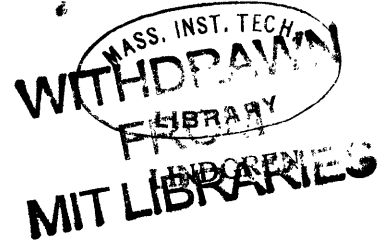A Study of some Electro-Kinétic properties

of Rocks

by

André J. Kermabon

Submitted in partial fulfillment of the requirements for

the degree of Master of Science in Geophysics at the

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Signature of Author ............................................
André J. Kermabon

Certified by ...........................................
Thesis Supervisor

Head of Department ...........................................
R.R. Shrock

## ABSTRACT

## A STUDY OF SOME ELECTRO-KINETIC PROPERTIES
## OF ROCKS

In this paper the author investigates the effects
and importance of streaming potentials in the measurement
of induced polarization.

Several specimens of sedimentary rocks of
various pore sizes were investigated.

Water was pushed through solid and ground rocks
and the streaming potentials measured.

Surface conductance appeared to be an important
factor which was computed to make the necessary corrections
in the $\xi$ potentials of the various specimens.

In order to corrolate the streaming potentials
with the determination of the $\xi$ potentials and to
explain any discrepancies in the results, all the possible
physical characteristics of the rocks which might influence
these results (porosity, permeability, tortuosity), were
measured.

The $\xi$ potentials computed from solid rocks
seem to be very close of the $\xi$ potential of the minerals

composing the rocks.

However the streaming potentials were found
to be small and therefore their effects practically
negligible when measuring induced polarization.

Thus, after measuring the streaming potential,
the $\xi$ potential and the surface conduction, the
induced polarization can be determined.

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# I- INTRODUCTION

In about 1860, Quincke discovered that when
he forced water through a clay diaphragm a potential
developed accross it - He realized that this effect
was a phenomenon inverse to electro-osmosis, which had been
observed as early as 1807 by Reuss . The next significant
contribution to a clarification of streaming potential -
in fact, to the whole field of electro-kinetics; was
made by Helmholtz in his classical theoretical analysis;

When a liquid flows through a conduit, the
ions of the movable layer are carried along with the
liquid flow. If there is a surplus of charge in the
displaced layer (subsequently referred as a displaceable
charge), a streaming current is generated.

This ionic convection current tends to cause
a deficiency of charge at the entrance of the conduit
and a surplus of charge at its exit. - To prevent the
formation of the deficiency and surplus of charge at the
opposite ends, a conduction current develops through any
electrical path that may be present. If no external path
exists and the walls of the tube are a non conductor, the
only path for the conduction current is through the bulk
of the solution.

It was originally thought that this electro-kinetic electrical property of rocks might be of importance as a property of rocks that might cause induced polarization type effects.

Although the first experimental showed no important effect from this point of view, it was decided to tie down the effects enough so that one had a reasonable understanding of the phenomena.

The general theory of electro-kinetic effects is made in the case of laminar fluid flow. However it is possible to make corrections in the case of surface conduction.

If the fluid flow is turbulent, the problem of setting up an equation for the streaming potential becomes difficult to handle mathematically.

In order to explain the possible discrepancies of the results, it was decided to measure all the possible physical characteristics of the rocks which might play a role.

The surface conductance, (the detailed conception of this phenomenum will be given later), can be relatively important in the case of low resistance of the liquid circulation inside the capallaries.

This resistance depends upon the conductivity

of the liquid circulating inside the capillaries, the cross section and the length of the capillaries.

The porosity and permeability give an importance of the pore size and allow us to get an idea of the surface conductance, in comparison to the bulk conductivity of the liquid inside the capillaries.

The toxtuosity (the square root of the ratio :

$$\frac{\text{length of the path of water in the porous plug}}{\text{length of the specimen}})$$

can be of importance as far as the law of liquid flow inside the specimen is concerned.

## II - STREAMING POTENTIALS

A calculation of the streaming potential can be based upon the following considerations. The difference of pressure applied to the end of a capillary (or to both sides of a porous plug) causes a flow through the capillary. This liquid stream carries along with it part of the charge of the "double layer" (a detailed conception of this physical phenomenum will be given below) and so is the bearer of an electric convection current.

As a consequence of this transport of charge, a potential difference arises between the ends of the capillary, which causes a conduction current through the capillary directed oppositely to the convection current.

In the stationary state, the convection current, which is proportional to the pressure difference P, just counterbalances the conduction current which is proportional to the potential difference E. Consequently the streaming potential E is proportional to the pressure P. The factor of proportionality can be determined by a reasoning given below.

The electro-kinetic phenomena are based on the properties of the double layer and the $\xi$ potential.

The electrical double layer consists of excess ions (or electrons) present on the solid phase and an equivalent amount of ionic charge of opposite sign distributed in the solution phase near the interface.

The charge on the solid "wall" is treated as a surface charge smeared out uniformly over the surface. The space charge in the solution is considered to be built up by unequal distribution of point-like ions. The solvent is treated as a continuous medium influencing the double layer only through its dielectric constant.

The Coulomb interaction between the charges present in the system is described by Poisson's equation

$$\nabla^2 \varphi = - \frac{4\pi \rho}{\varepsilon} \qquad (1)$$

between the potential 4, which changes from a certain value    at the interface to zero in the bulk of the

solution and the charge density

$\varepsilon$ is the dielectric constant

$\nabla^2$ Laplace operator.

## 1- ZETA POTENTIAL -

It appears that, in all modes of calculation the electrical potential in the slipping plane between the fixed and the flowing liquid is determinative for the electro-kinetic phenomena.

This potential is usually called the Zeta-potential $\left(\xi\right)$ .

## 2- DERIVATION OF THE FORMULA -

In the case of water pressed through a glass capillary, the wall is negatively and the liquid positively charged. These positive charges are carried with the liquid (convection of electric charge); if the length of the capillary is "l", the radius of the circular section $(r_1)$, the velocity of the liquid in the capillary is given by :

$$v_{(r)} = \frac{P}{4\eta l} \left(r_1^2 - r^2\right)$$

$$\frac{dv}{dr} = -\frac{Pr}{2\eta l}$$

$P$ hydrostatic pressure through the capillary

$\eta$ viscosity of the liquid.

The gradient of the velocity at the wall is

$$\left(\frac{dv}{dr}\right)_{r=r_1} = -\frac{Pr_1}{2\eta l}$$

The diffuse electric charge in the liquid is situated in the immediate neighborhood of the wall; the thickness of the diffuse layer is very small in comparison with the radius of the capillary; therefore, in the calculation of the transport of electric charge by convection, the wall of the capillary may be considered to be flat;

The velocity of the liquid in the immediate neighborhood of the wall, at a distance  x  from the wall will be

$$v(x) = \left(\frac{dv}{dx}\right)_{x=0} \qquad x = \frac{P r_1}{2 \eta \ell} x$$

The electric charge carried away per second amounts to

$$I_1 = 2\pi r_1 \int_0^\infty \rho(x)\, v(x)\, dx = -2\pi r_1 \int_0^\infty \frac{\varepsilon}{4\pi} \frac{P r_1}{2\eta \ell} \frac{d^2\psi}{dx^2} x\, dx$$

$\varepsilon$ : dielectric constant of the liquid

$$I_1 = -\frac{\varepsilon P r_1^2}{4\eta \ell} \left[ x \frac{d\psi}{dx} \right]_0^\infty + \frac{\varepsilon P r_1^2}{4\eta \ell} \int_0^\infty \frac{d\psi}{dx}\, dx = -\varepsilon \zeta r_1^2 \frac{P}{4\eta \ell}$$

$\zeta$ : Zeta potential of the double layer.

This transport of charge will cause an electric potential difference $E_1$ between the two ends of the capillary, which will give rise to a current of conduction $I_2$ given by :

$$I_2 = \nabla \frac{E_1}{\ell} \pi r_1^2$$

stationary state $I_1 + I_2 = 0$  and therefore

$$\frac{E_1}{P} = \frac{\varepsilon \zeta}{4\pi \eta \lambda}$$

$\lambda$ specific electric conductivity of the liquid.

This is the Helmholtz-Smoluchowski equation : the length $l$ and the radius $r_1$, of the capillary do not appear in the final equation.

## 3- ASSUMPTIONS UPON WHICH THE STREAMING POTENTIAL FORMULA IS BASED.-

a) $\varepsilon$ the dielectric constant of the liquid in the region of an interface is assumed to be equal to that of the liquid in bulk. Measurements of the dielectric of water in the presence of an electric field show that for water can be lowered from a value of 80 to a value of 1 by placing the water in an electric field of the order of 500.000 volts per centimeter.

Helmholtz and Quincke estimated the distance across an interface to be of the order of $10^{-8}$ centimeter, that is the thickness of the molecule. If the $\xi$ potential where then of an order of 0,2 volts, it is easily seen that the liquid in the interfacial layer is being acted upon by an extremely high electrical fiels and its dielectric constant might be greatly reduced.

According to the theory of Gouy on the existence of a diffuse double layer, which postulates a much greater distance between the centers of electrical charge than that estimated by Helmholtz, it seems probable that the electrical

field extant in interfacial regions may not be high
enough to entirely eliminate ( $\varepsilon$ ) from the equation.

b) $\eta$ the viscosity of the liquid is assumed
to remain a constant for dilute salt solutions and to be
equal to that of the pure liquid in the bulk.

