurements at different applied currents repeated.

For all three experiments if the current is strong enough then the misfit can reach 45% (but not 200-300% as was observed on laboratory measured data). However if the current decreases the dependence of current to amplitude becomes linear. No IP effect was observed.

To prove our theoretical consideration some samples were selected. These are Dwyka shale, shale with dropstones, mudstone, tillite, hematite, lava and manganese ore (Figure 3).

Figure 3. Photo of samples CP813-1C – shale, CP813-2C – shale with dropstones, CP813-2C – mudstone, CP813-4B – tillite, CP813-5A – hematite, CP813-6A – lava, CP813-7C– Mn-ore

Figure 4 shows an example of the mathematical modeling of mudstone sample for three values of electrical current. This figure demonstrates the good agreement of mathematical and experimental data for the calculated model of pores space.

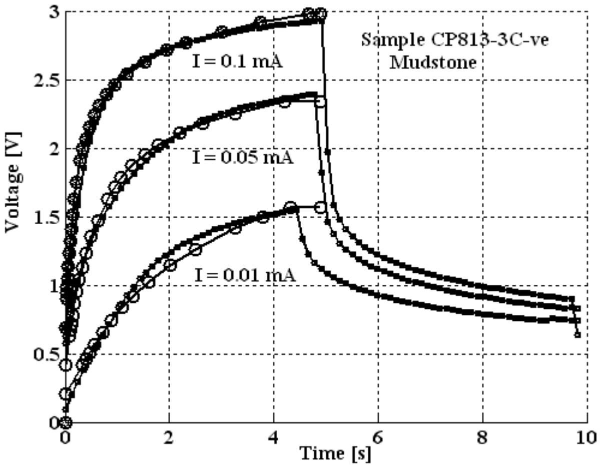


Figure 4. Mathematical model of membrane polarization of sample (bold dots) and experimental data (circles)

Three important parameters characterize the samples: range of pore radius, prevalent pore radius and relative amount of “shaped” pores of total pore space or effect of anisotropy. “Shaped” pores are real pores; they are larger than surrounding channels. The radius of maximal number of pores of same size is the prevalent radius. The amount of “shaped” pores $R_{sh}=V_{sh}/V_{total}$ is that part of pore spaces occupied by “shaped” pores. Here V_s is the volume occupied by “shaped” pores and V_{total} is the total volume of pores. Another part of the pore space is occupied by “straight” pores $R_{st}=(V_{total} - V_{sh})/V_{total}$, i.e. pores where the IP effect can be neglected due to small differences of transfer numbers of the connected pores. V_{total}/V_{sample} is the porosity of the samples. The effect of anisotropy R_P can be regarded as the ratio of $R_P= R_{sh\_al}/ R_{sh\_ve}$, where indexes indicate the direction of current flow through the sample: along z (*al*) and along y (*ve*). However the ratio R_P must be more then 1, that is why R_{sh} in nominator is always bigger than R_{sh} in denominator (as well as ρ_n and ρ_l) whether it is R_{sh_al} or R_{sh_ve}.

The last parameter is the well known coefficient of anisotropy:

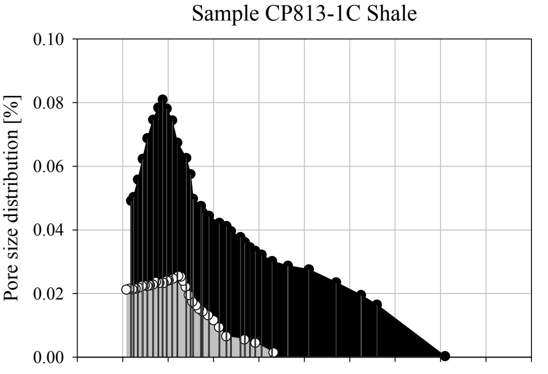
$$\lambda = \rho_n / \rho_l = \rho_{al} / \rho_{ve}, \qquad (1)$$

where $\rho_n = \rho_{al}$ is resistivity perpendicular to the layers, $\rho_l = \rho_{ve}$ is resistivity parallel to the layers (platey).

