Процессы, происходящие в горных породах при наложении электрического тока и разности потенциалов: вызванная поляризация

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Outline

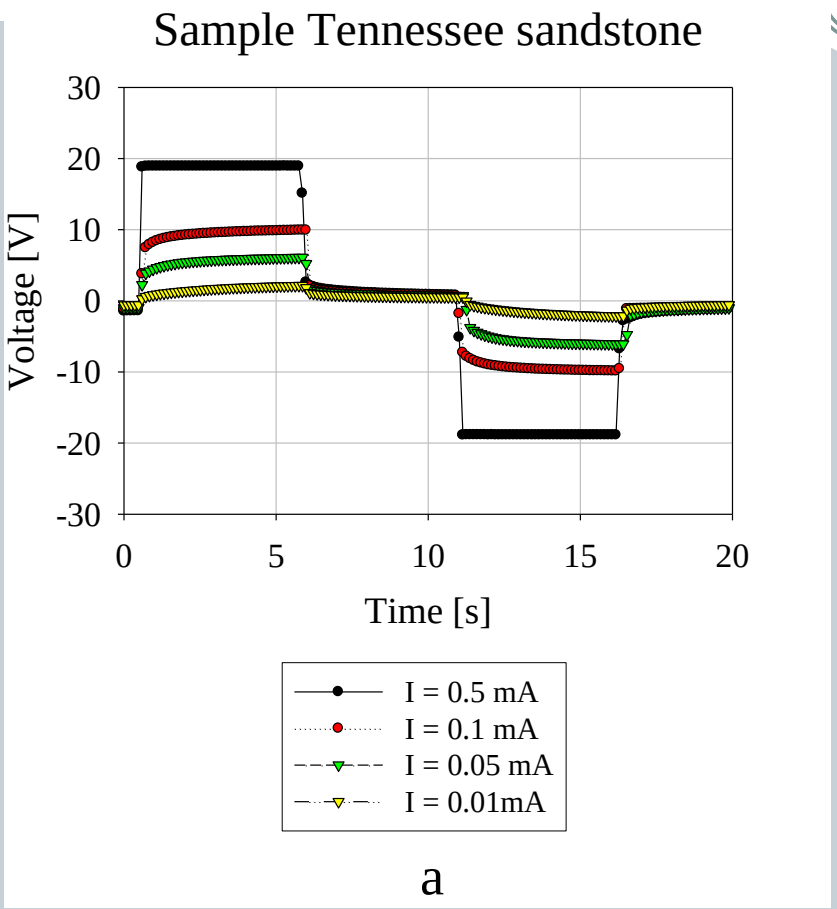
Исследование эффектов вызванной поляризации

1. Не линеарные процессы
   мембранная поляризация
2. Линеарные процессы:
   электроосмос
   эффект Максвелла-Вагнера
   электролитический эффект
3. Комбинированные эффекты:
   электроосмос + мембранная поляризация

Types of IP effects

- The effect of Induced Polarization (IP) occurs in the rocks due to distribution of ions in the pores when continuous electrical current is applied. There are several types of induced polarization effects observed in geophysical surveys and laboratory measurements on samples. These are
- electrolytic polarization
- Maxwell-Wagner effect
- electroosmosis
- and membrane polarization.

Начало исследований



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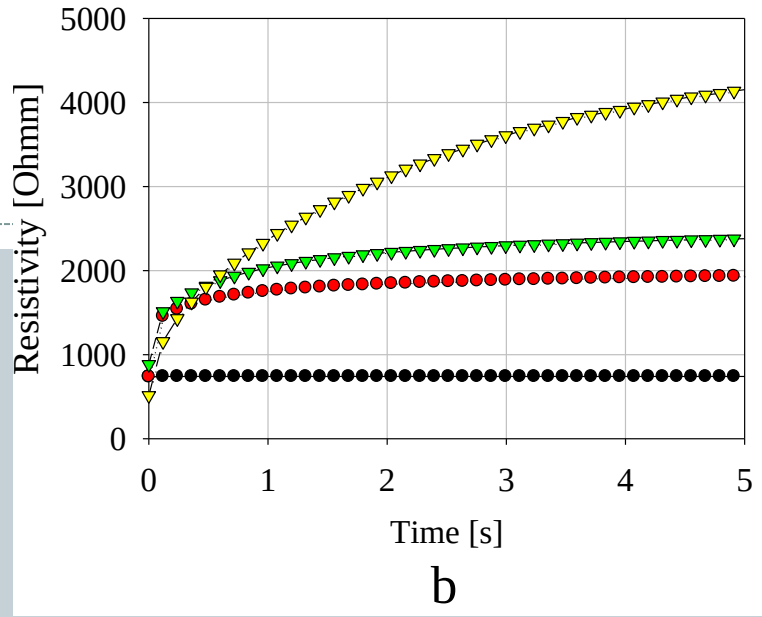

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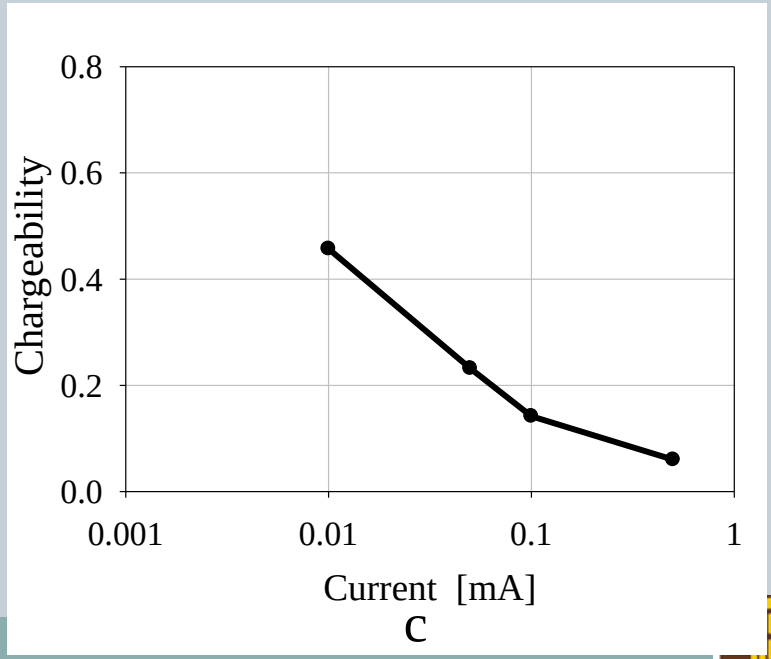


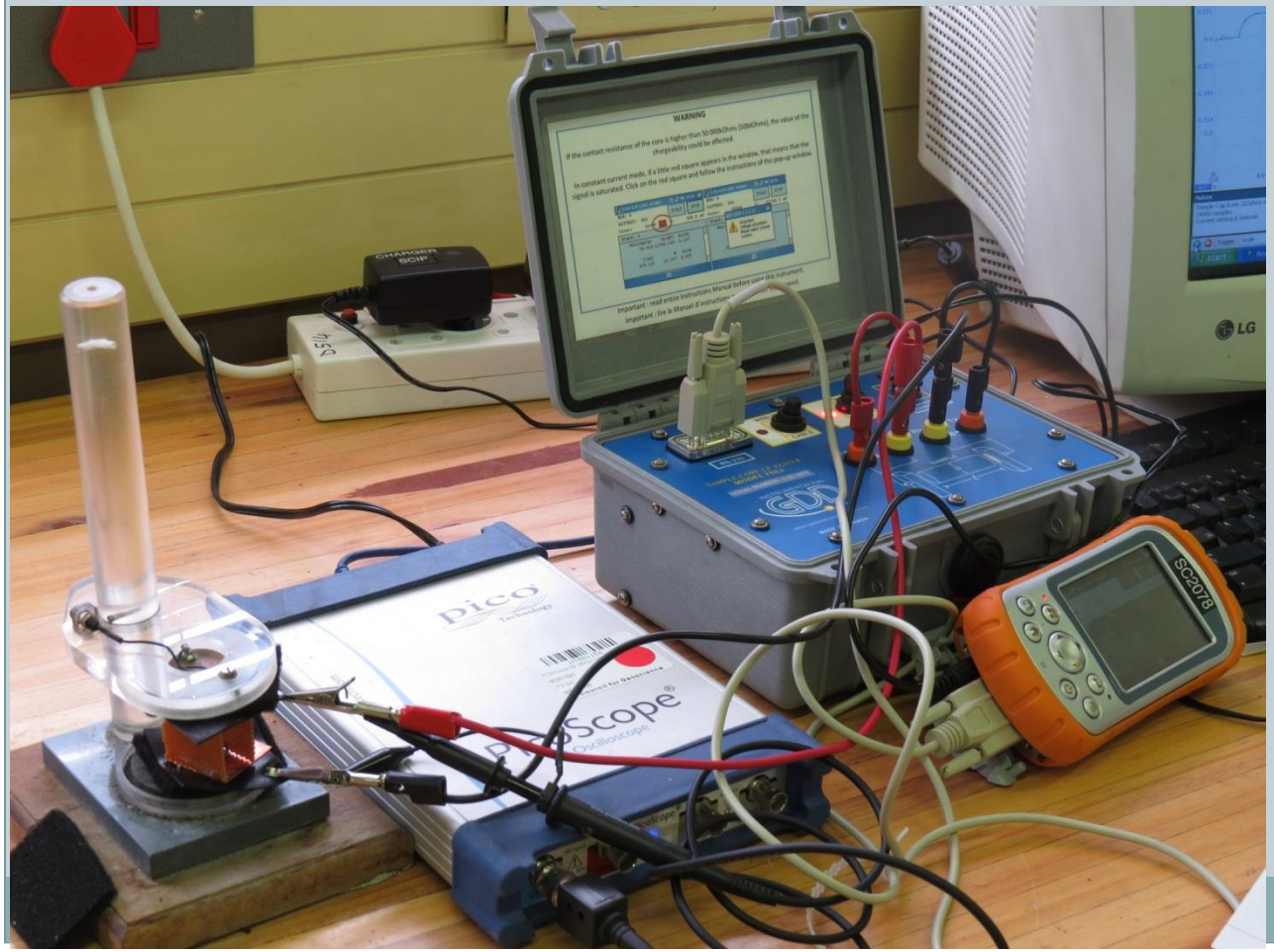
c

Очевиден не линейный процесс.
Модель время от времени критиковалась, в основном понялось на аппаратуру
Однако…..

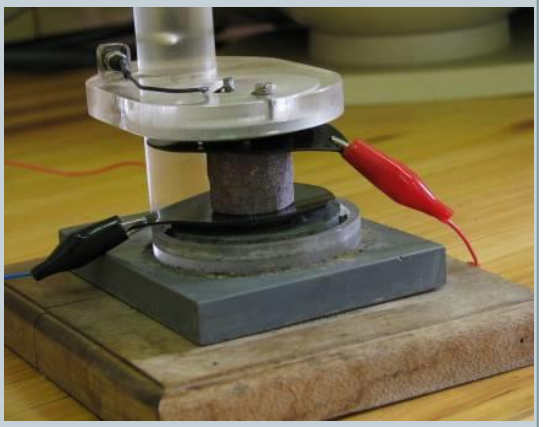
Наши инструменты

SCIP Tester
(Core Sample IP Tester)