Helmholtz's equation also leaves out of consideration any effect due to slippage of the liquid layer
along the surface of the solid, assuming all motion to
be between two liquid layers, where $\eta$ would be the
only factor. LAMB, however introduces a term, $1/\beta$
into all the equations of Helmholtz, where $\beta$ = the
coefficient of slippage at solid-liquid interface and
linear magnitude of this slippage.

c) The flow of liquid.

As to the flow of liquid one postulates a
purely laminar flow, with a coefficient of viscosity,
having the same value throughout the whole system.

There have been some differences of opinion
concerning the boundary conditions of the movement of
the liquid. In considerations using Perrin's condenser
layer, the liquid is assumed to be at rest in a plane
coinciding with the charge on the wall.

Helmholtz and especially Lamb have taken account
of the possibility of a slip along the wall, but no

experimental evidence in favour of such a slip has ever
been found.

In 1928, Reichardt showed in his doctoral thesis
that it is not necessary to assume that the entire liquid
flow be laminar in order that the displaced ions be moved
with constant velocity parallel to the wall. The basis
of his presentation was that a film exists at any liquid-
solid interface whose flow is always laminar even if the
flow in the interior of the liquid is turbulent; therefore,
the necessary criterium is that the flow be established or
be developed so as to cause the steady state.

Bocquet, Sliepcevich, Bohr, in a recent paper
have checked experimentally this theory and found that
the Helmholtz-Smoluchowski equation for the streaming
potential is valid for both laminar and turbulent flow.

d- $\lambda$   the specific conductivity factor found
in the equation refers to that of the liquid. In the
derivation of the streaming potential formula it will
be remembered that the solid phase is assumed to have a
negligible amount of conductivity. Also any surface
conductivity is disregarded.

The surface conduction is the extra conductivity
along the capillary.

This surface conductivity has for its origin:

- The double layer contains more ions that the one
bulk of the liquid . These excess ions cause the surface
conductivity by their motion in the electrical field.

- The effect of this surface conduction is important
when the bulk resistance of the fluid inside the capil-
laries is small. The pore size of the specimens can
play an important role and contribute to minimize or
increase the surface conduction.

It is not difficult to make the necessary corrections
for the surface conductance, if the streaming potential
is determined by a capillary of radius (r).

In the case of a porous plug (assemblage of
capillaries in parallel) the return current is proportional
to $n \pi r^2 \lambda + 2 n \pi r \lambda_s$ instead of $n \pi r^2 \lambda$
and the corrected equation for the streaming potential
becomes :

$$\frac{E}{P} = \frac{\varepsilon \zeta}{4 \pi \eta (\lambda + \frac{2\lambda_s}{r})}$$

$\lambda$ : bulk conductivity of the liquid

$\lambda_s$ : specific surface conductance.

# III - STREAMINGS POTENTIALS AND THE ONSAGER'S PRINCIPLE

The Onsager's principle deals with irreversible phenomena. According to Onsager's theory the "forces" are causes which can give rise to the occurence of irreversible phenomena.

These forces are denoted by $X_i$ $(i = 1, 2, 3 \ldots n)$

These forces cause certain irreversible phenomena. These are called together "fluxes" or sometimes flow or current.

They are symbolized by $J_i$ $(i = 1, 2, 3 \ldots n)$

The irreversible phenomena can be expressed by phenomenological relations of the general type.

$$J_i = \sum_{k=1}^{n} L_{ik} X_k \qquad (i = 1, 2, 3 \ldots n)$$

$L_{ik}$ $(i, k = 1, 2, 3 \ldots n)$ are the phenomenological coefficients

Onsager's fundamental theorems states that provided a proper choice is made for the "fluxes" $J_i$ and "forces" $X_i$, the matrix of phenomenological coefficients is symmetric, i.e.

$$L_{ik} = L_{ki} \qquad (i, k = 1, 2, 3 \ldots n)$$

These identities are called the Onsager reciprocal relations.

In electro-kinetic effects, the "fluxes" are the electrical current ( I ) and the flow of water ( J ) ; the "forces" are the streaming potential $\Delta \varphi$ and the pressure gradient $\Delta P$

The phenomenological equations are :

$$I = L_{11} \Delta \varphi + L_{12} \Delta P \quad (1)$$
$$J = L_{21} \Delta \varphi + L_{22} \Delta P \quad (2)$$
$$L_{12} = L_{21}$$

The streaming potential is defined as the potential difference corresponding to unit pressure difference in the stationary state with zero electrical current.

$$\left( \frac{\Delta \varphi}{\Delta P} \right)_{I=0} = - \frac{L_{12}}{L_{11}}$$

$L_{11}$ is an electrical resistance

$L_{12}$ is connected to the $\xi$ potential and the double layer properties

$$L_{11} = \frac{1}{\lambda + \left( \frac{2 \lambda_d}{r} \right)} \quad \text{if surface conduction}$$

The streaming potential can then be derived directly from the Onsager's equations.

The second Onsager's equation

$$J = L_{12} \Delta \varphi + L_{22} \Delta P$$

shows the liquid flow through a capillary does not depend only on the pressure gradient $\Delta P$ but also on the streaming potential $\Delta \varphi$

$L_{22}$ is the hydrodynamical resistance of the

specimen.

$\angle_{\mathfrak{a} \mathfrak{z}}$  is connected to the  $\xi$  potential and the double layer property.

In the calculation of permeability and rate of flow, we will come back later on, on the value and importance of  $\angle_{\mathfrak{a} \mathfrak{z}} \, \Delta \varphi$  term.

Fig I



10Ω    100-100.000 Ω

1.5V

By comparing the direction of the
external voltage applied to the
electrodes 1 and 2 and the
streaming potential, the
polarity of the streaming
potential is easily determined

A    B

A    B

chopper    V

position A    reversible switch
    1+            2 -
position B
Fig II    1-            2 +