Figure 5 demonstrates pore size distribution obtained due to mathematical modeling of the IP effect for some samples. The range of pore radii in shale, shale with dropstones and mudstone are quite large (from 2 to 12-17 μm). Pore radii in the Mn-ore, hematite and especially lava are more unified in size and narrower (2-7 μm). This parameter is important for discrimination as, for example, the porosity of shale and shale with dropstones are nearly the same, 7.58 % and 8.19 %. The shale with dropstones contains more or less the same range of pores (2-17 μm).

Prevalent pore radii of the shale with dropstones and shale are 11-14 μm and 3.5-4.1 μm respectively. Obviously, having the same porosity, shale with dropstones can accumulate small amount of fluid in the pores; however, the amount of free water in shale will be considerably less.

Another parameter is the prevalent pore radius. Figure 6 demonstrates the prevalent pore radii of all samples. Each segment of Figure 6 contains two bars for measurements along z and along y. These bars characterize the anisotropy of the rocks.



a

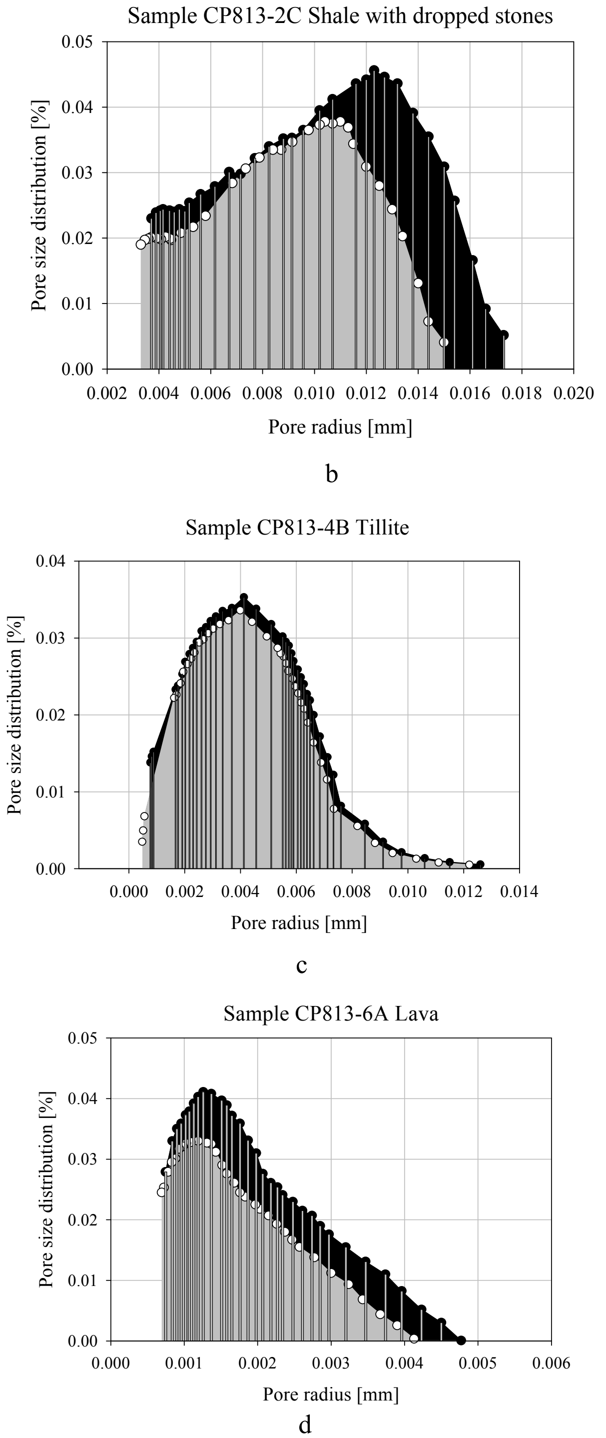


Figure 5. Pore size distribution of selected samples

Obviously rocks with sporadically distributed structure have the same prevalent radius of pore with different direction (lava, mudstone, tillite and hematite). Rocks with thin platey structure (shale, Mn-ore) are characterized by different pore distributions along different directions and different prevalent radii as well. Shale with dropstones demonstrates the largest prevalent radius (12 µm). The prevalent pore radius of the lava is very small 1.2 µm.