GDD, Canada, www.gdd.ca



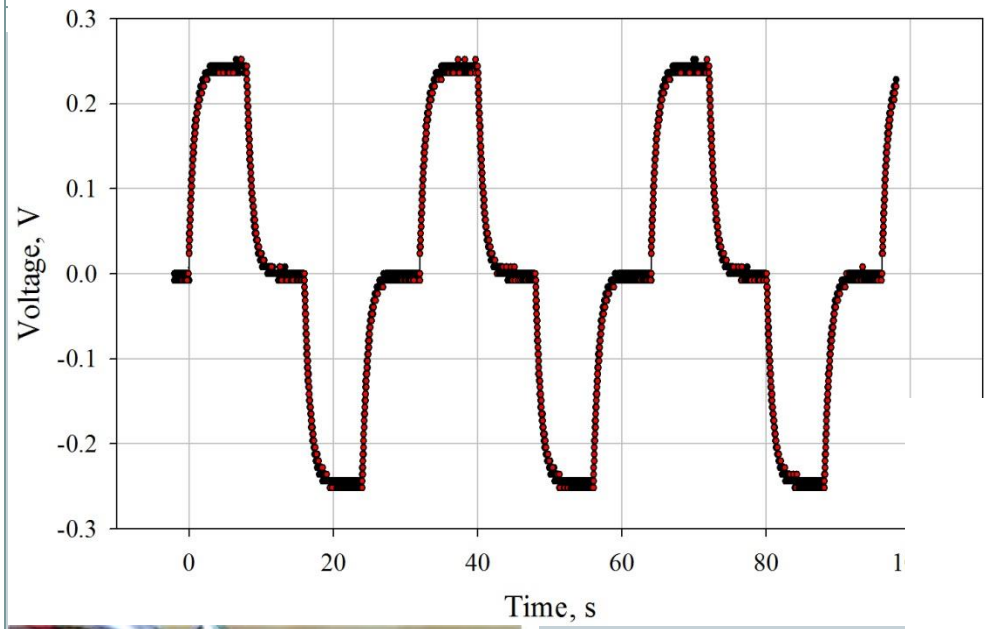
RIP

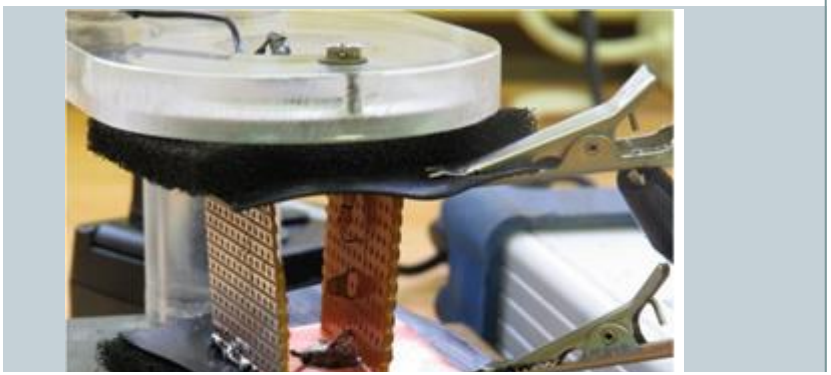


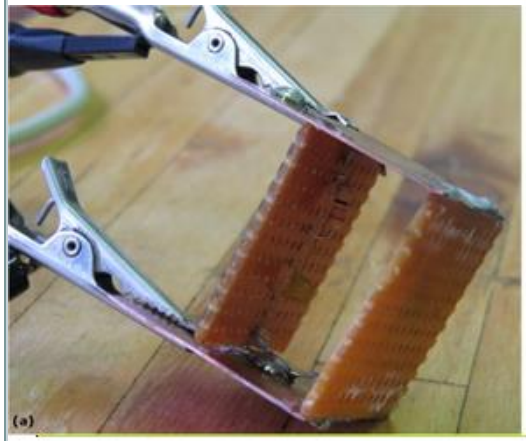
Holder for solid samples

Тестирование аппаратуры и электродов

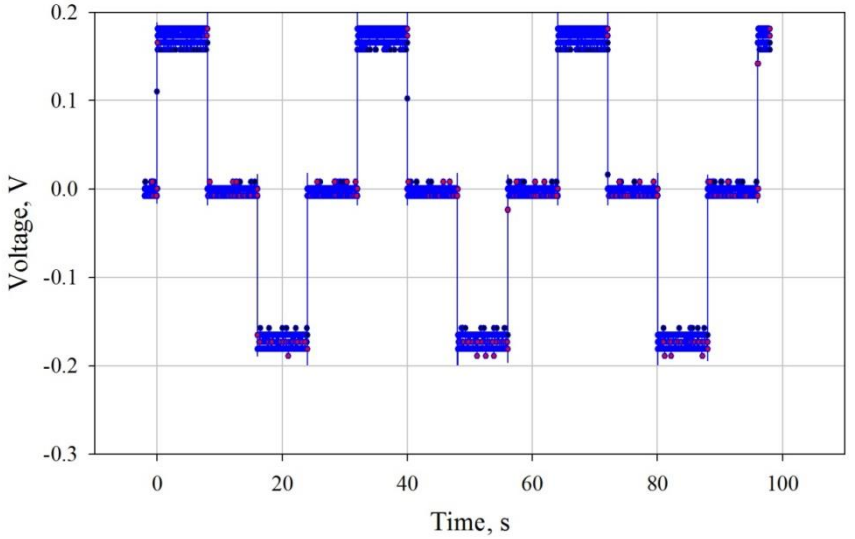
Cap and 1MOhm capacitor,
connecting directly to the copper plate (black) and silicon electrodes (red)





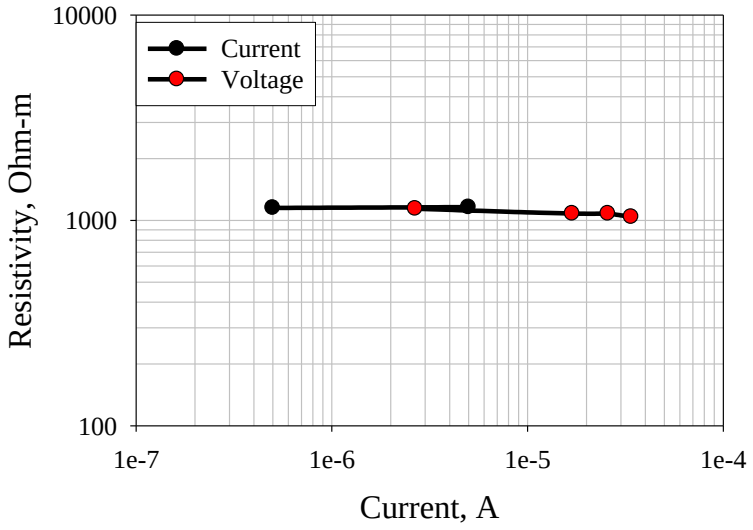


Cap and 3.3KOhm capacitor,
connecting directly to the copper plate (blue) and silicon electrodes (red)
Current 50 μA

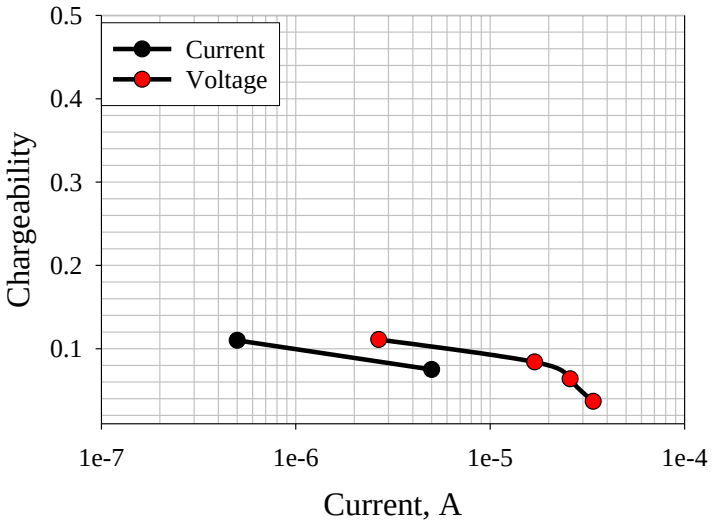


Однако существуют примера и линейного эффекта, например в рудах.

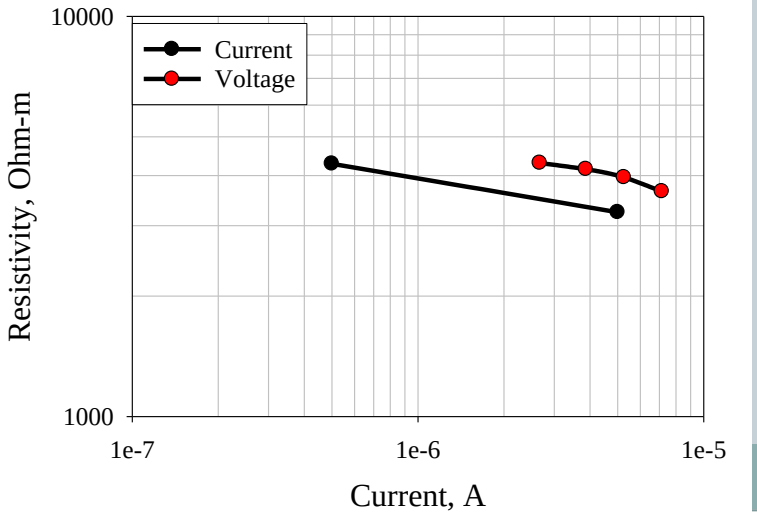
C14302 Ferrigenous vein



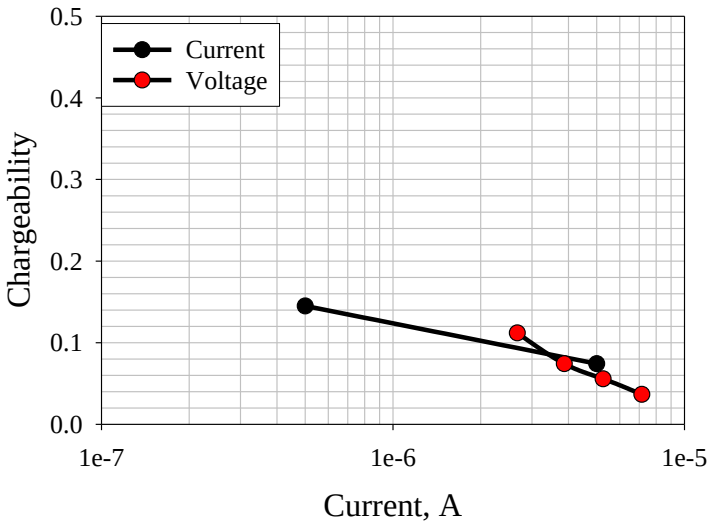
C14302 Ferrigenous vein

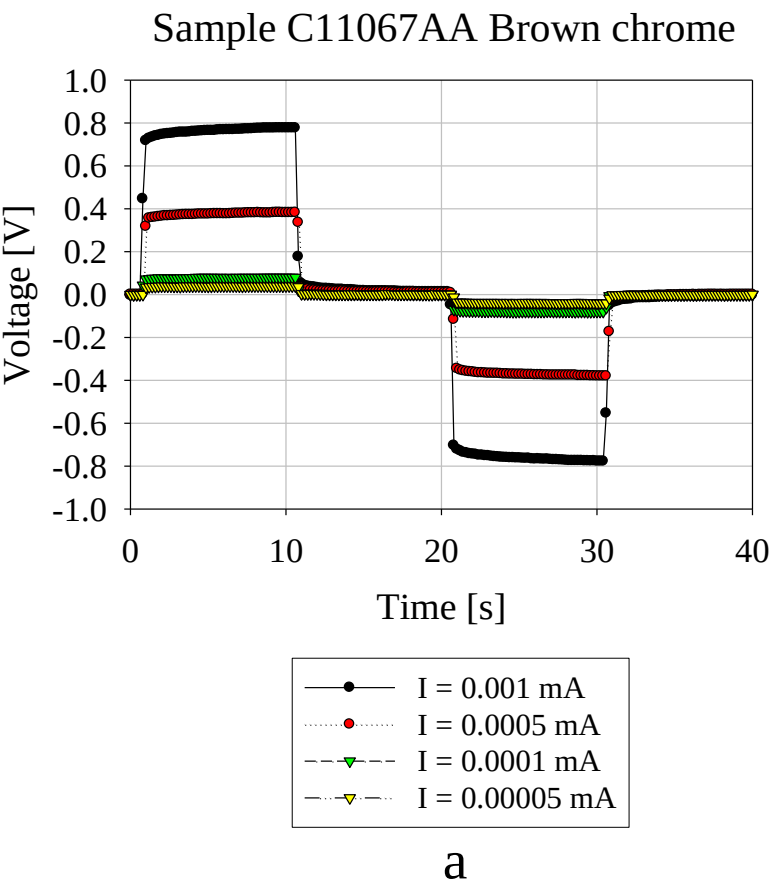


C14301 Ferrigenous quartz vein, brecciated



C14301 Ferrigenous quartz vein, brecciated





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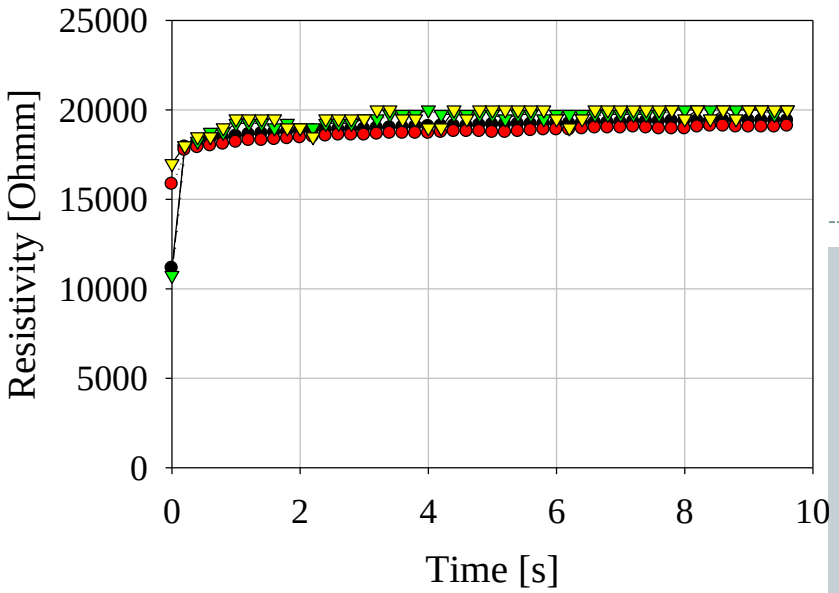
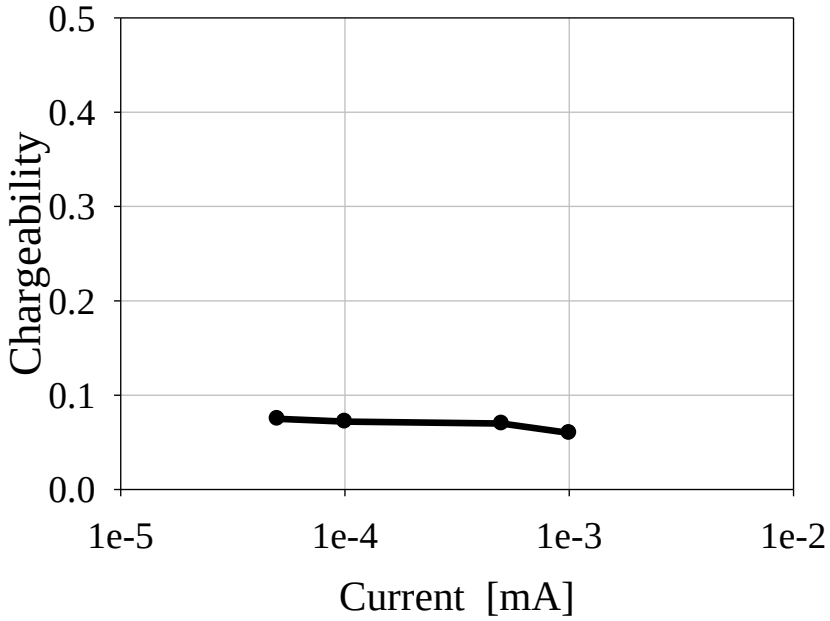