1    2

Water Head

nyloncloth
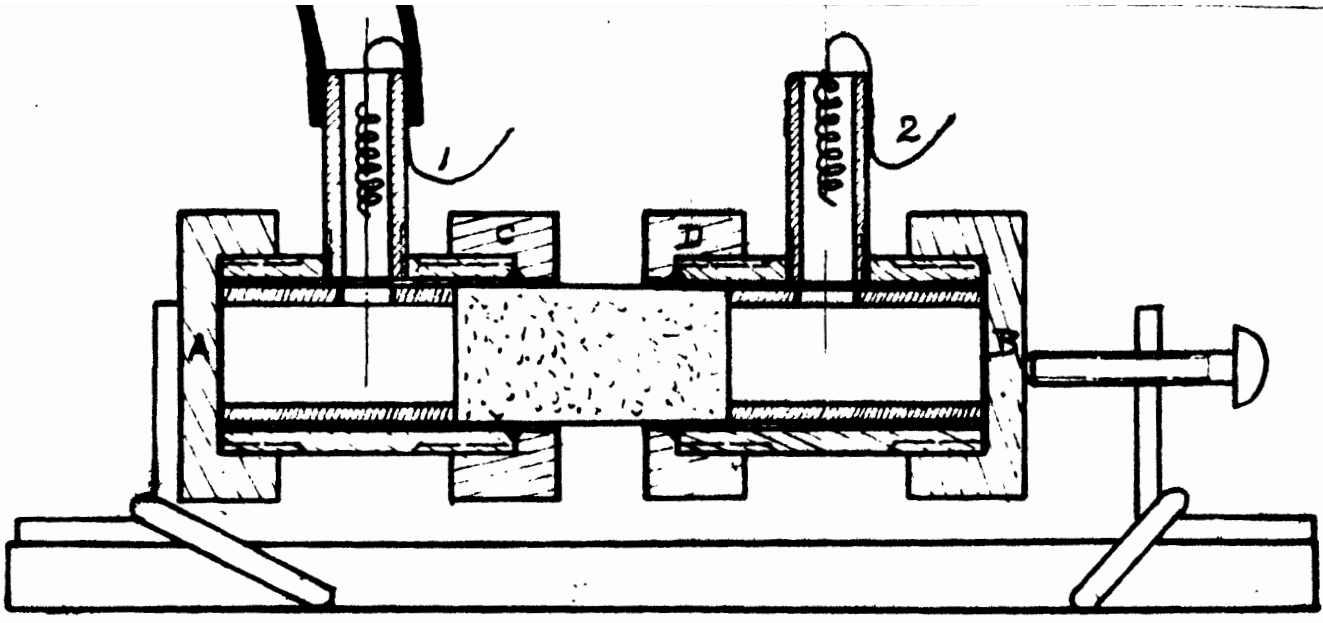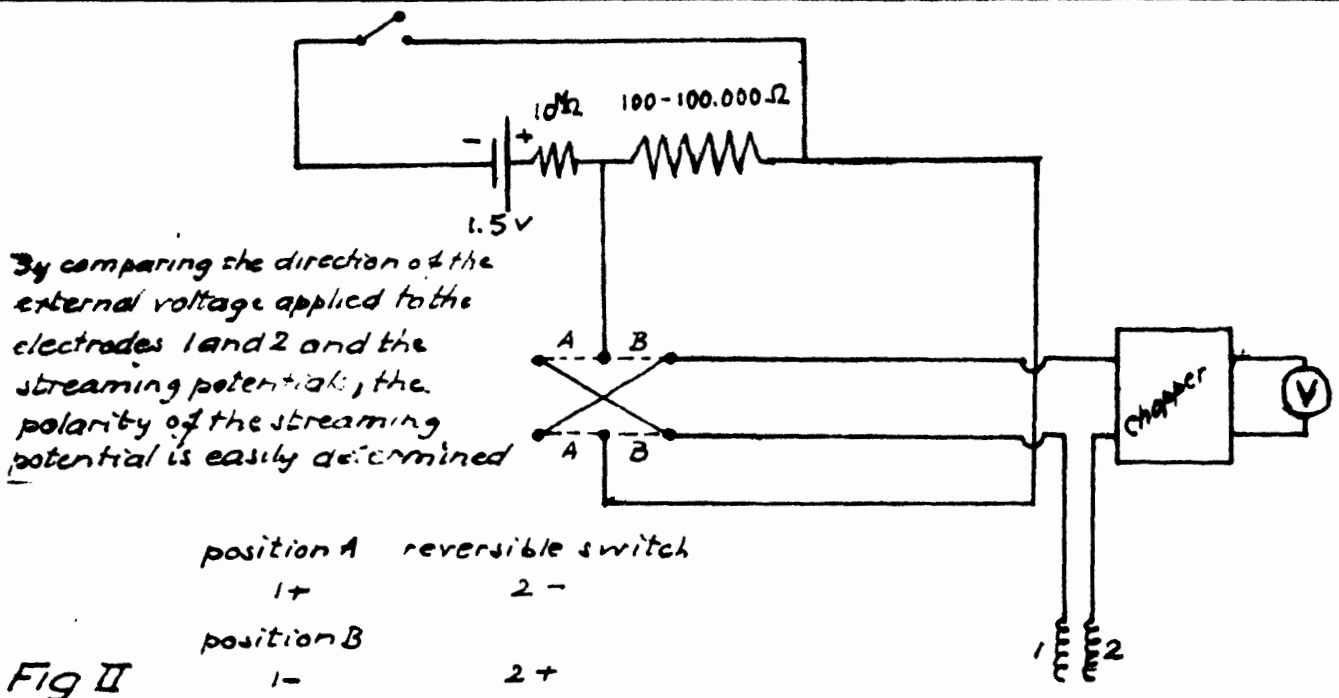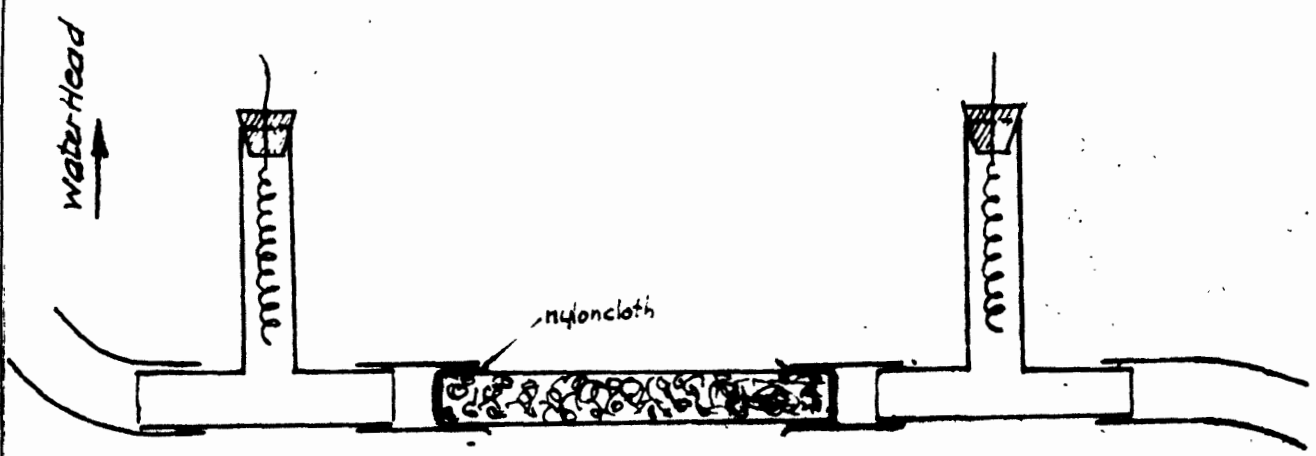
IV - EXPERIMENTAL PART

The purpose of this study is to show
electro-kinetic properties of sedimentary rock.
importance of streaming potentials in these rocks.

As was already noted in the previous part,
the streaming potential depends upon the general properties
of capillaries or porous plugs.

The pore size and permeability were found to
be important factors. They determine the importance of
surface conductance compared to the importqnce of the
resistance of the liquid circulating inside the capilla-
ries and the type of flow that may be expected inside
the capillaries.

To eliminate the surface conductance which
seemed to play an important role in the case of solid
rocks of relatively small porosity, we ground the rocks
and studied the streaming potentials in the ground particles
of rocks - We then measured the $\xi$ potentials of these
rocks.

1)- EQUIPMENT

a) - The equipment shown in fig. (1) was used to
measure the streaming potential in cylindricals rocks.

The specimen is placed between two chambers
filled with water. One chamber (pipe 1), is connected

to an air pressure pipe controlled by a gauge. Two
platinum wire electrodes dip in the liquid one in each
chamber.

The voltage created between these two elec-
trodes is chopped and measured with an A-C voltmeter.

In order to know the polarity of the created
voltage, the circuit (fig.II) is connected in series
with the electrodes 1 and 2.

Many difficulties were encountered in setting
up the equipment.

The first problem that had to be solved was
an electrode problem.

- The first electrodes used were the two brass
flasks A and B of the chambers - As soon as the measuring
circuit was closed, a large polarization effect was
noticed (several hundreth of a volt in a few seconds).

It was therefore decided to change the brass
electrodes for a less polarizable metal.

It is known that the contact electrode-liquid
can be represented as a resistance and a condensor in
parallel. This circuit is in serie with the resistance
of the voltmeter.
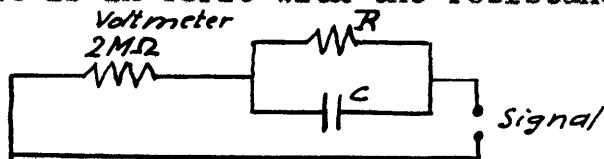
If the polarization resistance is small, the

condenser is shorted out - No problems of reading are then encountered.

If the polarization resistance is big, one must try to increase the time constant of the circuit to make the readings possible.

- The capacitance of the electrodes must be large - as well as the resistance of the voltmeter.

For this reason, a relatively large surface contact liquid-electrodes must be used.

- Platinum electrodes, two wires o$\frac{1}{2}$ $\phi$ $\frac{1}{2}$mmlength 50mm were then used.

- An appreciable polarization was still noticed.

- The surface area of the electrodes was then increased by soldering two thin plates of platinum to the original platinum wires (length 30 mm - width 20 mm - thickness 1/10 mm.) .

However the solder complicates the cleaning procedure and again some polarization was noticed.

The electrodes were cleaned thoroughly with a standard cleaning solution (sulfuricacid + potassium dichromate) and then dipped in nitric acid for 15 minutes - Finally the electrodes were boiled in distilled water for one hour; the water was changed three times during that time.

The platinum wire electrodes originally used were finally adopted since a thorough cleaning minimizes the polarization effect.

- The circuit was kept closed only during the minimum time required for the measurements.

- The entire equipment was made of plastic except the parts A-B-C-D, which were in brass and insulated from the electrical circuit.

- The cylindrical surface of the specimens was painted with a waterproof paint, deposited in thin layers and dried in an oven at 90° c. for two days.

- Water leakage problems in the equipment were solved after several tries by means of grease and flax.

b) - In order to measure the streaming potential in ground rocks the equipment described in fig. III was used.

The pressure is obtained by a waterhead.

The ground rock is placed in a glass tube ( $\phi$ 8 mm.) the ends of which are closed by two stoppers of nylon cloth.

The platinum wire electrodes are the same as those used in part 1).

## 2)- MESUREMENT OF POROSITY

No special equipment was used.

The specimen is weighed when soaked with water and when dry after remaining one day in an oven at 110° C.

- The difference of weights gives the content of water, and the volume of the porous part of the specimen.

The porosity is the ratio of this volume over the total volume of the specimen.

## 3)- MEASUREMENT OF PERMEABILITY

The equipment described in section 1) is used to measure the permeability of the rock specimens.

A pipe of glass, $\phi$ / mm, is connected to the plastic pipe 2.

The pipe 1 is connected to an air pressure pipe at the pressure 30

The water level rise is measured on the glass tube.

- The rate of flow ca be measured in $cm^3/s$

The permeability in Darcys is given by the formula

$$k = \frac{Q \mu L}{\theta P A}$$

$\frac{Q}{\theta}$ : rate of flow in $cm3/s$

$\frac{Q}{\theta}$ = rate of flow in

$\mu$ = viscosity of water in centipoises

$P$ = pressure in atmo**s**phere

$\ell$ = length of the specimen

It has previously been shown that the liquid flow through a capillary does not depend only on the pressure gradient $\Delta P$ but also on the streaming potential

$$ J = L_{12} \, \Delta \varphi + L_{22} \, \Delta P $$

The value of $L_{12} \, \Delta \varphi$ and its importance in the determination of "J" rate of flow shall be treated later on.