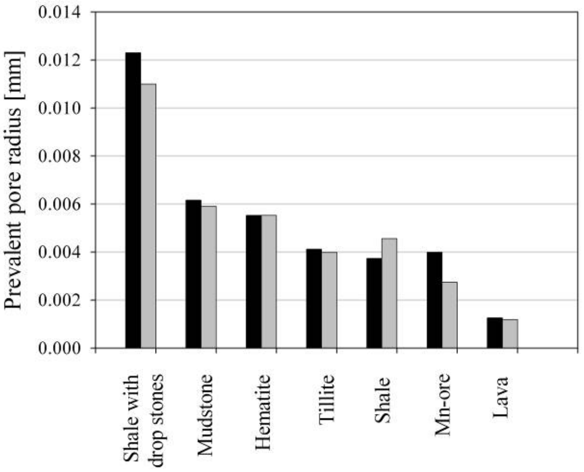


Figure 6. Prevalent radius of pores in the samples for two perpendicular directions of current flow

SHORT SUMMARY

Here we discuss the results obtained from mathematical modeling of the pore structure of investigated rock samples.

<u>Shale</u>. Range of pore radius is 2 µm up to 18 µm, while the prevalent pore size is only about 3.5-4.1 µm for both directions. These are anisotropic sedimentary rocks, due to platey clays minerals. Parameter of shaped pore anisotropy reach $P_P = 2.24$, $\lambda = 1.36$.

<u>Shale with dropstones</u>. Range of pore radius is 3 µm up to 17 µm; however, prevalent pore size is only about 0.0123 µm and 0.0110 µm. These are slightly anisotropic sedimentary rocks and the dropstones possibly block the pore channels with clay. Parameter of shaped pore anisotropy reach $P_P = 1.123$, $\lambda = 1.049$.

<u>Mudstone</u>. Range of pore radius is 2 µm up to 12 µm, prevalent pore size is practically the same: 6.16µm and 5.91µm. These are slightly anisotropic sedimentary rocks due to presence of clays materials. Parameter of shaped pore anisotropy is $P_P = 1.076$, $\lambda = 1.091$.

<u>Tillite</u>. Range of pore radius is 1 µm up to 12 µm, but the amount of large pores are less than in mudstone. Prevalent pore size is also smaller and equal for both directions of sample: 4.12 µm and 3.99 µm. No evidence of anisotropy in the conglomerate of finer and larger debris .$P_P = 1.049$, $\lambda = 1.015$.

<u>Hematite</u>. It was more difficult to find a suitable model for the hematite samples. The range of pore radii are 1 µm up to 9-10 µm, but prevalent pore size of the sample is 5.53 µm. Sedimentary origin of hematite provide very strong anisotropy, $P_P = 1.34$, $\lambda = 1.51$. The layered structure of hematite can be easily distinguished in the sample (Figure 3).

<u>Lava.</u> The smallest pores have been predicted in the lava sample: 0.5 µm – 4.5 µm, prevalent pore radii are ~ 1.2 µm. Sporadically distributed pores in the rocks cause very small effect of anisotropy: $P_P = 1.07$, $\lambda = 1.068$.

Mn-ore contains very small pores of 1-5 μm or more. The effect of anisotropy is also relatively small: P_P = 1.168, λ = 1.08. This is the only rock type where the prevalent pore radii are different for the different directions: 3.99 μm and 2.74 μm. It suggests that during the sedimentation and lithification of manganese bearing layers normal stress exceeded lateral stress.

Figure 7 demonstrates overlapping pore size distribution for all the samples. Only maximal data of the two measured directions were selected. This figure summarizes the pore size distribution of our samples and gives a good impression of the differences in pore structure. Coloured bars are separated to improve visualization of hidden data. This figure clearly demonstrates different pore distributions within the respective rock samples.