b

Известный нам закон Ома работает



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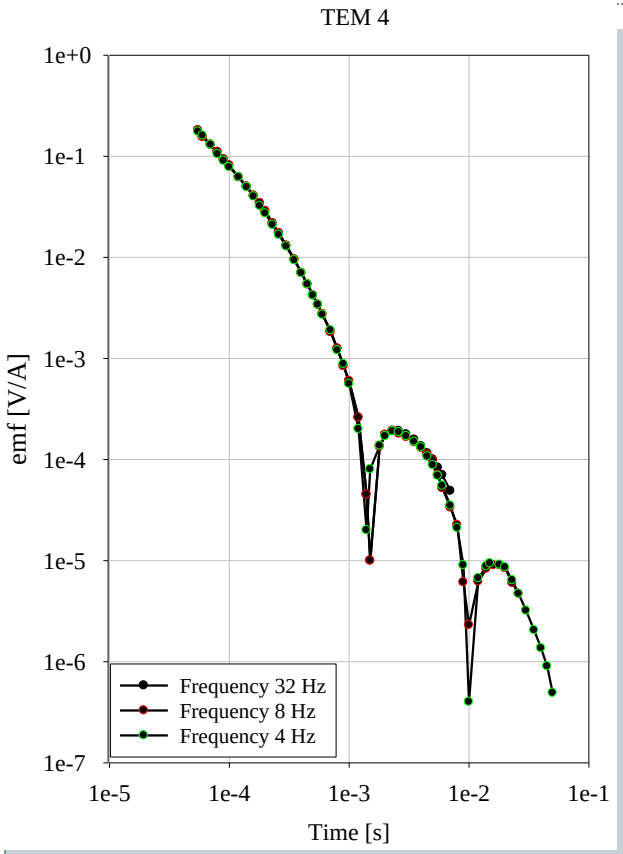
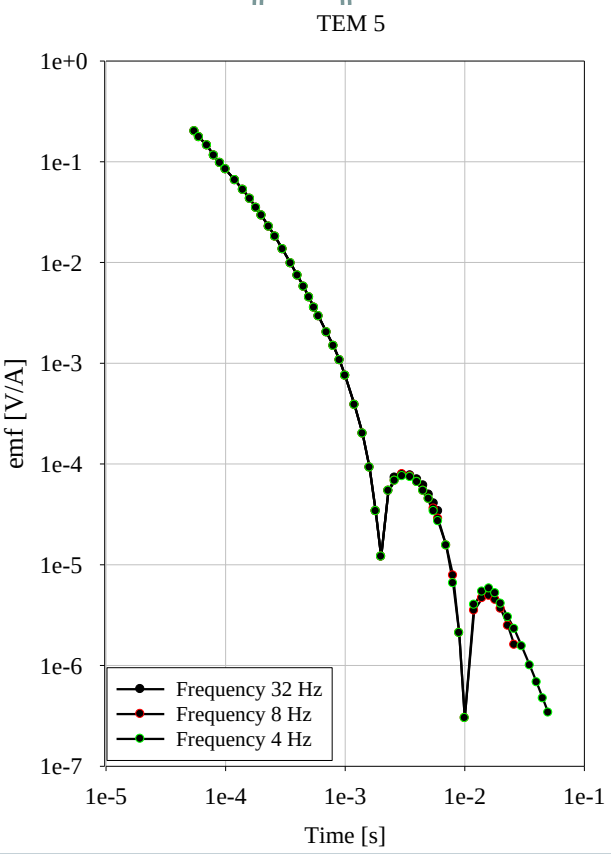
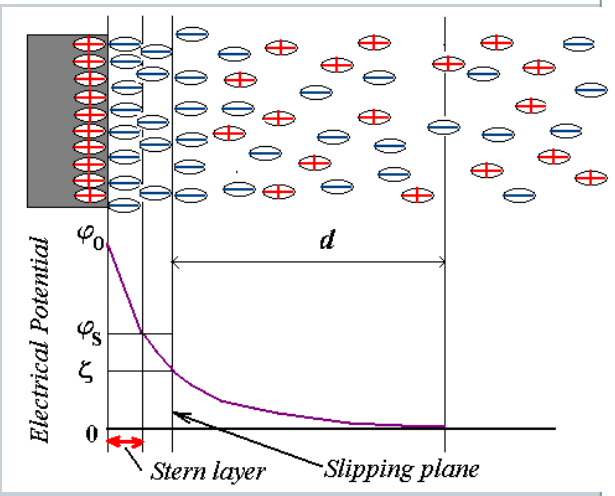
Второй пример линейной поляризации – электроосмос, обусловленный присутствием двойных электрических слоев на контактов пор и флюида







Caused by double electric layers

Helmholtz Smolihowsky equation

$$I = \alpha \cdot grad\, V$$

Измерения производились на частотах токового сигнала в 32, 8 и 4 Гц, то есть длина токовых импульсов составляет 0.03125с, 0.125 с и 0.25 с

EO type of polarization is opposite to the current flow. There is linear dependence of water velocity and electrical current and does not depends on duration of current pulses provides be TEM transmitter.

- Mechanism of electroosmosis effect is described by Helmholtz-Smoluhowsky equation:

$$I = \frac{\varepsilon \varepsilon_0 \zeta}{4\pi \sigma_f} V_f,$$

- where I is an secondary electrical current arising due to water flowing through pore, ε is dialectical permittivity, ε_0 is the electric constant $(1/36\pi 10^9\ F/m)$, ζ is a zeta potential (in V), ϱ_f is conductivity of fluid filled pore (including double electrical layers), V_f is velocity of water flowing in the pore (in m/s).

Обычно используемая формула для инверсии

В частотной области

$$\rho(\omega) = \rho_0 \left\{1 - \eta \left[1 - \frac{1}{1 + (i\omega\tau)^c}\right]\right\},$$

Во временной области

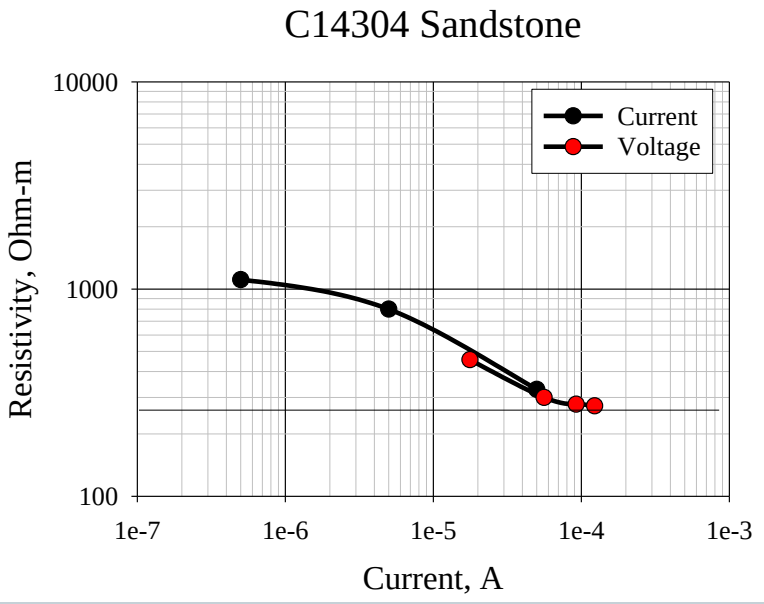
$$\sigma(t) = \frac{\sigma_0}{1+\eta}\left[1 - \eta \cdot exp\left(-\frac{1-\eta}{\tau}\ t\right)\right],$$

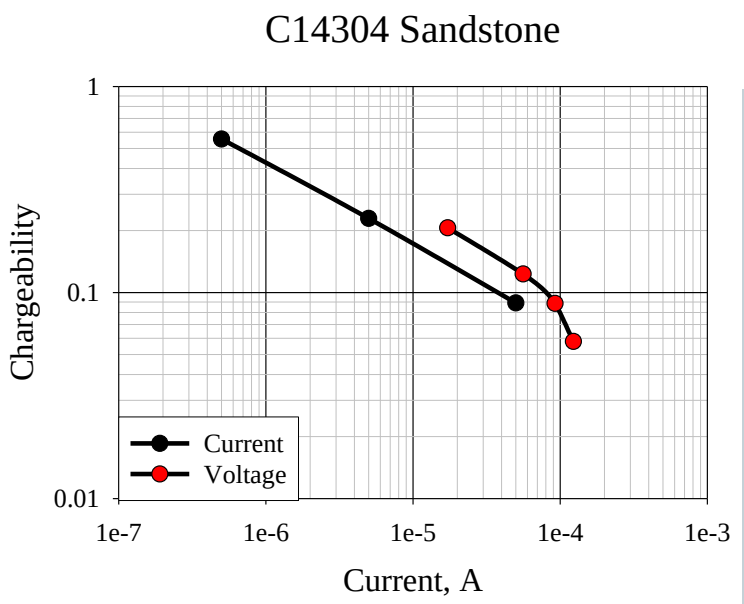
Физический смысл параметров поляризации

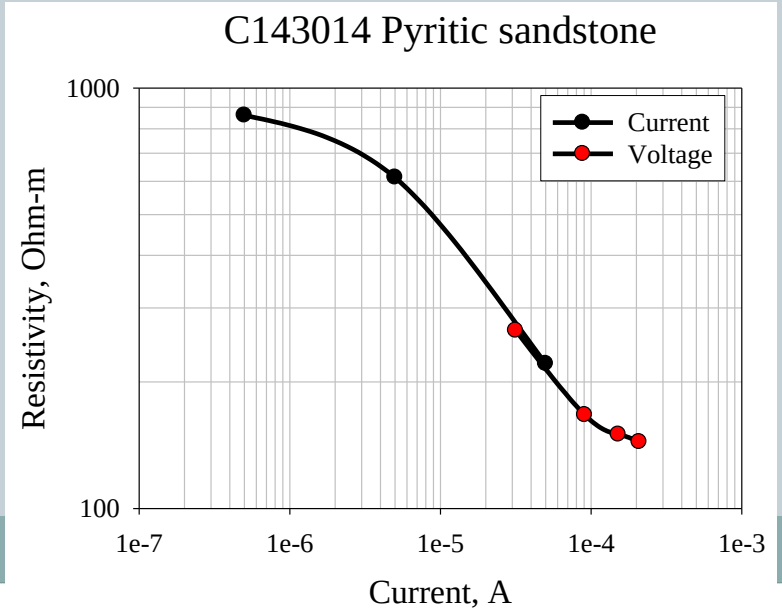
- Hallbauer–Zadorozhnaya and Bessonov (2002) showed that the chargeability η can be written as:
- $$\eta = \frac{\sigma_\Delta}{\sigma_\chi},$$
- his means that η is the ratio of surplus electrical conductivity to the electrical conductance of the pore fluid. According to (5) the values of polarizability η can be in the range from 0, for sediments with large pore radiuses when the contribution of the EDL is negligible, to 1, in sediments such as some types of clay, where the pore radii are very small where $\sigma_\Delta \approx \sigma_\chi$ (all anions are immobile and represent the dense and diffuse layers and all cations are dissolved in a fluid and able to carry electrical current).
- Hallbauer–Zadorozhnaya and Bessonov (2002) also showed that the time decay depends on square of pore radius r:
- $$\tau = \frac{(1-\eta)r^2}{5.78\nu_k},$$
- where ν_k is dynamic viscosity of fluid.