## 4)- SURFACE CONDUCTION MEASUREMENT

The rock specimen after soaking in water (conductivity $\lambda_1$ ) is placed under a high frequency potential of 5 volt amplitude.

The measured current passing through the specimen is $X \mu A$

A high frequency voltage is used to minimize the electrode impedance.

To the same specimen, after soaking in a saturated salt solution (conductivity $\lambda_2$ ), when the same 5 volt potential is applied, the current passing through the specimen is $Y \mu A$

In both cases the current is passing through the specimen can be expressed by the relation written below

$$i = k \left( 2\pi r \lambda_s + \pi r^2 \lambda \right)$$

$$r : \text{radius of the pores}$$

$\lambda_s$    specific surface conductance for the rock sample

$\lambda$    bulk conductivity of the liquid .

We then get the system of equation

$$X = k \left( 2\pi r \lambda_s + \pi r^2 \lambda_1 \right)$$
$$Y = k \left( 2\pi r \lambda_s + \pi r^2 \lambda_2 \right)$$

$$\frac{X}{Y} = \frac{\frac{2\lambda_s}{r} + \lambda_1}{\frac{2\lambda_s}{r} + \lambda_2}$$

Knowing the currents $X$ and $Y$ , as well as $\lambda_1$ and $\lambda_2$ , we can compute $\dfrac{2\lambda_s}{r}$

## 5) - TORTUOSITY

If $L$ is the length of the specimen and $L_e$ , the length of the flow path, the tortuosity is defined as below

$$T = \left( \frac{L_e}{L} \right)^2 = \text{tortuosity of the porous medium.}$$

The resistance of a homogeneous porous medium saturated with conducting fluid of resistivity $\rho_e$ , may be considered to be the resistance of a volume of fluid of length $L_e$ , area $\phi A$ , where $L_e > L$ and $L$ is the macroscopic length of a porous medium of porosity $\phi$

Thus, the resistance of a saturated porous medium is $\rho_c \dfrac{Le}{\phi A}$

However the resistance of the volume of fluid of the same external dimensions as the saturated porous medium and measured using the same orientation of electrodes is :

Fluid resistance : $\rho_c \dfrac{L}{A}$

Hence

$$F = \underline{\dfrac{\text{Resistance of saturated porous medium}}{\text{Resistance of fluid}}}$$

$$= \dfrac{Le}{L} \times \dfrac{1}{\phi}$$

$$= T^{1/2} \phi$$

$$T = F^2 \phi^2 \qquad T^{1/2} = \dfrac{L}{Le} = F\phi$$

F can be measured easily as shown in section IV using a calibrated resistance in the AC measuring equipment.

The resistance of the fluid is easy to measure when the dimension of the specimen and the conductivity of the liquid are known.

The $\phi$ porosity is known (see section II).

## V - SPECIMENS

Five specimens of sedimentary rocks have been used in the experiments.

### 1- SPECIMEN $A_1$

a) **Origin:** South Maunie field
Palestine sand (Mississipian)
White county  (Illinois)

b) **Mineralogy** Quartz 90 % - Mica

c) **Dimensions** cylinder

length = 4 cm;

$\phi$ = 2.8 cm.

d) **Porosity**

Weight of specimen soaked with water: 59.99 g
Weight of dry specimen: 56.87

Weight of water : 03.12 g

that is a volume of pore of 3.12 cm$^3$

porosity = 13. %

e) **Permeability**

Under a pressure of $30\,psi$, the rise of water level, per minute in a tube of $\phi = 1mm$ is $\frac{47}{5} mm$

rate of flow = 0. 123 $10^{-3} cm^3/s$

**Permeability in Darcys** $k = \dfrac{Q \mu \ell}{\theta P A}$

$\dfrac{Q}{\theta}$ rate flow in $cm^3/s$

$\mu$ viscosity water in centipoises = 1

$P$ atmospheres $= 3 \times 0.069$

$L = 4$ cm.

Under a pressure of $30 psi$, the rise of
water level, per minute in a tube of $\phi = 1mm$ is $\frac{47}{5}$ mm

rate of flow $= 0.123 \cdot 10^{-3}$ cm$^3$/s

## f) Resistivity measurement

AC measurement.

- Calibration of our measurement apparatus.

For 5 volts, high frequency AC current, a
resistance of $100,000 \Omega$ corresponds to a reading of $32.5 \mu A$

1) Measurement with specimen soaked with tap
   water (conductivity $\frac{1}{1925} \Omega^{-1} cm^{-1}$ )

Resistance of specimen soaked with water
$34200 \Omega$

2) Measurement with specimen dipping in salt
   saturated water (conductivity $\frac{1}{4.82} \Omega^{-1} cm^{-1}$).

We have recorded the variation of resistance
versus time, until the specimen is completely saturated
with liquid. See table I and corresponding curve
for specimen A$_1$

## g) Tortuosity

Resistance of fluid : $1250 \Omega$

Resistance specimen : $34200 \Omega$

porosity : $13\%$

$T^{1/2} = 3.5$

2- SPECIMEN $A_2$

a) Origins:     slaughter field
                San Andreas (Permian)
                Cochron Co - Texas

b) Mineralogy

    Dolomite - calcite

c) Dimensions    Cylindrical

    length  :  4.8 cm.
    $\phi$  :  2.8 cm.

d) Porosity

    Weight of specimen soaked with water:  81.66  g
    Weight of dry specimen:                80.37  g

    Weight of water                         1.29  g

        that is   $1.29 \, cm^3$

    Porosity =  4 %

e) Permeability    raise   26.5 mm in 70 minutes


    $k$ Darcys  =  $1.88$        ——          Darcys

f) Resistivity measurement

    1) with specimen soaked with tap water ( $L = \frac{1}{1925} \, \Omega^{-1} cm^{-1}$ )

        Resistance of specimen   $59000 \, \Omega$


    2) specimen in salt water

        see table (I) and curve for $A_2$

g) Tortuosity

    Resistance of fluid  :  $1500 \, \Omega$

    Resistance specimen  :  $59000 \, \Omega$

    Porosity   4 %

        $T^{1/2} = 1.7$

3- SPECIMEN A₃

a) <u>Origins</u>:

West Seminde Field
San Andreas - Permian
Andrecas. Co - Texas

b) <u>Mineralogy</u>

Quartz   essentially

c) <u>Dimensions</u>   Cylindrical

$$l = 45 \text{ mm.}$$
$$\phi = 28 \text{ mm.}$$

d) <u>Porosity</u>

Weight specimen soaked with water:   68.66 g
Weight dry specimen :   <u>63.17 g</u>

5.49 g

that is  $5.49 \text{ cm}^3 \text{ water}$

Porosity = $20\%$

e) <u>Permeability</u>   raise   120 mm in two hours

tube: 8 mm   - pressure $30 psi$

flow = $0.050 \text{ cm}^3/_4$

$$k_{Darcys} = 1.7 \ 10^{-4} \text{ Darcys}$$

f) <u>Resistivity measurement</u>

1) specimen soaked with tap water ( $L = \frac{1}{1925} \ \Omega^{-1} cm^{-1}$ )

$$R = 13800 \Omega$$

2) salt water  - see table I and curve

g) <u>Tortuosity</u>

Resistance of fluid $1400 \Omega$

Resistance specimen $13800 \Omega$

Porosity $20\%$

$$T^{1/2} = 2$$

4- SPECIMEN A4

a) <u>Origin:</u>          Red sandstone - Massachusetts

b) <u>Mineralogy</u>

          Mica - quartz - hematite (very dispersed)

c) <u>Dimensions</u>

$$l = 4.35 \text{ cm.}$$
$$\phi = 2.8 \text{ cm.}$$

d) <u>Porosity</u>

Weight wet specimen:          69.00  g
Weight dry specimen:          67.23  g

Weight water                  1.77  g

     that is     $1.77 cm^3$ water.