CONCLUSIONS

Mathematical modeling of a little known model of IP referred to as “induced polarization caused by constrictivity of pores” was developed. The new algorithm was tested on laboratory measurements of selected samples of Dwyka shale, shale with dropstones, mudstone, tillite, hematite, lava, and manganese ore. Mathematical modeling of all samples has been performed for 3 values of electrical current to reach one reliable pore space model. Three important parameters are characterizing the samples: range of pore radius, prevalent pore radius and relative amount of “shaped” pores of total pore space. Shale with dropstones contains the largest pores whilst lava contained the smallest, mudstone, and tillite have no anisotropy. Mathematical modeling provided reliable information of the pore spaces of rocks, their anisotropy and provided a direction for further study of permeability and transportation, Mathematical modeling allows us to obtain information about anisotropy of pore spaces. Shale and manganese ore demonstrated the maximal anisotropy along perpendicular directions of current flow, while hematite, lava, mudstone, and tillite have no anisotropy. Mathematical modeling provided reliable information of pores’ space of rocks, their anisotripy and provided a direction for the further study of permeability and transportation, especially for contaminant compounds.

REFERENCES

Anderson, L.A., and G.V. Keller (1964), A study in induced polarization. *Geophysics* **24**, 5, 848-864

Marshal, D.J., and T.R. Madden (1959), Induced Polarization, a Study of its cases, Geophysics **24**, 4, 790-816.

Pipe H., L. Riere, and J.R. Schopper (1987), Theory of semi-similar network structures in sedimentary and igneous rocks and their investigations with microscopical and physical methods, *Journal Microscopy* **2**, 121-147.

Schön J. (1996), *Physical Properties of Rocks. Fundamental and Principles of Petrophysics. Handbook of Geophysical Exploration. Seismic Exploration. Volume 18.* New York, Pergamon, Press, Inc., p.583. ISBN 0 08 0410081.

Titiov K., V. Komarov, V. Tarasov, and A. Levitski (2002), Theoretical and experimental study of time domain-induced polarization in water saturated sands, *Journal of Applied Geophysics*, **50**, 417-433.

Zadorozhnaya V.Yu., and M.E. Hauger (2007), Membrane polarization on rocks and measured resistivity. **In:** Spichak, V.V. (ed.), *Earth Elecrtomagnetic Investigations. III International School-Seminar on Electromagnetic Sounding of the Earth (EMS-2007),* Moscow, Russia. Lecture, 149-167.

Zadorozhnaya, V.Yu. (2008), Resistivity measured by direct and alternating current: why are they different? Advances in Geosciences, **19**, 45-59.

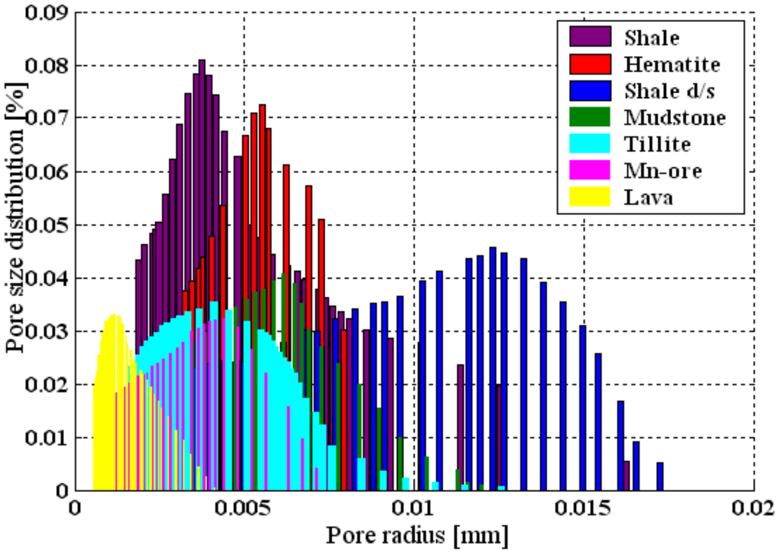


Figure 7. Overlapping pore size distribution for all the samples demonstrating the differences in pore structure.