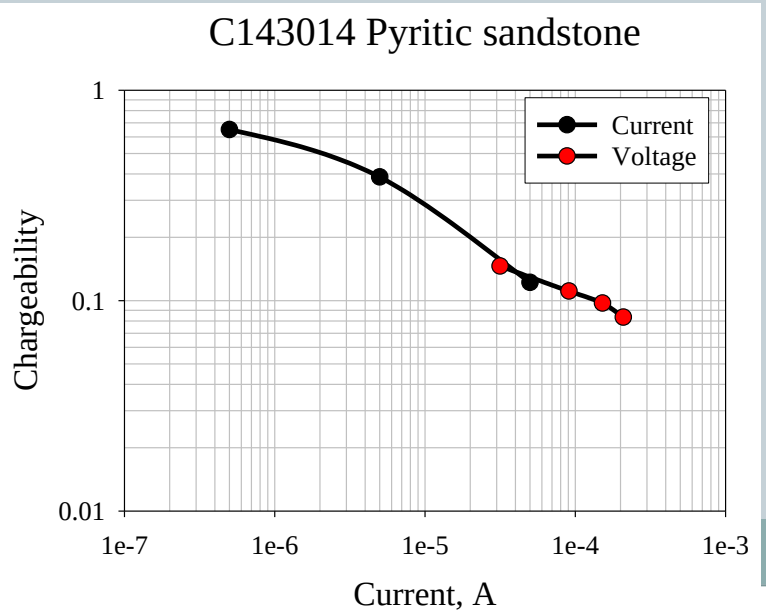
Table 1: 1D petrophysical models of soundings 4, 5 and 6					
Sounding	# of layer	ρ Ohmm	Thick-ness m	η	τ s
4	1	18	13	2.8e-3	0.0125
	2	3.5	25	-	-
	3	0.75	25	-	-
	4	0.5	45	-	-
5	1	18	13	2.7e-3	0.01
	2	3.5	25	-	-
	3	0.75	25	-	-
	4	0.8	45	-	-
6	1	18	13	2.9e-3	0.02
	2	1.7	22	-	-
	3	0.5	35	-	-
	4	0.7	35	-	-

Песчаники, нелинейная поляризация. Какая? Мамбранная

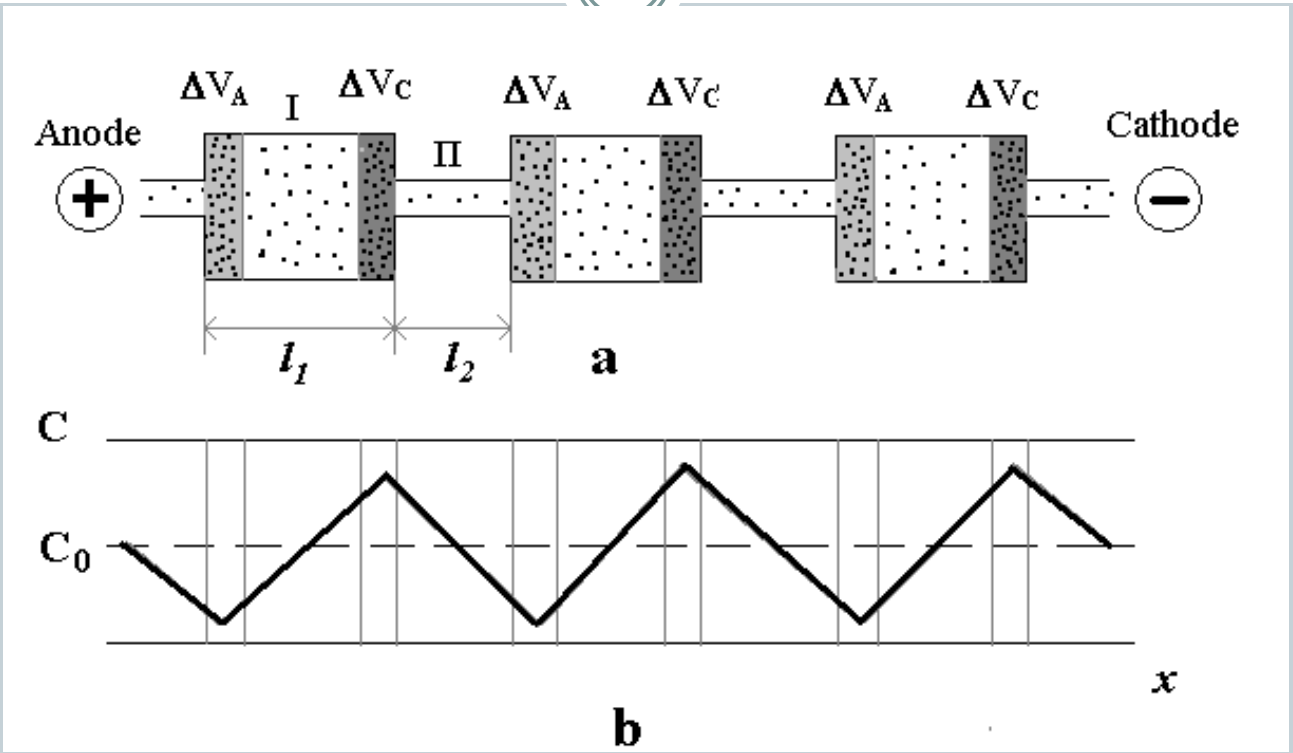








Model of membrane polarization caused by constrictivity of pores and concentration distribution of ions in the pores



Our approach is based on

1. It was not linear dependence between IP measured resistivity and applied electrical current;

2. Boundary conditions for time on are linear;

3. Processes of IP at time on and time off are not the same

Одномерное тепловое уравнение (Второй закон Фика):

$$\frac{\partial u}{\partial t} = a^2 \frac{\partial^2 u}{\partial x^2}, \qquad (1)$$

где u концентрация электролита, $a^2 = D$ коэффициент диффузии.

Граничные и начальные условия

$$u\Big|_{t=0} = \varphi(x).$$

$$u\Big|_{x=0} = \psi_1(t), \quad u\Big|_{x=l} = \psi_2(t)$$

Граничные условия:

Граничные условия линейны от времени:

$$\psi_1(t) = u_{\Delta k2}(t) = \frac{I^2 \mathrm{M}_{0k} t}{FzDS_1S_2\sigma_k}\left(n_{k2} - n_{k1}\right)$$

$$\psi_2(t) = u_{\Delta k3}(t) = \frac{I^2 \mathrm{M}_{0k} t}{FzDS_1S_2\sigma_k}\left(n_{k1} - n_{k3}\right)$$

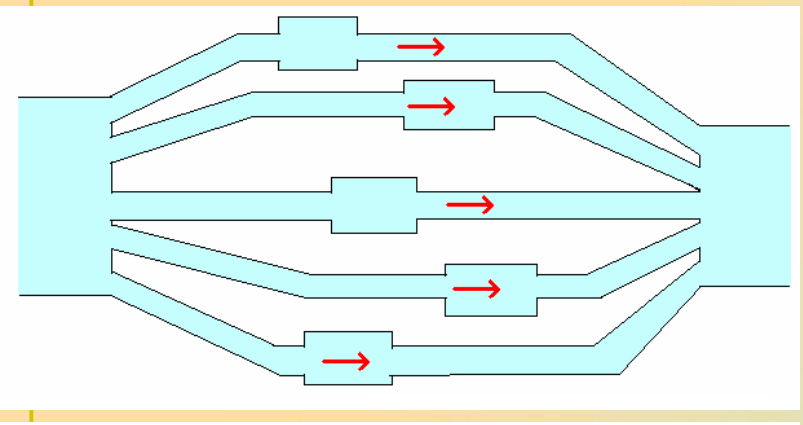
Но не линейны от тока.

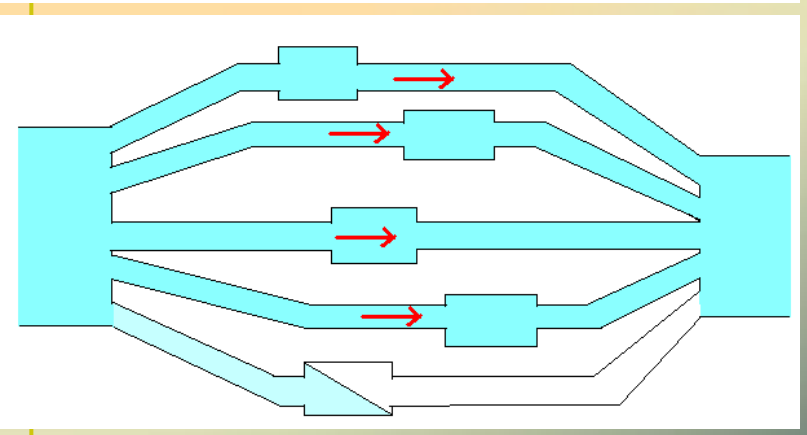
Time limitation

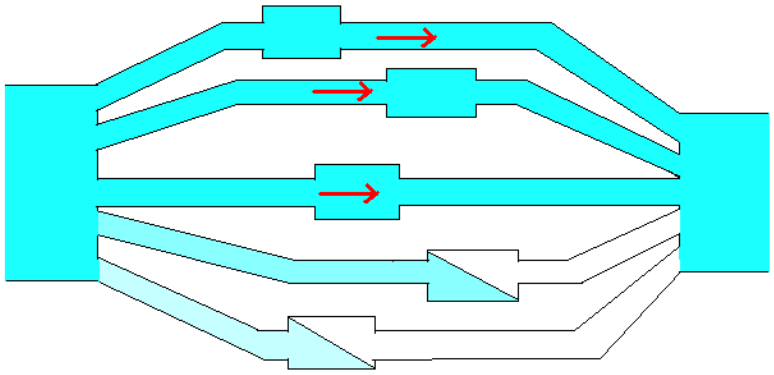
$$t_0 = \frac{u_{0k} Fz\, D\, S_1 S_2 \sigma_k}{I^2 \mathrm{M}_k (n_{k3} - n_{k1})}$$

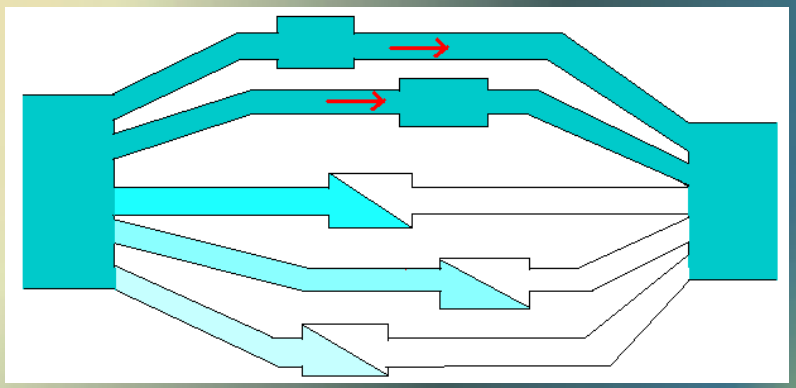
где t_0 Время полной блокировки пор.