Porosity =   7%

e) <u>Permeability</u>

Water level rise  334 mm in 55 minutes

     tube  1 mm.     pressure  $30 psi$

Flow  :   $8 . 10^{-5} cm^3/_s$

Darcys =        $2.73 \ 10^{-7}$                    Darcys

f) <u>Resistivity measurement</u>

1) Specimen soaked with tap water
     $L = \frac{1}{1925} \ \Omega^{-1} cm^{-1}$
     $R = 37,300 \ \Omega$

2) Specimen soaked with salt water
     see table I and curve.

g) <u>Tortuosity</u>

Resistance of fluid  $1350 \Omega$

Resistance specimen $37,300 \, \Omega$

Porosity : $7\%$

$$T^{1/2} : 1.8$$

## 5- SPECIMEN A5

a) <u>Origin</u>　　　　Unknown

b) <u>Mineralogy</u>

　　　　　　　Shale

c) <u>Dimensions</u>

　　　　$\ell = 5.3$ cm.
　　　　$\phi = 2.8$ cm.

d) <u>Porosity</u>

Weight wet specimen :　　　　　90.51　g
Weight dry specimen :　　　　　90.16　g

Weight water　　　　　　　　　0.35　g

　　　that is　　$0.35 \, cm^3$

Porosity = $1\%$

e) <u>Permeability</u>

Water level rise　7.1 mm in 131 minutes

　　$\phi$ tube　1 mm.　　Pressure $30 \, psi$

Flow = $7.15 \quad 10^{-7} \, cm^3/s$

　　$k_{Darcys} = 3.10^{-9} \, Darcy$

f) <u>Resistivity measurement</u>

1) Specimen soaked with tap water
$$L = \frac{1}{1925} \, \Omega^{-1} cm^{-1}$$
$$R = 50,000 \, \Omega$$

2) with salt water
see table I and curve A5

g) <u>Tortuosity</u>

Resistance of fluid      $1645 \ \Omega$

Resistance specimen    $50,000 \ \Omega$

Porosity            $1\%$

$$T^{1/2} = 3.2$$

## Table I

| Time Hours | Conduction Solution $\Omega^{-1}cm^{-1}$ | A1 specimen | | A2 specimen | | A3 specimen | | A4 | | A5 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Current MA | Resistance $\Omega$ | Current MA | Resistance $\Omega$ | Current MA | Resistance $\Omega$ | Current MA | Resist. $\Omega$ | Current $\mu A$ | Resist. $\Omega$ |
| 0 | 1/4,82 | 95 | 34,200 | 65 | 59,200 | 235 | 13,800 | 87 | 37,400 | 67 | 48,500 |
| 1 | | 95 | 34,200 | 65 | 50,000 | 285 | 11,400 | 92 | 35,300 | 69 | 47,200 |
| 2 | | 185 | 17,600 | 68 | 48,000 | 325 | 10,000 | 95 | 34,200 | 77 | 42,500 |
| 4,75 | | 225 | 14,400 | 71 | 44,000 | 415 | 7,840 | 160 | 20,300 | 89 | 36,500 |
| 8 | | 265 | 12,300 | 77 | 42,300 | 530 | 6,140 | 205 | 15,900 | 95 | 34,200 |
| 11 | | 320 | 10,200 | 80 | 40,700 | 710 | 4,580 | 260 | 12,500 | 148 | 22,000 |
| 19,50 | | 515 | 6,300 | 85 | 38,200 | 960 | 3,390 | 425 | 7,650 | 195 | 16,700 |
| 23 | | 600 | 5,400 | 80 | 40,700 | 960 | 3,390 | 470 | 6,930 | 198 | 16,400 |
| 27 | | 730 | 4,450 | 83 | 39,200 | 1820 | 1,790 | 560 | 5,810 | 225 | 14,400 |
| 31 | | 870 | 3,700 | 84 | 38,700 | 2210 | 1,470 | 670 | 4,860 | 245 | 13,300 |
| 44 | | 1600 | 2,030 | 86 | 37,800 | 2,620 | 1,240 | 910 | 3,570 | 310 | 10,500 |
| 50 | | 1750 | 1,860 | 86 | 37,800 | 2,700 | 1,200 | 1120 | 2,900 | 335 | 9,700 |
| 69,50 | | 2100 | 1,550 | 87 | 37,400 | 2,820 | 1,150 | 1600 | 2,030 | 400 | 8,130 |
| 75,50 | | 2230 | 1,450 | 87 | 37,400 | 2,820 | 1,150 | 1560 | 2,080 | 410 | 7,930 |
| 79,75 | | 2270 | 1,430 | 88 | 36,900 | 2,900 | 1,120 | 1625 | 2,000 | 430 | 7,560 |
| 94,50 | | 2420 | 1,340 | 88 | 36,900 | 2,880 | 1,130 | 1790 | 1,830 | 470 | 6,920 |
| 98 | | 2400 | 1,350 | 89 | 36,500 | 2,950 | 1,100 | 1800 | 1,810 | 490 | 6,640 |

## VI - STREAMING POTENTIALS

The streaming potentials created in our rock samples were measured in order to compute an average potential for these rocks.

However we found thatthe surface conduction plays a very important role in these electro-kinetic phenomena.

- We then tried to make a correction for the surface conduction, in the evaluation of the $\xi$ potential.

- The role played by surface conduction in brought out by resistivity measurements of each specimen soaked in liquids of different conductivities. If the resistances of the sample do not vary proportionally with the specific resistivity of the liquids in which they soak, we have a proof of the role of surface conduction and a way to compute its influence.

### I- A$_1$ SPECIMEN

a) Rock specimen

The specimen after soaking in water (conductivity $\frac{1}{1925}$ $\Omega^{-1}cm^{-1}$) is placed under a high frequency potential of 5 volts amplitude.

The measured current passing through the

specimen is $95 \mu A$

When a 5 volts potential is applied to the same specimen after soaking in a saturated salt solution of conductivity $\frac{1}{4.82} \Omega^{-1} cm^{-1}$, the current passing through the sample is $2400 \mu A$

$$\frac{95}{2400} = \frac{\frac{2\lambda_4}{r} + \lambda_1}{\frac{2\lambda_4}{r} + \lambda_2}$$

If $\frac{2\lambda_4}{r} = A$

$$\frac{95}{2400} = \frac{\frac{1}{1925} + A}{\frac{1}{4.82} + A}$$

We get $A = 8.10^{-3} \Omega^{-1} cm^{-1}$

Total conductivity

$$(0.52 + 8.10^{-3}) \Omega^{-1} cm^{-1}$$

Or after conversion in the c.g.e.s. system :
$8.52 . 10^{-3} \; 9.10^{11} = 8.52 \times 9 \times 10^{8}$ cgses units

We know from equation (9)

$$\frac{\xi}{\zeta} = \frac{E 4 \pi \eta \left(\lambda + \frac{2\lambda_4}{r}\right)}{P_x \, \epsilon}$$

$\eta$ : coefficient of viscosity in poises       for water.

$\epsilon$ : the dielectric constant of water has been considered as having the value 80

$P$ : must be expressed in dynes/

$E$ = in millivolts

$\lambda + \frac{2\lambda_4}{r}$ observed in $\Omega^{-1} cm^{-1}$ must be multiplied by $9 \times 10^{11}$ to convert it into c.g.e.s. units.

Average for $E$ = 16 millivolts (Table II)

## TABLE II

## A₁ SPECIMEN - Rock sample

## Streaming potentials

| Tests | Voltage at 0 psi in Millivolts | Voltage at 30 psi in Millivolts | Streaming Potential in Millivolts | Voltage at 30 psi in Millivolts | Voltage at 0 psi in Millivolts | Streaming Potential in Millivolts |
|---|---|---|---|---|---|---|
| 1 | 38 | 24 | 14 | 28 | 44 | 16 |
| 2 | 38 | 22,5 | 15.5 | 25 | 39 | 14 |
| 3 | 36 | 21 | 15 | 23 | 39 | 16 |
| 4 | 36 | 20 | 16 | 24 | 39 | 15 |
| 5 | 34 | 18 | 16 | 22 | 37 | 15 |
| 6 | 32 | 16 | 16 | 20 | 36 | 16 |
| 7 | 28 | 12 | 16 | 18 | 34 | 16 |
| 8 | 30 | 14 | 16 | 18 | 34 | 16 |
| 9 | 30 | 14 | 16 | 18 | 35 | 17 |
| 10 | 30 | 14 | 16 | 18 | 36 | 18 |
| 11 | 30 | 14 | 14 | 18 | 36 | 18 |
| 12 | 30 | 14 | 16 | 15 | 32 | 17 |
| 13 | 30 | 14 | 16 | 15 | 31 | 16 |
| 14 | 30 | 14 | 16 | 15 | 32 | 17 |
| 15 | 30 | 14 | 16 | 17 | 35 | 18 |

Average streaming potential

16 ± 1 millivolts

+        -
|————|————|————> P    polarity

# TABLE III

## $A_1$ SPECIMEN - Ground rock

### Streaming potential

| Tests | Voltage P= 0cm water in millivolts | Voltage P= 85cm w. in millivolts | streaming potential in millivolts | Voltage P= 85cm water in millivolts | Voltage P= 0cm water in millivolts | streaming Potential in millivolts |
|-------|-----|-----|-----|-----|-----|-----|
| 1 | 18.6 | 17.4 | 1.2 | 17.4 | 19 | 1.6 |
| 2 | 18.6 | 17.2 | 1.4 | 17.2 | 19.4 | 2.2 |
| 3 | 18.6 | 17 | 1.6 | 16.4 | 19 | 2.6 |
| 4 | 18.6 | 16.4 | 2.2 | 16.4 | 18.7 | 2.3 |
| 5 | 18.4 | 16.2 | 2.2 | 16.8 | 18.6 | 1.8 |
| 6 | 18.2 | 16 | 2.2 | 16 | 18.4 | 2.4 |
| 7 | 18.2 | 16 | 2.2 | 16 | 18.4 | 2.4 |
| 8 | 18.2 | 16 | 2.2 | 16 | 18.4 | 2.4 |
| 9 | 18.2 | 16 | 2.2 | 16 | 18.4 | 2.4 |
| 10 | 18.2 | 15.8 | 2.4 | 15.8 | 18.2 | 2.4 |
| 11 | 18 | 15.8 | 2.2 | 15.8 | 18.1 | 2.3 |
| 12 | 18 | 15.6 | 2.4 | 15.6 | 18.1 | 2.5 |
| 13 | 18 | 15.5 | 2.5 | 15.5 | 18 | 2.5 |
| 14 | 18 | 15.5 | 2.5 | 15.5 | 17.8 | 2.3 |
| 15 | 17.6 | 15.2 | 2.4 | 15.2 | 17.6 | 2.4 |

Average streaming potential

$$2 \pm 1 \text{ mv.}$$

polarity

$P \rightarrow$   Pressure
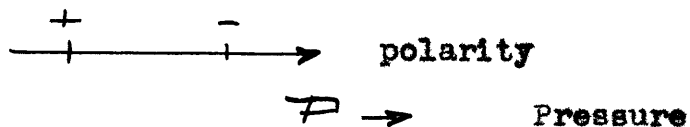
b) <u>Ground specimen</u>

No evidence of surface conduction was noted. This has
been checked by measuring the resistance of a glass
tube filled with the ground specimen, impregnated with
liquids of various conductivities.

$$\frac{\varepsilon}{\gamma} = \frac{E \; 4\pi \; \eta \; \lambda}{p \; \varepsilon}$$

$$E = 2 mv \qquad \text{Table III}$$

$$\eta = \; 0.01 \; poises$$

$$\lambda = \frac{1}{2600} \; 9 \cdot 10'' \; cgses \; units$$

$$\varepsilon = \; 80 \; cgses \; units$$

$$p = \; 85 \; cm \; water \; = \; 85 \times 980.638 \; dynes/cm$$

$$\frac{\varepsilon}{\gamma} = \frac{2 \times 0.01 \times 9 \times 10'' \times 4\pi}{2600 \times 85 \times 980.638 \times 80}$$

$$= -14 \; millivolts$$

## 2- A₂ SPECIMEN

a) <u>Rock specimen</u>

Specimen after soaking in water (conductivity
$\frac{1}{1925} \; \Omega^{-1} cm^{-1}$ )

Potential  $5V - A.C$    Current  $55 \mu A$

Specimen after soaking in salt water
(conductivity $\frac{1}{4.82} \Omega^{-1} cm^{-1}$ )

Potential  $5V \; A.C$    Current  $89 \mu A$

Determination of surface conduction :

# TABLE IV

## A$_2$ SPECIMEN - Solid rock

### Streaming potential

| Tests | Voltage p=0 psi in Millivolts | Voltage p=30 psi in Millivolts | Streaming Potential in Millivolts | Voltage p=30 psi in Millivolts | Voltage p=0 psi in Millivolts | Streaming Potential in Millivolts |
|-------|-------|-------|-------|-------|-------|-------|
| 1 | 30 | 26.5 | 3.5 | 34 | 38.5 | 4.5 |
| 2 | 33 | 30 | 3 | 35 | 38 | 3 |
| 3 | 36 | 33 | 3 | 36 | 39.5 | 3.5 |
| 4 | 35 | 32 | 3 | 36 | 40 | 4 |
| 5 | 36 | 32.5 | 3.5 | 38 | 41 | 3 |
| 6 | 37 | 33 | 4 | 37 | 41 | 4 |
| 7 | 36 | 32.5 | 3.5 | 36 | 39.5 | 3.5 |
| 8 | 36 | 32 | 4 | 35 | 39 | 4 |
| 9 | 36 | 32 | 4 | 34 | 38.5 | 4.5 |
| 10 | 35 | 31 | 4 | 35 | 39 | 4 |

Average streaming potential

$4 \pm 1$ mv.

polarity

+      − 

⟶ Pressure

# TABLE V

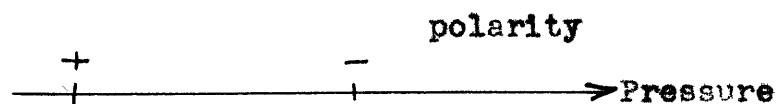## A$_2$ SPECIMEN - Ground rock

### Streaming potentials

| Test | Voltage p=0 cm.water | Voltage p=80 cm.water | Streaming potential | Voltage p=80 cm.water | Voltage p=0 cm.water | Streaming potentials |
| --- | --- | --- | --- | --- | --- | --- |
| | in millivolts | millivolts | millivolts | millivolts | millivolts | millivolts. |
| 1 | 14 | 9.6 | 4.4 | 9.6 | 15.6 | 6 |
| 2 | 16 | 11 | 5 | 11 | 16.2 | 5.2 |
| 3 | 16.6 | 11.8 | 4.8 | 11.8 | 17 | 5.2 |
| 4 | 17 | 12.2 | 4.8 | 12.2 | 17.2 | 5 |
| 5 | 17.6 | 12.6 | 5 | 4.2 | 9.2 | 5 |
| 6 | 18 | 13.2 | 4.8 | 13.6 | 18.3 | 4.7 |
| 7 | 18.2 | 12.6 | 5.6 | 12.6 | 16.6 | 4 |
| 8 | 16 | 11.2 | 4.8 | 11.2 | 16 | 4.8 |
| 9 | 15 | 10 | 5 | 10 | 15 | 5 |
| 10 | 14.6 | 10 | 4.6 | 10 | 14.6 | 4.6 |
| 11 | 15 | 10 | 5 | 10 | 15 | 5 |
| 12 | 15 | 10.4 | 4.6 | 10.4 | 15 | 4.6 |
| 13 | 16 | 11.4 | 4.6 | 11.4 | 16.4 | 5 |
| 14 | 16.4 | 11.8 | 4.6 | 11.8 | 17 | 5.2 |
| 15 | 17 | 12.4 | 4.6 | 12.4 | 17 | 4.6 |

Average streaming potentials

5 ± 1 mv.

+            −            polarity

———————————————————→    Pressure
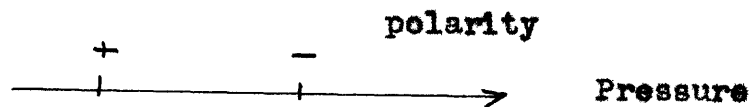
$$\frac{55}{89} = \frac{\frac{1}{1925} + A}{\frac{1}{4.82} + A}$$

$$A = 324 . \; 10^{-3} \Omega^{-1} cm^{-1}$$

$$\frac{\mathcal{E}}{7} = \frac{E 4 \pi \eta \left( \lambda + \frac{2 \lambda \prime}{r} \right)}{p \times \epsilon}$$

E= 324 millivolts

$$\lambda + \frac{2\lambda \prime}{r} = (324 + 0.52) \, 10^{-3} \times 9 \times 10^{11} \, \Omega^{-1} cm^{-1}$$

all other factors see p (17)

$$\frac{\mathcal{E}}{7} = - \; 830 \; millivolts$$

b) <u>Ground specimen</u>

No surface conduction

$$P = 80 \, cm \; water = 80 \times 980.638 \; dynes/cm^2$$

$$E = 4.87 \; millivolts$$

others factors, see section about $A_1$ specimen.

$$\frac{\mathcal{E}}{7} = - \; 34 \; millivolts$$

3- $A_3$ SPECIMEN

a) Specimen after soaking in water

(conductivity $\frac{1}{1925}$ $\Omega^{-1} cm^{-1}$)

Potential 5V     AC     Current 235 $\mu A$

Specimen after soaking in salt water

(conductivity $\frac{1}{4.82}$ $\Omega^{-1} cm^{-1}$)

Potential     5V.    AC    Current 2950 $\mu A$

# TABLE VI

## A₃ SPECIMEN - Solid rock
## Streaming potentials

| Test. | Voltage P = 0 psi  millivolts | Voltage P = 10 p.s.i  millivolts | Streaming potential  millivolts | Voltage 10 p.s.i  millivolts | Voltage p: 0 psi  millivolts | Streaming potential  millivolts. |
|-------|------|------|------|------|------|------|
| 1  | 20   | 37   | 17   | 37   | 20   | 17   |
| 2  | 17   | 35   | 18   | 30   | 12   | 18   |
| 3  | 13   | 31   | 18   | 31   | 13   | 18   |
| 4  | 11   | 28   | 17   | 25   | 8    | 17   |
| 5  | 11.5 | 28   | 16.5 | 25   | 8    | 17   |
| 6  | 8    | 28   | 20   | 28   | 8    | 20   |
| 7  | 8    | 28   | 20   | 23   | 7    | 16   |
| 8  | 9    | 25   | 16   | 25   | 9    | 16   |
| 9  | 7    | 23   | 16   | 21   | 5    | 16   |
| 10 | 6    | 25   | 19   | 42   | 22   | 20   |
| 11 | 18.5 | 36   | 17.5 | 33   | 16   | 17   |
| 12 | 16.5 | 34.5 | 18   | 31   | 15   | 16   |
| 13 | 15   | 33   | 18   | 30   | 12.5 | 17.5 |
| 14 | 15   | 33   | 18   | 30   | 13   | 17   |
| 15 | 15   | 33   | 18   | 32   | 13   | 19   |

Average streaming potentials

18 ± 1 mv.