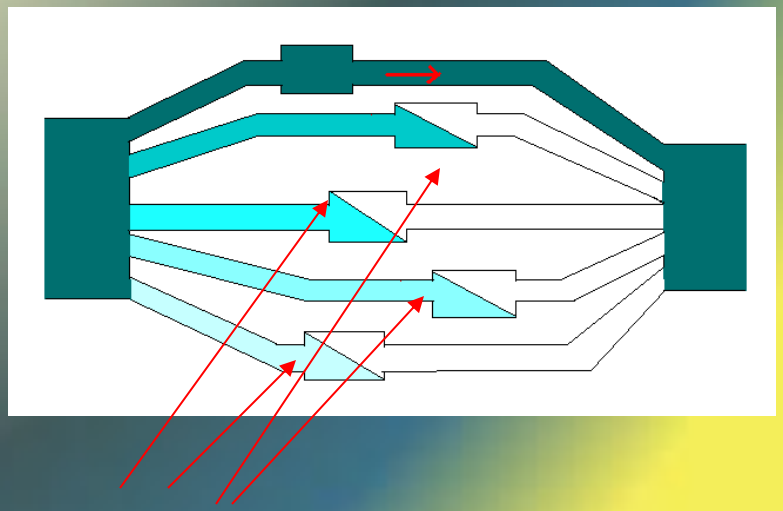
Последовательная блокировка пор





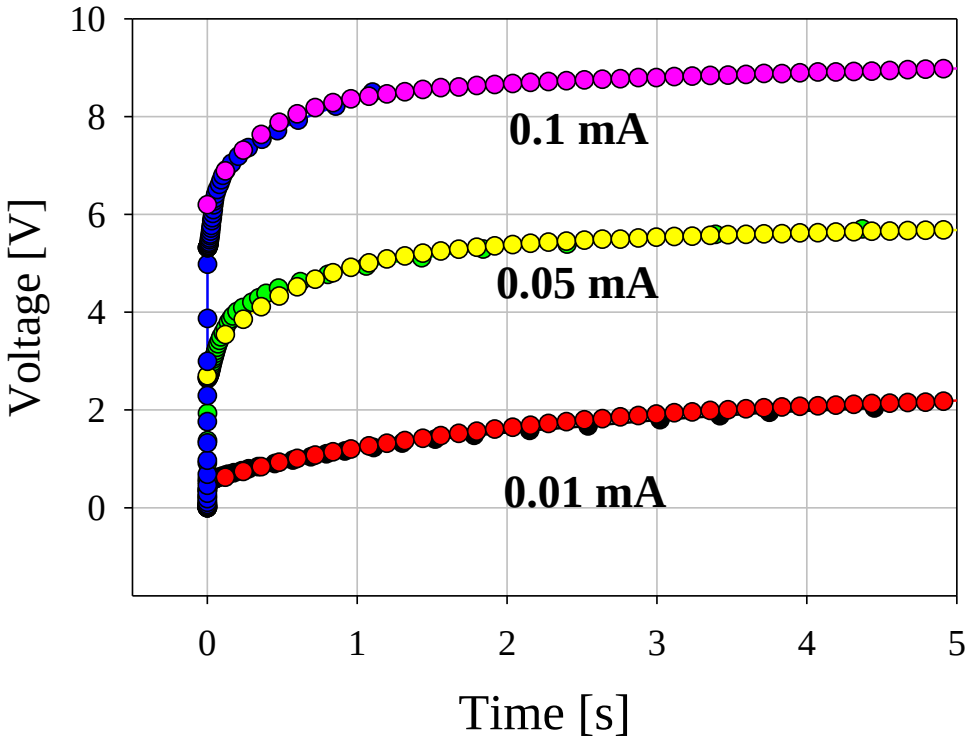






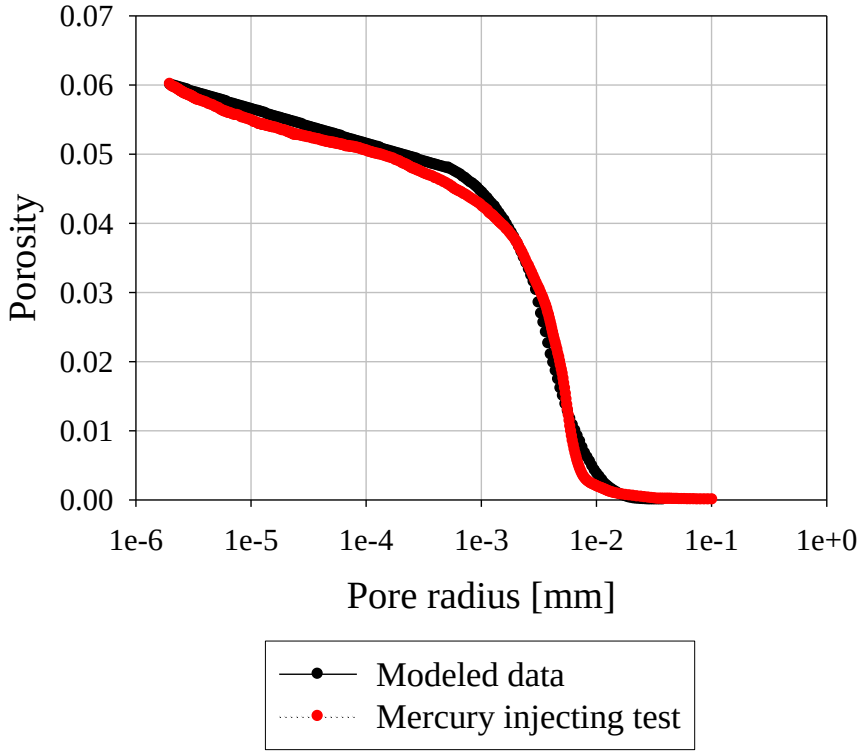
Immobile pores

Tennessee sample

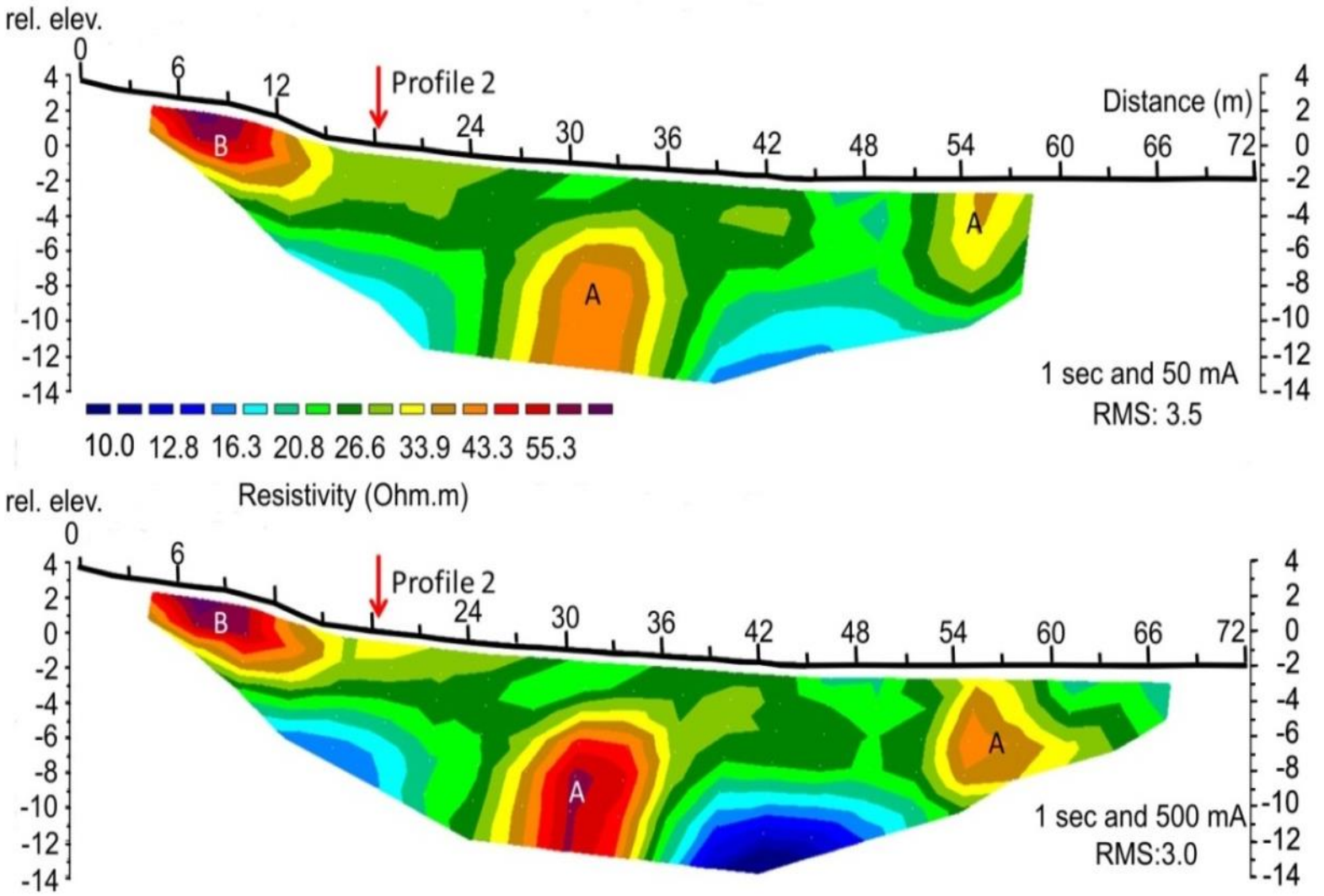


Calibration with mercury injection capillary test (after Baker, 2001).

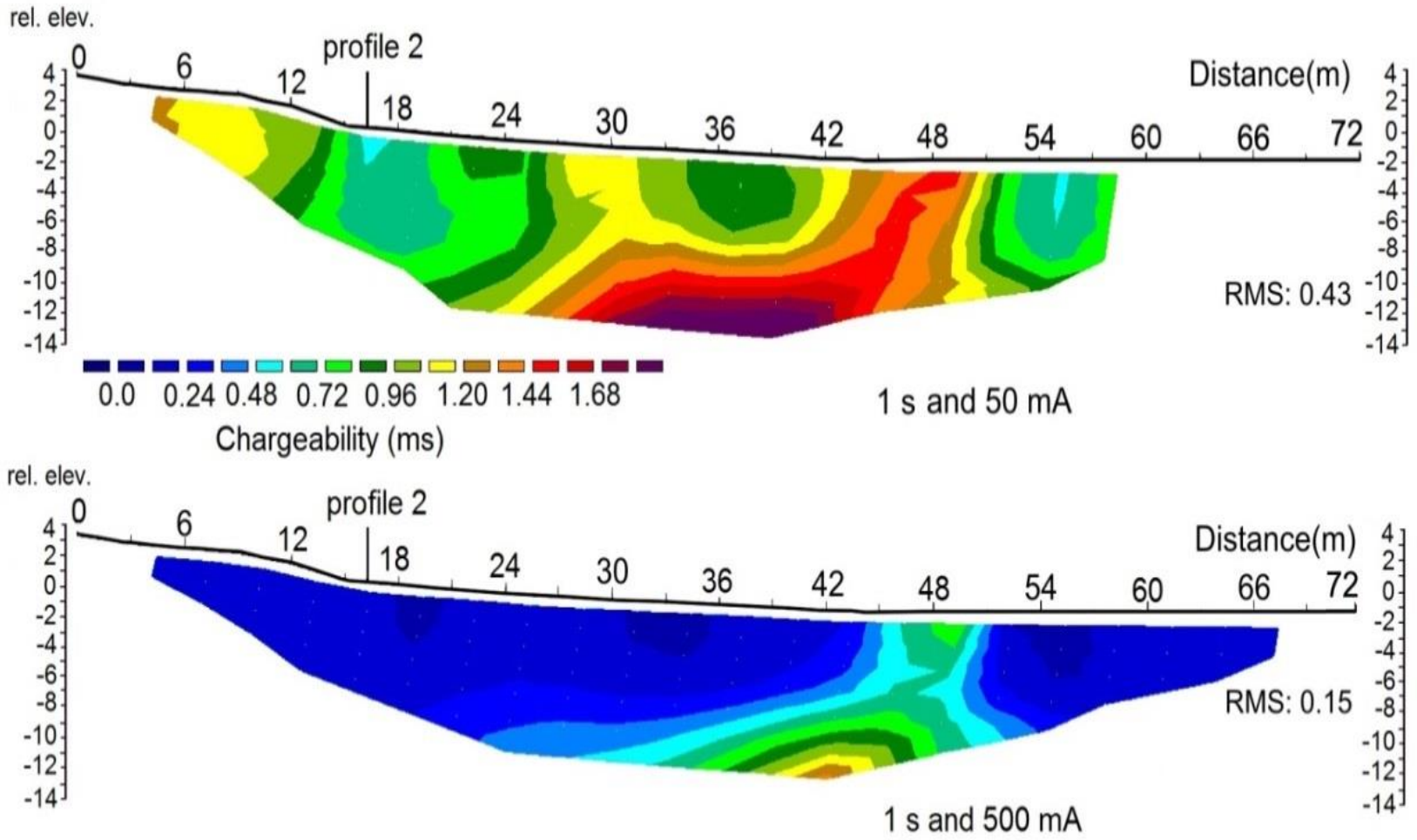
Tennessee sample



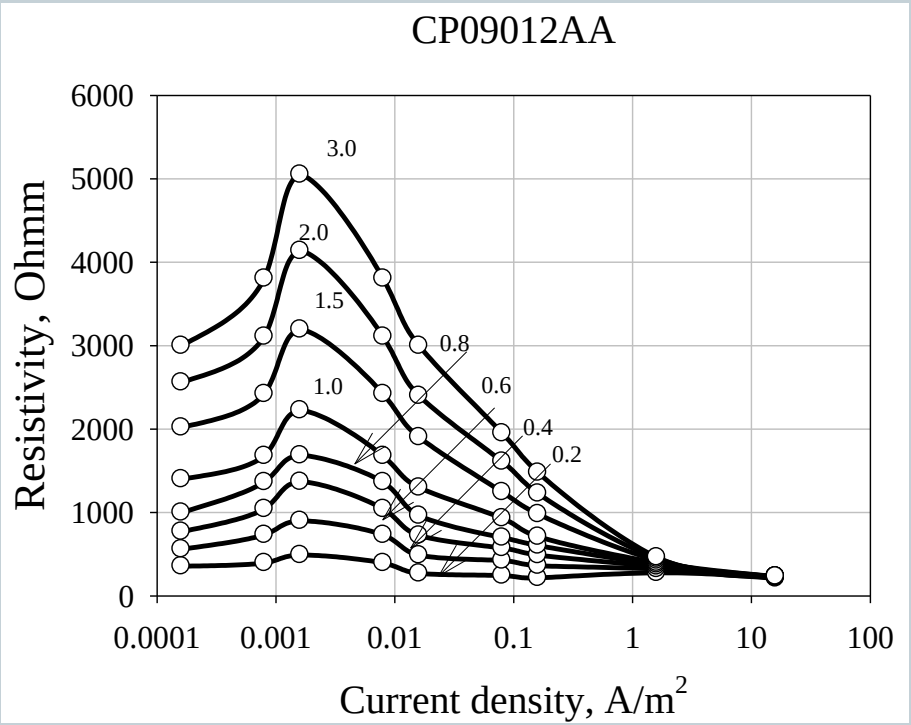
Resistivity model sections of Profile 1. Upper window: section obtained at 50 mA of supplied current; lower window: section obtained using a supplied current of 500 mA.

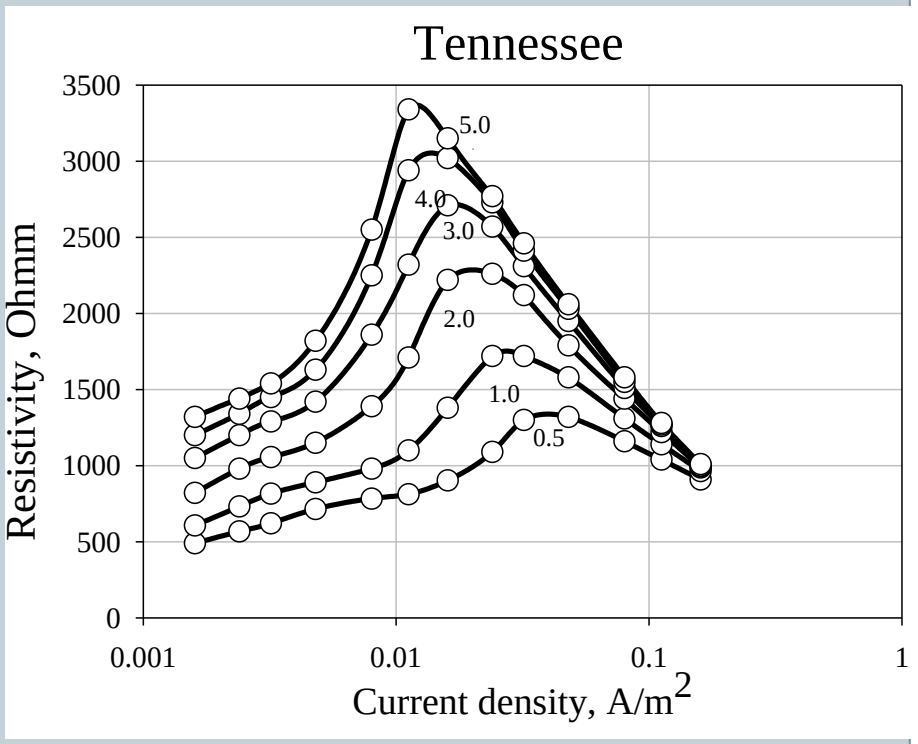


Chargeability *model sections of profile 1. Above: section obtained at 50 mA of supplied current; below: section obtained using a supplied current of 500 mA.*

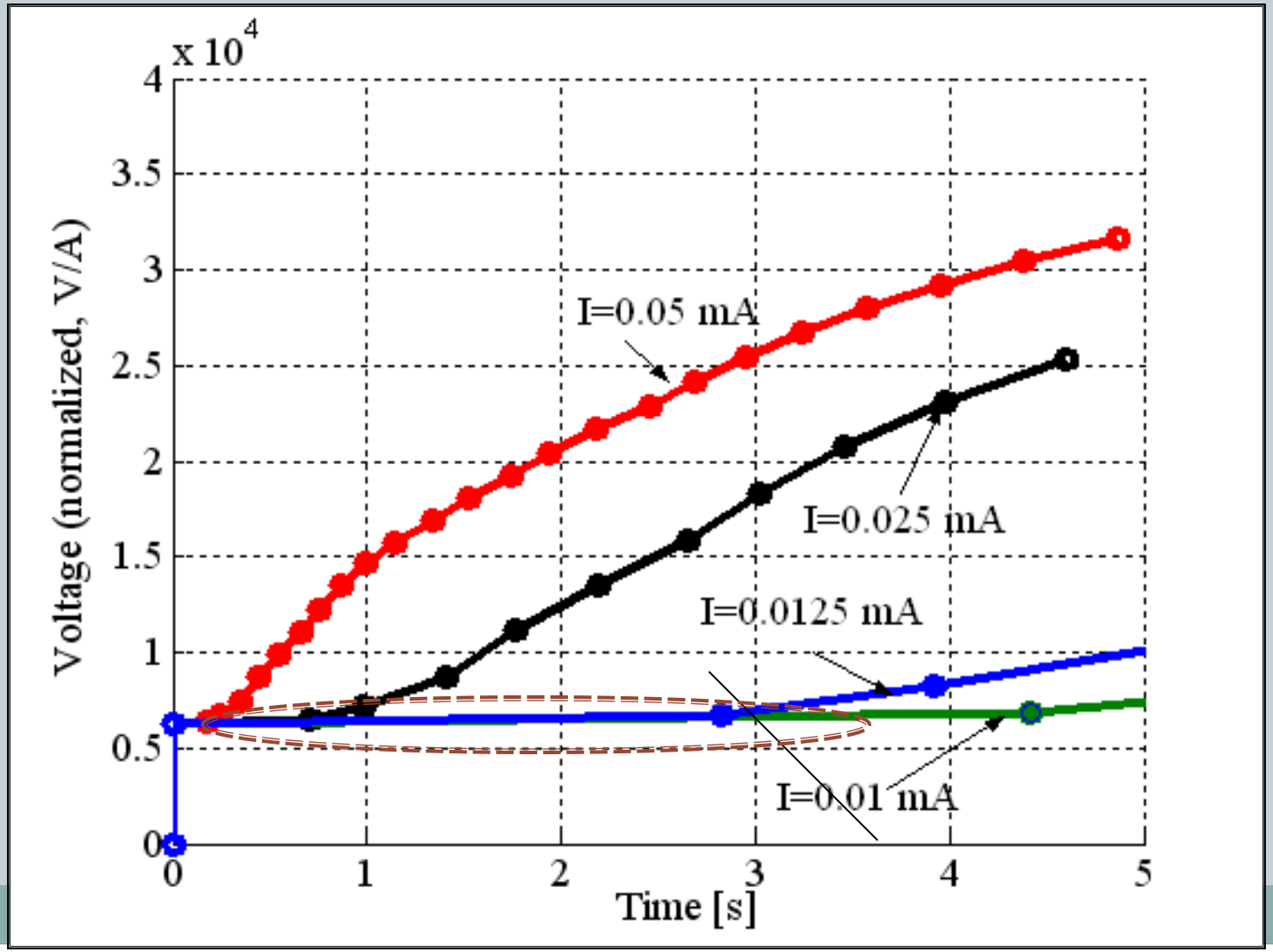


Resistivity has direct relationship with current density if the latter is small and reverse relationship if current density is larger: a – laboratory measurement data, b – theoretical data. Numbers on curves indicate time of current flow (in s).

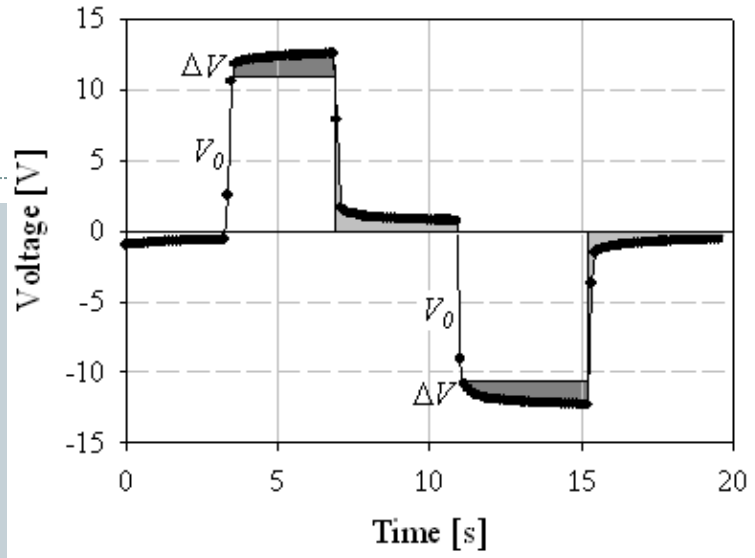




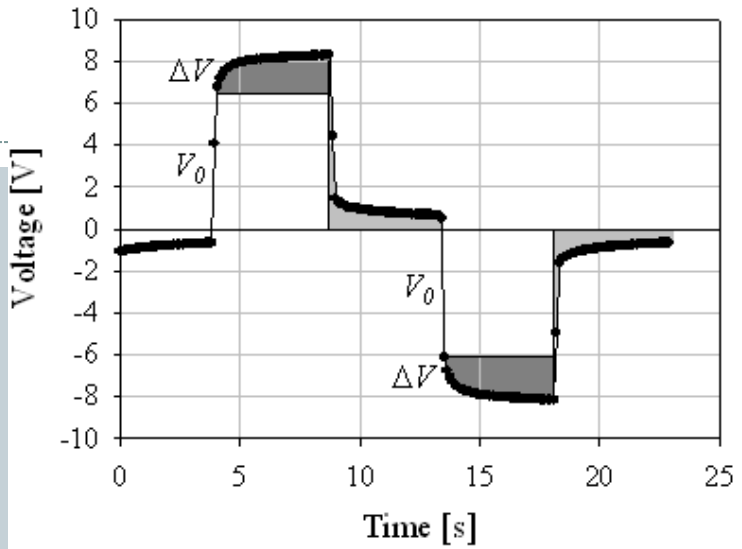
Разность потенциалов на малых токах



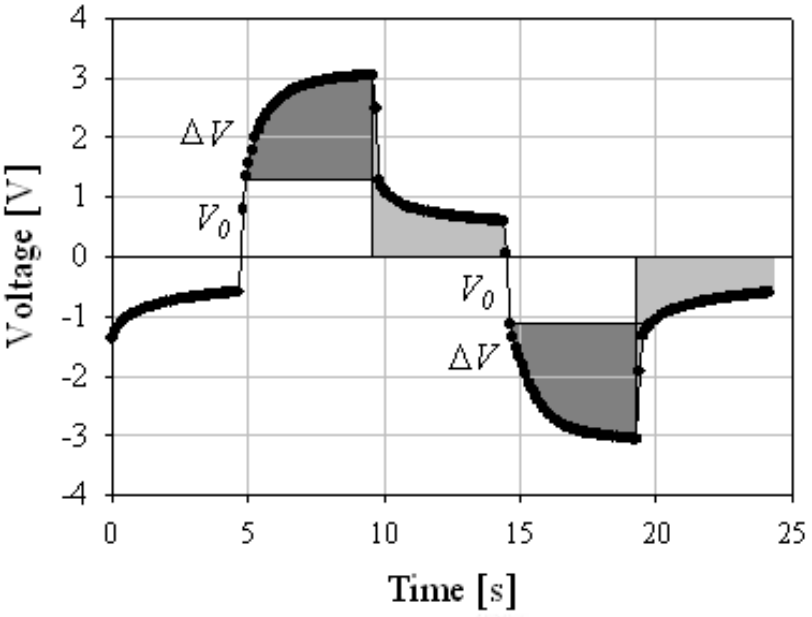
I = 0.1 mA



I = 0.05 mA



I = 0.01mA



Поляризуемость

$$\eta = V_{0.5} / V_P$$

$$\eta = \frac{1}{\Delta T V_P} \int_{t_1}^{t_2} V(t)\,dt$$

$$\eta = \frac{1}{\Delta T V_P} \int_{t_1}^{t_2} V(t)\,dt$$

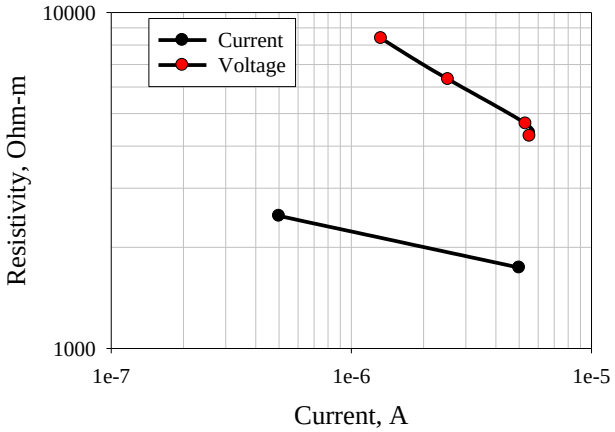
$$\eta = V_{0.5} / V_P$$

Ток *I* [mA]	Разность потенциалов V [V]	Эффект ВП ΔV [V]	Сопротивление [Ohmm] $\rho = V_0 \cdot S / I \cdot l$	Кажущееся сопротивление $\rho_a = (V_0 + \Delta V) * S/I * l$ [Ohmm]	Поляризуемость η (eq.1a)	Поляризуемость η (eq.1b)
0.1	~ 11.5	~ 1.8	1990	2245	0.104	0.306
0.05	~ 6.2	~ 1.8	2145	2860	0.14	0.316
0.01	~1.25	~ 1.7	2160	5260	0.348	0.524

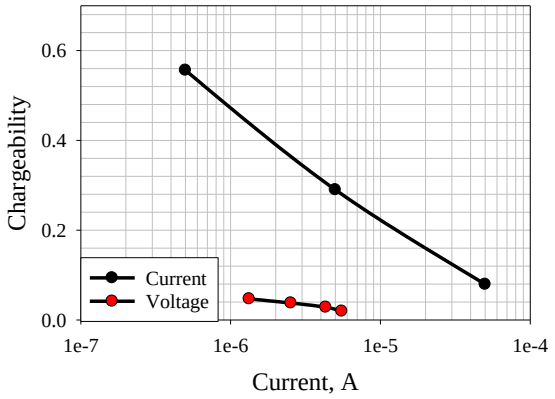
#	Number of sample	Rocks description	Resistivity Ohm-m	Maximal chargeability at 0.5mA		Resitivity Fit?
1	C14301	Ferrigenous quartz vein, brecciated	4020	0.14		No
2	C14302	Ferrigenous vein	1090	0.11		No/Yes
3	C14303	Quartz-muscovite-feldspar pegmatite with columbite-tantanite and cassiterite mineralization	5050	0.11		No
4	C14304	Sandstone	330	0.56		Yes
5	C14305	Claystone, graphitic black schists (shale)	110	0.61		Yes
6	C14306	Quartz vein with very few haematite/tungsten mineralization	12300	0.57		No
7	C14307	Fine-grained muscovite pegmatite	365	0.61		Yes
8	C14308	Muscovite pegmatite	249	0.49		Yes
9	C14309	Granular quartz muscovite pegmatite	205	0.49		No/Yes
10	C14310	Coarse grained kaolinitisized quartz-feldspar-muscovite pegmatite	330	0.46		Yes
11	C14311	Quartz pegmatite with muscovite	4210	0.11		No
12	C14312	Quartz with haematite and limonite	1150	0.21		Yes
13	C14313	Haematite vein	~ 100	0.52		Yes
14	C14314	Pyritic sandstone	140	0.65		Yes
15	C14315	Tungsten vein	70	0.17		
16	C14316	Gneissic like schist with haematite	370	0.1		Yes

Ток и разность потенциалов. Никакой связи.