polarity

+      −      Pressure
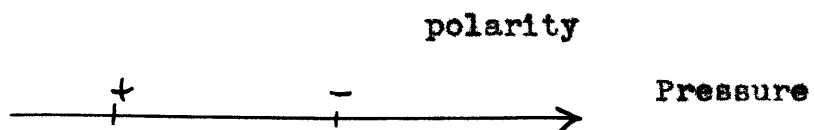
# TABLE VII

## $A_3$ SPECIMEN - Ground rock
## Streaming potentials

| Test. | Voltage p=0 p.s.i millivolts | Voltage p=10 p.s.i millivolts | Streaming Potentials millivolts | Voltage 10 p.s.i millivolts | Voltage p=0 p.s.i millivolts | Streaming potential millivolts |
|---|---|---|---|---|---|---|
| 1 | 8.6 | 6.4 | 2.2 | 6.4 | 9.2 | 2.8 |
| 2 | 9.2 | 6.6 | 2.6 | 6.6 | 9.6 | 3 |
| 3 | 9.4 | 6.6 | 2.8 | 6.8 | 10 | 3.2 |
| 4 | 9.8 | 7 | 2.8 | 7 | 10.2 | 3.2 |
| 5 | 10 | 7 | 3 | 7 | 10.4 | 3.4 |
| 6 | 10.2 | 7.2 | 3 | 7.2 | 10.6 | 3.4 |
| 7 | 10.4 | 7.3 | 3.1 | 7.3 | 10.8 | 3.5 |
| 8 | 10.6 | 7.4 | 3.2 | 7.8 | 11.2 | 3.4 |
| 9 | 11 | 7.8 | 3.2 | 7.8 | 11.2 | 3.4 |
| 10 | 11.0 | 7.8 | 3.2 | 7.8 | 11.2 | 3.4 |
| 11 | 10.8 | 7.8 | 3.2 | 7.8 | 11.3 | 3.8 |
| 12 | 11 | 7.8 | 3.2 | 7.8 | 11.3 | 3.5 |
| 13 | 11 | 8 | 3 | 8 | 11.4 | 3.4 |
| 14 | 11.2 | 8.2 | 3 | 8.2 | 11.6 | 3.4 |
| 15 | 11.4 | 8.3 | 3.1 | 8.3 | 11.8 | 3.5 |

Average streaming potentials

3 ± 1 mv.

polarity

+        −

$$\frac{235}{2950} = \frac{\frac{1}{1925} + A}{\frac{1}{4.82} + A}$$

$$A = 17.6 \quad 10^{-3} \Omega^{-1} cm^{-1}$$

$$\lambda + \frac{2\lambda_d}{r} = (17.6 + 0.52) 10^{-3} \Omega^{-1} cm^{-1} = 18.1 \ 10^{-3} \Omega^{-1} cm^{-1}$$

$$\frac{\mathscr{E}}{7} = -70 \ millivolts$$

### b) Ground rock

No surface conduction

$$P = 85 \, cm \ water = 85 \times 980.638 \ dynes/cm^2$$

$$E = 3 \, mv$$

other factors identical to the ones used for

$$\frac{\mathscr{E}}{7} = -16 \ millivolts$$

### 4- A₄ SPECIMEN

### a) Rock specimen

Specimen after soaking in water (conductivity $\frac{1}{1925} \Omega^{-1} cm^{-1}$)

Potential  $5V \quad AC$　　　　Current  $87 \mu A$

Specimen after soaking in salt water

Conductivity  $\frac{1}{4.82} \Omega^{-1} cm^{-1}$

Potential  $5V \quad AC$　　　　Current  $1800 \mu A$

$$\frac{87}{1800} = \frac{\frac{1}{1925} + A}{\frac{1}{4.82} + A}$$

$$A = 0.010 \ \Omega^{-1} cm^{-1}$$

$$\lambda + \frac{2\lambda_d}{r} = (10 + 0.52) 10^{-3} \Omega^{-1} cm^{-1}$$

$$\frac{\mathscr{E}}{7} = -82 \ millivolts$$

# TABLE VIII

## A4 SPECIMEN — Solid rock

## Streaming potentials

| Test. | Voltage p:0 p.s.i millivolts | Voltage p:30 p.s.i millivolts. | Streaming potential millivolts | Voltage p:30 psi millivolts | Voltage p:0 p.s.i millivolts | Streaming potential millivolts. |
|-------|------|------|------|------|------|------|
| 1 | 43 | 32 | 11 | 32 | 45 | 13 |
| 2 | 45 | 34 | 11 | 34 | 45 | 11 |
| 3 | 45 | 34 | 11 | 34 | 45 | 11 |
| 4 | 45 | 34 | 11 | 34 | 45.5 | 11.5 |
| 5 | 45.7 | 35 | 10.7 | 35 | 46.5 | 11.5 |
| 6 | 46.5 | 35 | 11.5 | 35 | 47 | 12 |
| 7 | 47 | 36.5 | 10.5 | 36.5 | 47 | 10.5 |
| 8 | 47.5 | 36.5 | 11 | 36.5 | 47.5 | 11 |
| 9 | 47.5 | 36.5 | 11 | 36.5 | 48.5 | 12 |
| 10 | 49 | 37.5 | 11.5 | 37.5 | 49.5 | 12 |
| 11 | 50 | 38.5 | 11.5 | 38.5 | 50 | 11.5 |

Average Streaming Potentials

11 ± 1 mv.

# TABLE IX

## A4 SPECIMEN – Ground rock

## Streaming potentials

| Test. | Voltage p: 0 cm. water millivolts. | Voltage p: 75 cm water millivolts | Stream. potential millivolts | Voltage p: 75 cm water millivolts | Voltage p: 0 cm. water millivolts | Streaming potential millivolts |
|---|---|---|---|---|---|---|
| 1 | 57.4 | 52.4 | 5 | 52.4 | 57.4 | 5 |
| 2 | 55 | 50.2 | 4.8 | 50.2 | 55 | 4.8 |
| 3 | 49.4 | 54.2 | 4.8 | 54.2 | 49 | 522 |
| 4 | 48 | 53 | 5 | 53 | 48 | 5 |
| 5 | 48 | 53 | 5 | 53 | 48 | 5 |
| 6 | 47.8 | 52.4 | 4.8 | 52.4 | 47.8 | 4.8 |
| 7 | 57.4 | 53 | 4.4 | 53 | 57.4 | 4.4 |
| 8 | 58.7 | 53.6 | 5.1 | 53.6 | 58.7 | 5.1 |
| 9 | 59 | 54.4 | 4.6 | 54.4 | 59 | 4.6 |
| 10 | 59.2 | 54.2 | 5 | 54.2 | 59.2 | 5 |
| 11 | 59.6 | 54.6 | 5 | 54.6 | 59.6 | 5 |
| 12 | 60 | 54.8 | 5.2 | 54.8 | 60.2 | 5.4 |
| 13 | 60.2 | 55 | 5.2 | 55 | 60.3 | 5.3 |
| 14 | 38 | 33 | 5 | 33 | 38 | 5 |
| 15 | 38 | 32.8 | 5.2 | 32.8 | 38 | 5.2 |

Average streaming potential

5 ± 1 mv.

b) <u>Ground specimen</u>

No evidence of surface conduction

$$\frac{\xi}{\zeta} = \frac{E \, 4\pi \eta \lambda}{p \, \epsilon}$$

$E = 5 \, millivolts$      $p = 75 \times 980. \, 638 \, dynes/cm^2$

for other factors see previous calculation.

$$\frac{\xi}{\zeta} = -37 \, millivolts$$

## 5- A₅ SPECIMEN

a) <u>Rock specimen</u>

Specimen after soaking in water

Conductivity $\frac{1}{1925} \, \Omega^{-1} cm^{-1}$

Potential $5 \, V$    $AC$      Current   $65 \mu A$

After soaking in salt water      $2950 \mu A$

Surface conductance determination

$$\frac{65}{490} = \frac{\frac{1}{1925} + A}{\frac{1}{4.82} + A}$$

$$A = 31.1 \quad 10^{-3}$$

$$\lambda + \frac{2\lambda d}{r} = 31.62 \times 10^{-3}$$

$$E = 2 \, millivolts$$

$$\frac{\xi}{\zeta} = -40$$

# TABLE X

## A₅ SPECIMEN - Solid rock

## Streaming potentials

| Test. | Voltage p: 0 p.s.i millivolts | Voltage p: 30 p.s.i millivolts | Streaming potential millivolts | Voltage p: 30 p.s.i millivolts | Voltage p: 0 p.s.i millivolts | Streaming potential millivolts |
|-------|-------|-------|-------|-------|-------|-------|
| 1  | 36   | 35   | 1   | 35   | 37   | 2   |
| 2  | 37   | 35.6 | 1.4 | 35   | 37.7 | 2.7 |
| 3  | 36   | 35   | 1   | 35   | 38   | 3   |
| 4  | 38   | 36.5 | 1.5 | 36.5 | 38.5 | 1.5 |
| 5  | 38   | 36.5 | 1.5 | 36.5 | 39   | 2.5 |
| 6  | 37.5 | 36   | 1.5 | 36   | 39   | 3   |
| 7  | 38.5 | 37   | 1.5 | 37   | 39   | 2   |
| 8  | 38   | 37   | 1   | 37   | 40   | 3   |
| 9  | 40   | 38   | 2   | 38   | 40   | 2   |
| 10 | 40   | 38   | 2   | 38   | 40   | 2   |
| 11 | 40   | 38   | 2   | 38   | 40   | 2   |
| 12 | 40   | 38   | 2   | 38   | 40   | 2   |
| 13 | 40   | 38.5 | 1.5 | 38   | 39.5 | 1.5 |
| 14 | 39   | 37.5 | 1.5 | 37.5 | 39   | 1.5 |
| 15 | 39   | 37.5 | 1.5 | 37.5 | 39.5 | 2   |

Average streaming potential

2 ± 1 mv.

# TABLE XI

## A5 SPECIMEN - Ground rock

### Streaming potentials

| Test. | Voltage p: 0 cu. water milli volts | Voltage p: 35 cu. water milli volts | Streaming potential milli volts | Voltage p: 35 cu. water milli volts | Voltage p: 0 cu. water milli volts | Streaming potential milli volts. |
|---|---|---|---|---|---|---|
| 1  | 30   | 34   | 4   | 33  | 29   | 4   |
| 2  | 30   | 34   | 4   | 34  | 31   | 3   |
| 3  | 31   | 34.5 | 3.5 | 34  | 31.7 | 2.3 |
| 4  | 32   | 35   | 3   | 35  | 32   | 3   |
| 5  | 31.5 | 35   | 3.5 | 34  | 31   | 3   |
| 6  | 31   | 34   | 3   | 34  | 31   | 3   |
| 7  | 31   | 34   | 3   | 34  | 31   | 3   |
| 8  | 31   | 34   | 3   | 34  | 31   | 3   |
| 9  | 31   | 34   | 3   | 34  | 31   | 3   |
| 10 | 29.5 | 33   | 3.5 | 32  | 29   | 3   |
| 11 | 29   | 32   | 3   | 31.5| 29   | 2.5 |
| 12 | 29   | 32   | 3   | 31.5| 29   | 2.5 |
| 13 | 29   | 31   | 2   | 31  | 29   | 2   |
| 14 | 28   | 31   | 3   | 30  | 28   | 2   |
| 15 | 28   | 31   | 3   | 30  | 27   | 3   |

Average streaming potential

$3 \pm 1$ mv.

b) <u>Ground rock</u>

No surface conduction

$$\frac{\xi}{\zeta} = \frac{E 4 \pi \eta \lambda}{p \epsilon}$$

$E = 3 mv$          $p = 85 \times 980.638 \ dynes/cm^2$

for other factors, see other specimens.

$$\frac{\xi}{\zeta} = -15 \ millivolts$$

As we can see our results are very divergent, even for $\xi$ potentials of the same type of rocks.

In order to relate these results to the physical properties of our rocks, it would be good to come back again on the permeability factor from Onsager's equation.

As we have already noticed in the previous section, the flow of liquid passing through the porous rocks depends not only upon the pressure factor, but also upon the streaming potential set up.

## VI- PERMEABILITY AND THE ONSAGER RELATIONS

$$I = L_{11} \, \Delta \varphi + L_{12} \, \Delta P$$
$$J = L_{21} \, \Delta \varphi + L_{22} \, \Delta P$$

Let us first try to find the dimension formulas of the coefficients $L_{11}, L_{12}, L_{21}, L_{22}$ , we want to compute

$I$ is a current          $\Delta \varphi$ a voltage          $\Delta P$ a pressure

Equation (1) can be written

$$\frac{q}{T} = L_{11} \left( \frac{F}{Q} L \right) + L_{12} \frac{F}{L^2}$$

$$L_{11} = \frac{q^2}{FTL} \qquad\qquad L_{12} = \frac{qL^2}{FT}$$

J is a volume of water per second.

Equation (2) can be written

$$\frac{L^3}{T} = L_{21} \left( \frac{FL}{Q} \right) + L_{22} \left( \frac{F}{L^2} \right)$$

$$L_{21} = \frac{qL^2}{FT} \qquad\qquad L_{22} = \frac{L^5}{TF}$$

dimensionally $\quad L_{21} = L_{12}$

Let us see now the importance of the term in the determination of J, that is in the determination of the permeability of our specimens of rocks.

### Let us consider the specimen Aₕ

a)    $I = L_{11} \, \Delta \varphi \quad$ when $\Delta P = 0$

that is the case of our resistivity measurement, a voltage of 5 volts being applied at the ends of our specimen

J is a volume of water per second.

Equation (2) can be written

$$\frac{L^3}{T} = L_{21}\ \frac{FL}{9} + L_{22}\ \frac{F}{L^2}$$

dimensionally

Let us now see the importance of the term
in the determination of J, that is in the determination
of the permeability of our specimens of rocks.

Let us consider the specimen $A_4$.

a)

that is the case of our resistivity measurement,
a voltage of 5 volts being applied  at the ends of our
specimen.

$L_{//}$  is merely the conductivity of the sample
of rock.

$L_{11}$ is merely the conductivity of the sample of rock.

Resistance of the specimen $\frac{37500}{9}$ $10^{-11}$ cgses units

$$L_{11} = \frac{9}{37500} \; 10^{11} \text{ cgses units}$$
$$= 2.4 \; 10^{7} \text{ cgses units}$$

$$I = 0 \qquad \frac{\Delta \varphi}{\Delta P} = -\frac{L_{12}}{L_{11}}$$

$$\Delta \varphi = 11.35 \text{ millivolts} = \frac{11.35}{1000 \times 300} \text{ cgses units}$$

$$\Delta P = 30 \times 68947 \text{ dynes/cm}^2$$

$$-L_{12} = -42 . 10^{-5}$$

$$J = 8 . 10^{-5} \text{ cm}^3/\text{s}$$

We then have :

$$8 . 10^{-5} = 16 . 10^{-9} + L_{22} \Delta P$$

We thus see that the term $L_{22} \Delta \varphi$ is small comparatively to J

and do not make any appreciable error by writing
$J = L_{22} \Delta P$

All our determinations of permeability have been made under this assumption. We shall consider them true.

## VII - DISCUSSION AND CONCLUSION

|  | A$_1$ | A2 | A3 | A4 | A$_5$ |
|---|---|---|---|---|---|
| $\xi$ rock sample in millivolts | -93 mv | -830 | -70 mv | -82 mv | -40 mv |
| $\xi$ ground rock sample | -14 mv | -34 mv | -16 mv | -37 mv | -15 mv |
| Porosity | 13 % | 4 % | 20 % | 7 % | 1 % |
| Permeability Darcys | $38.10^{-7}$ | $1.88.10^{-7}$ | $1.7.10^{-4}$ | $2.73.10^{-7}$ | $3.10^{-9}$ |
| Tortuosity $\frac{Le}{L}$ | 3.5 | 1.7 | 2 | 1.8 | 3.2 |
| Resistance sp. liquid: tap water | 34200 | 59000 | 13800 | 37300 | 50.000 |
| Resistance sp. liquid salt water | 1350 | 36500 | 1100 | 1810 | 6.640 |
| Surface cond. $\frac{2\lambda s}{r}$ $\Omega^{-1}cm^{-1}$ | $8.10^{-3}$ | $324.10^{-3}$ | $17.6 \ 10^{-3}$ | $10. \ 10^{-3}$ | $31.1 \ 10^{-3}$ |
| Conduct. liquid $\Omega^{-1}cm^{-1}$ | $0.52 \ 10^{-3}$ | $0.52 \ 10^{-3}$ | $0.52 \ 10^{-3}$ | $0.52.10^{-3}$ | $0.52.10^{-3}$ |

The important role played by surface conductance in electro-kinetic effects occuring in solid rocks is shown by these experiments.

This surface conductance effect seems to be an important factor in electro-kinetic measurements when the conductivity of the liquid is very low, or when the diameter of the pores is small.

The $\xi$ potentials computed from the streaming potentials occuring in solid rocks lead to fairly good results when the "surface conduction" correction has been made.

The results are very close to those which have been obtained with ground quartz.

1- $A_5$ has a very small porosity and small permeability. The factor of surface conductance is then very large as expected.

2- $A_1$ and $A_3$ are quartz samples. It is surprising to note that the surface conductance of $A_3$ is big compared to $A_1$, even though the porosity and permeability of $A_3$ are bigger than that of $A_1$

It is possible that there are some additional minerals in one of the specimens which have caused this discrepancy in the results.

The $\xi$ potential we obtain are an average of the $\xi$ potentials of the different minerals composing each specimen.

- The tortuosity is a factor which could affect the type of flow of the liquid inside the capillaries.

However, even if the flow is turbulent, it has been proved to remain laminar in the double layer.

The shape of the crystals in the rock specimen could also be a factor influencing the type of flow.

- The $\xi$ potentials obtained from ground rocks show very big discrepancies with the $\xi$ potentials obtained

from solid rocks.

- These discrepancies may be due to turbulent flow, or just to flaws in the equipment.

It is easy to see that since the value of streaming potentials are small, their importance will be small in the measurements of induced polarization effects.

The Onsager equation gives the following relationship:

$$J = L_{11} \, \Delta \varphi + L_{12} \, \Delta P \tag{1}$$

In the induced polarization effects, the value $\frac{I}{\Delta \varphi}$ is measured.

$L_{12} \, \Delta P$ seems to be a very small factor and practically $\frac{I}{\Delta \varphi} = L_{11}$ can be employed.

However, when the Zeta potential of the rocks, as well as their surface conduction (easy to measure) is known, the necessary correction can be made according to equation (1).

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