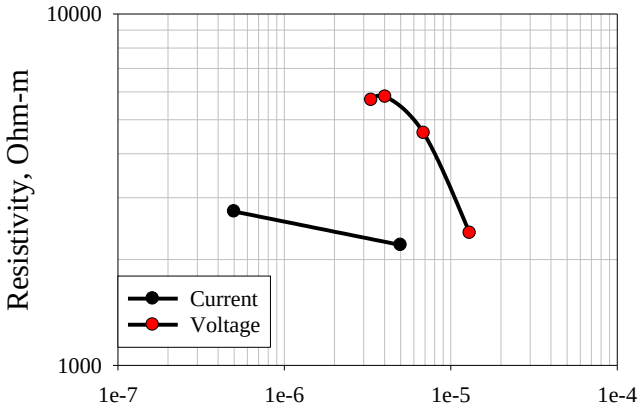
C14306 Quartz vein with very few heamatitic/tungstein mineralization



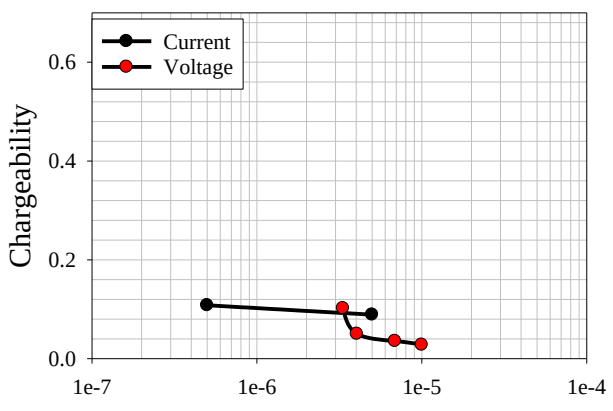
C14306 Quartz vein with very few heamatitic/tungstein mineralization



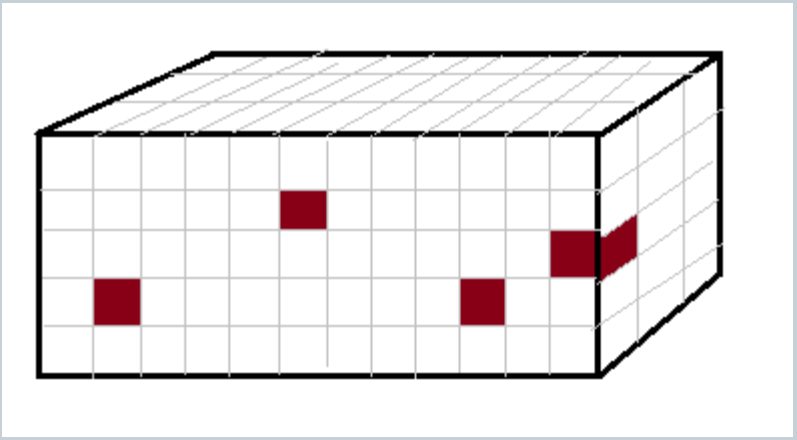
C143011 Quartz pegmatite with muscovite

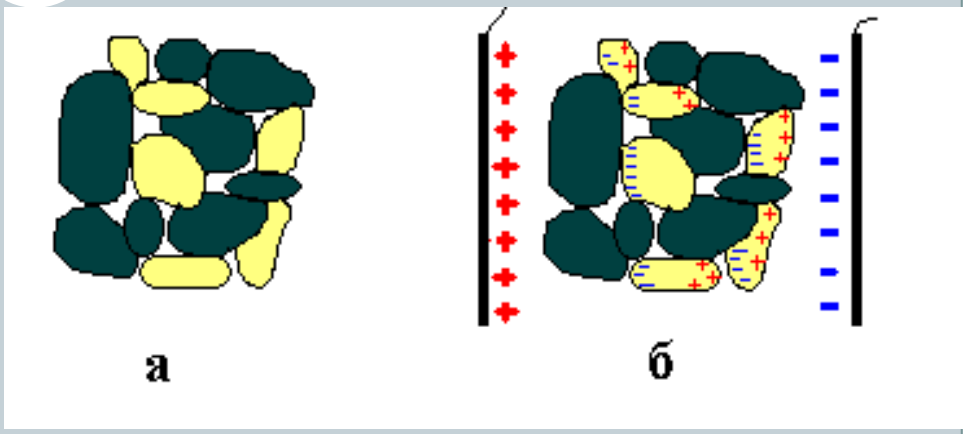


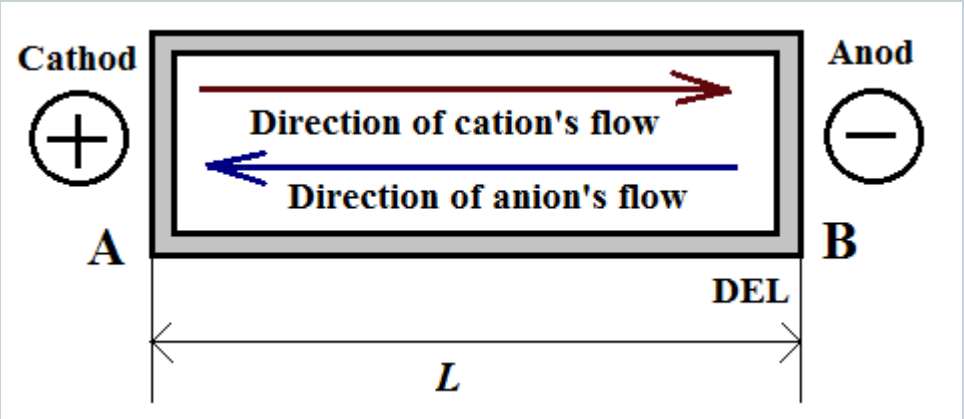
C143011 Quartz pegmatite with muscovite



Максвелл-Вагнер эффект (структурная, объемная поляризация) изолированные поры)







Одномерное тепловое уравнение (Второй закон Фика):

$$\frac{\partial u}{\partial t} = a^2 \frac{\partial^2 u}{\partial x^2}, \qquad (1)$$

где u концентрация электролита, $a^2 = D$ коэффициент диффузии.

Граничные и начальные условия

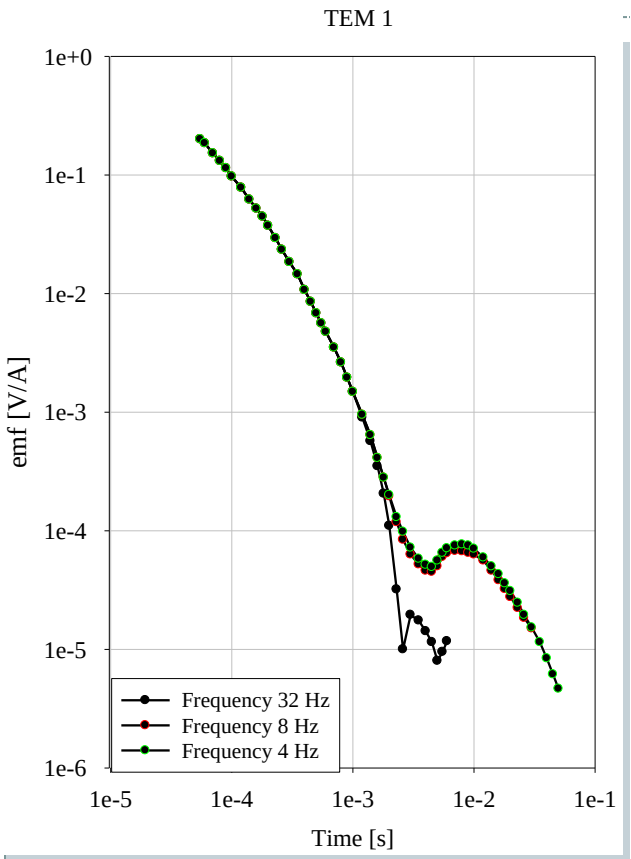
$$u\Big|_{t=0} = \varphi(x).$$

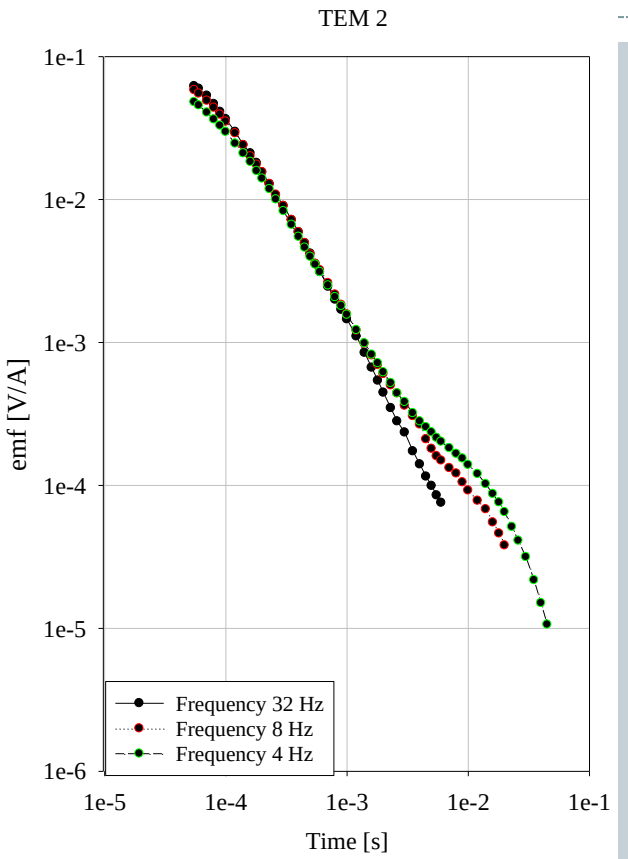
$$u\Big|_{x=0} = \psi_1(t), \quad u\Big|_{x=l} = \psi_2(t)$$

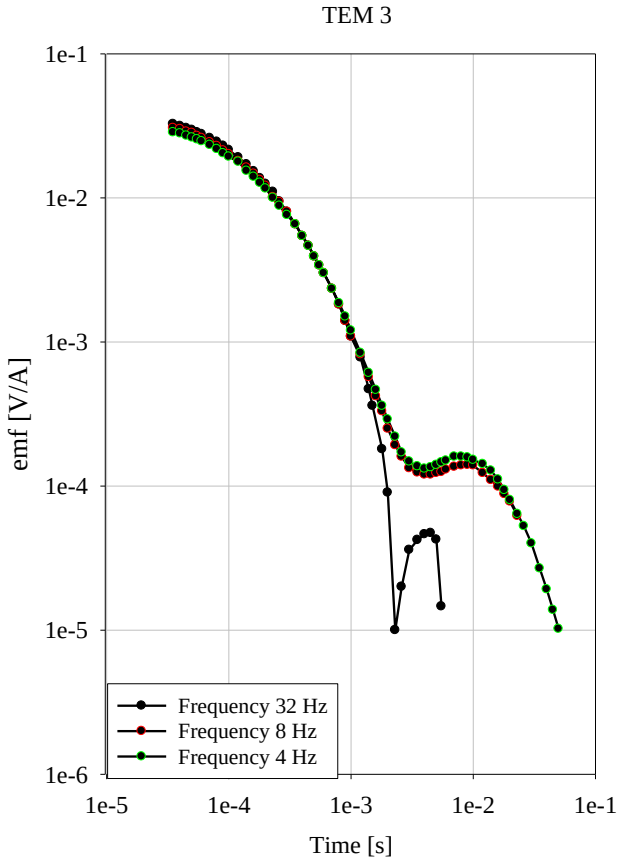
Граничные условия:

- Комбинированные эффекты

Combination of different kinds of IP effects:

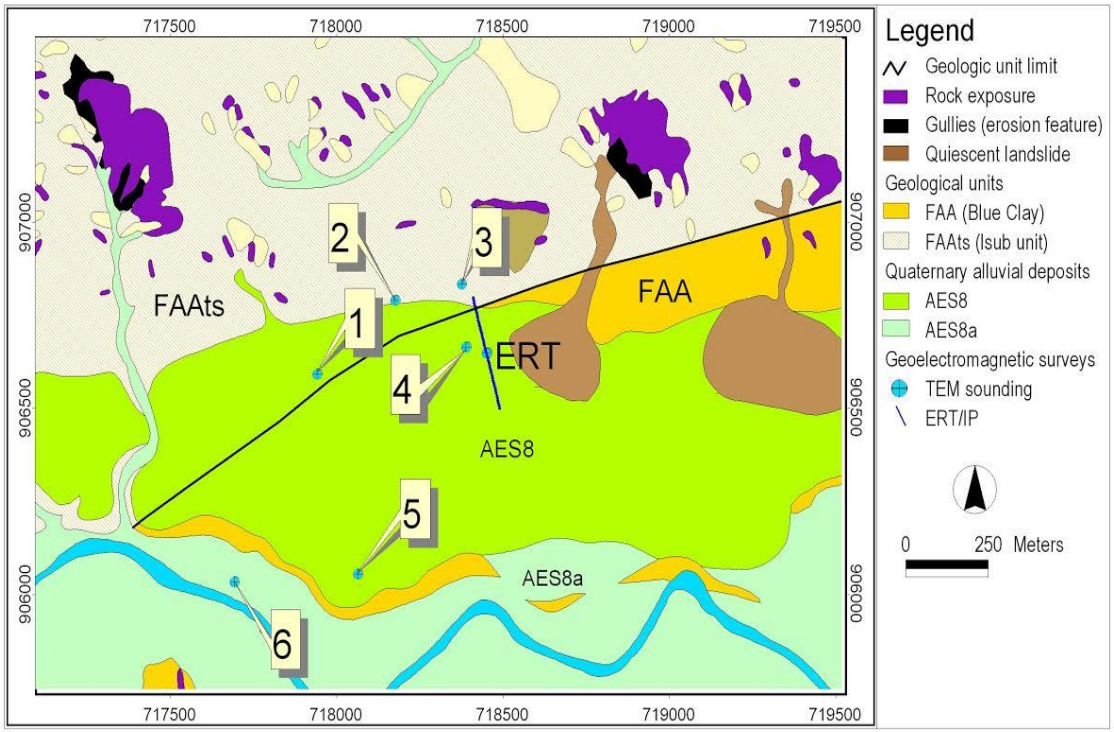






Measuring on 32, 8 и 4 Hz, it means length of current pulses are 0.03125s, 0.125 s и 0.25 s

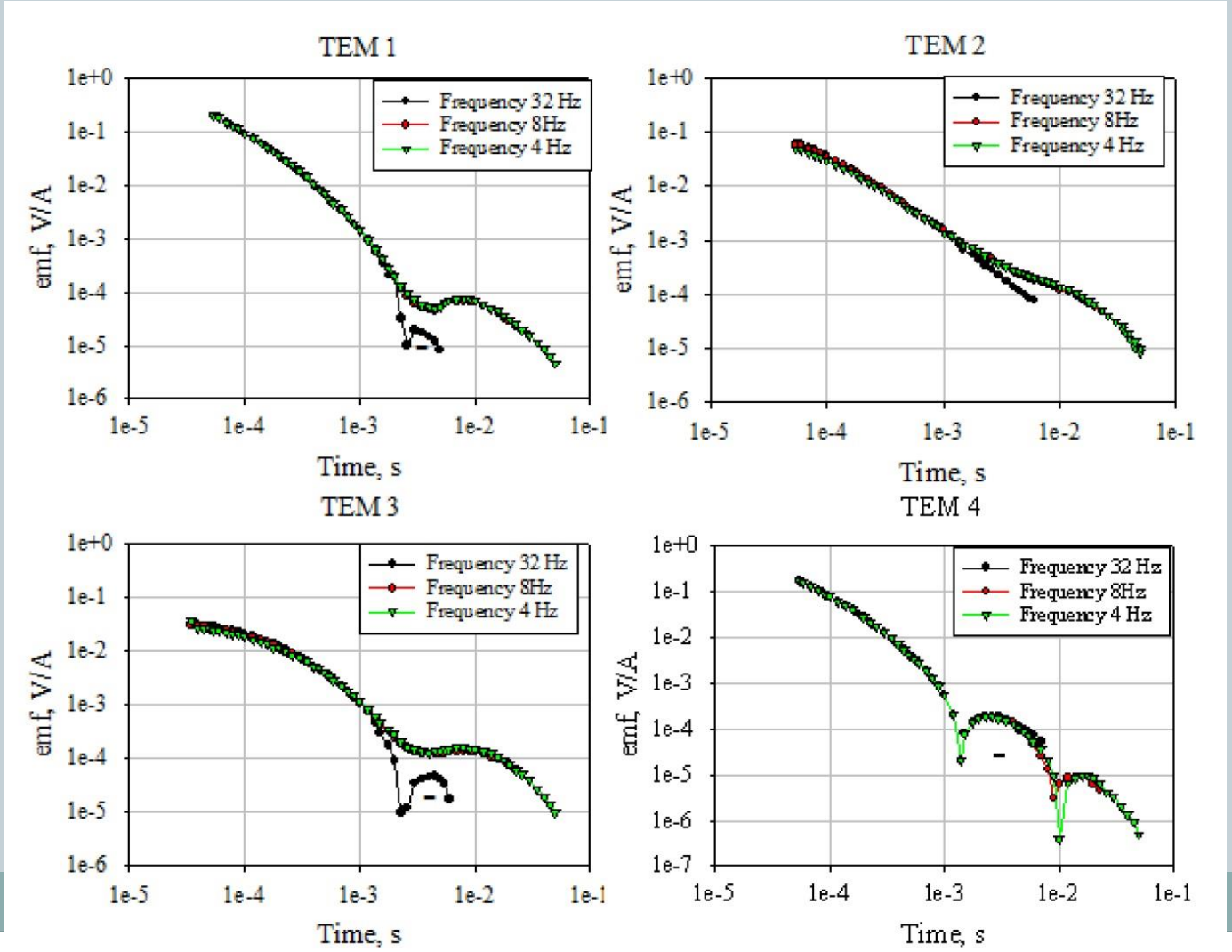
Расположение точек на геологической карте, Италия, Riolo Terme



Интерпретация комбинированного эффекта

- Как первое приближение мы добавили новую функцию, как зеркальное отображение Cole-Cole модели, учитывая амплитуду мембранного эффекта:
- $$p_{ME} = \alpha_2 \frac{\eta_2}{\tau_2} \exp\left(-\frac{1-\eta_2}{\tau_2} t\right),$$
- где η_2, τ_2 и α_2 поляризуемость, постоянная спада и коэффициент затухания эффекта.

TEM 1 – 4 и интерпретация (математическое моделирование с использованием двух функций Cole-Cole (continuous line: best-fitting 1D model).

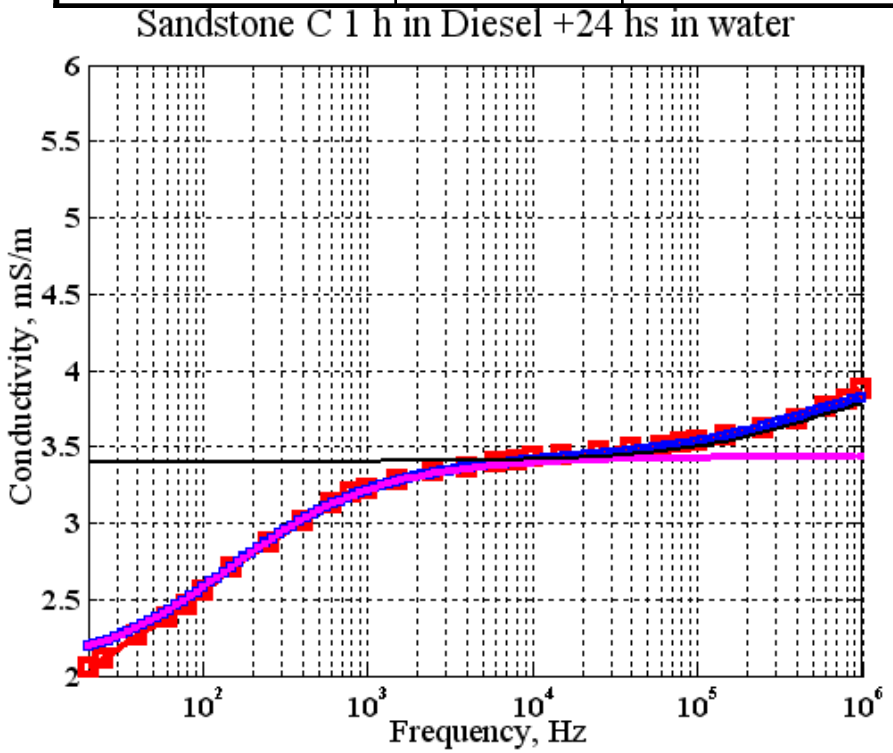


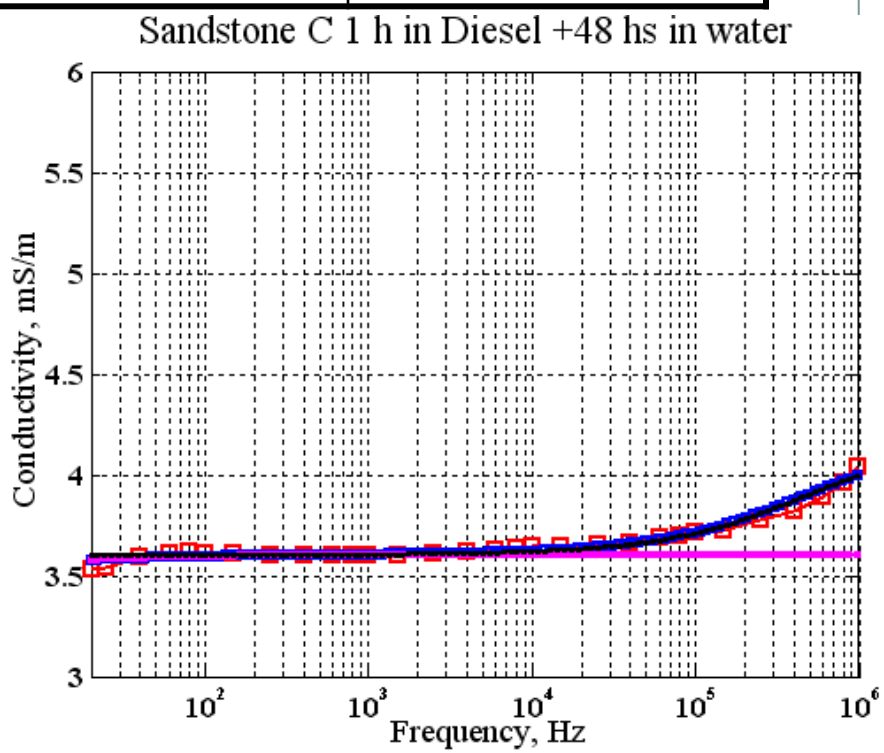
Сопоставление моделей,

Table 2										
1D petrophysical model of sounding 3 using the Cole-Cole formula at 32 Hz repetition rate						1D petrophysical model of sounding 3 using the Cole-Cole formula at 4 Hz repetition rate				
# of layer	ρ Ohmm	Thickness m	η	τ s		# of layer	ρ Ohmm	Thickness m	η	τ s
1	90	15	-	-		1	30	30	-	-
2	12	25	-	-		2	8	45	-	-
3	2.3	19	-	-		3	0.92	45	0.25	3e-3
4	0.5	20	0.25	3.5e-3		4	0.05	45	0.99	3.5e-3
5	0.5	25	0.25	3e-3		5	0.05	45	0.99	3e-3
6	0.6	24	0.25	3e-3		6	0.05	45	0.99	3e-3

Sandstone C, 1 h in Diesel and 24 hs in water – left
1 h in Diesel and 48 hs in water – right

Sample	C	Chargeability	Decay constant m, s	Resistivity, Ohmm
1 h in Diesel + 24 hs in water	$c_1 = 0.7$ $c_2 = 0.7$	$m_1 = 0.415$ $m_2 = 0.15$	$\tau_1 = 1.8e\text{-}3$ $\tau_2 = 3.5e\text{-}7$	$\rho_0 = 435$ $\rho_\infty = 263$
1 h in Diesel + 48 hs in water	$c_1 = 0.7$ $c_2 = 0.7$	$m_1 = 0.04$ $m_2 = 0.15$	$\tau_1 = 2.0e\text{-}2$ $\tau_2 = 4.0e\text{-}7$	$\rho_0 = 280$ $\rho_\infty = 250$





Заключение

- 1. Все типы поляризации имеют разную физическую природу.
- 2. Линейность процессов поляризации зависит от типа этой поляризации.
- 3. Амплитуда процессов ВП зависит от структуры порового пространства.
- 4. Амплитуда мембранной поляризации зависит от плотности электрического тока. При малых тока, где главенствует ВП процесс квазилинейный. Увеличение плотности тока приводит к не линеарности эффекта.
- 5. На данный момент не существует математического решения для электроосмотического эффекта к горных породах.
- 6. Эффекта Максвелла-Вагнера могут описываться различными уравнениями.
- 7. Эффект Максвелла-Вагнера могут описываться одним и тем же уравнением но с различными граничными условиями.
- 8. На наш взгляд стоит изучать каждый эффект в отдельности и представлять общее решение как сумму эффектов.

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