GASTEM International
Lecture Tour

Measurements, modelling and applications of the electro-kinetic properties of rocks

Paul Glover

Université Laval, Québec, Canada

Plan

- Introduction
- Origin
- Theory
- Laboratory determinations
- Applications
- Conclusions
- Future directions
- Acknowledgments

Introduction

Introduction I

What are electro-kinetic properties?

Electro-kinetic phenomena

The generation of an electrical potential difference across a porous medium by the flow of fluid through it, or vice versa

Flow causes potential → **Electro-kinetics**
Potential causes flow → **Electro-osmosis**

Electro-seismic phenomena

The generation of an electro-magnetic wave in a porous medium by the passage of an elastic wave through it, or vice versa

Elastic wave causes EM wave → **Seismo-electric conversion**
EM wave causes elastic wave → **Electro-seismic conversion**

Introduction II

Principal applications

- ➢ Electro-kinetic phenomena
  - ✓Hydrocarbon production
  - ✓Water reservoir management
  - ✓Remediation of polluted soils
  - ✓Volcano prediction
  - ✓Earthquake prediction
  - ✓Synthetic earthquakes

Polymer sciences, membrane sciences, catalysis, microfluidics, food science, medical science

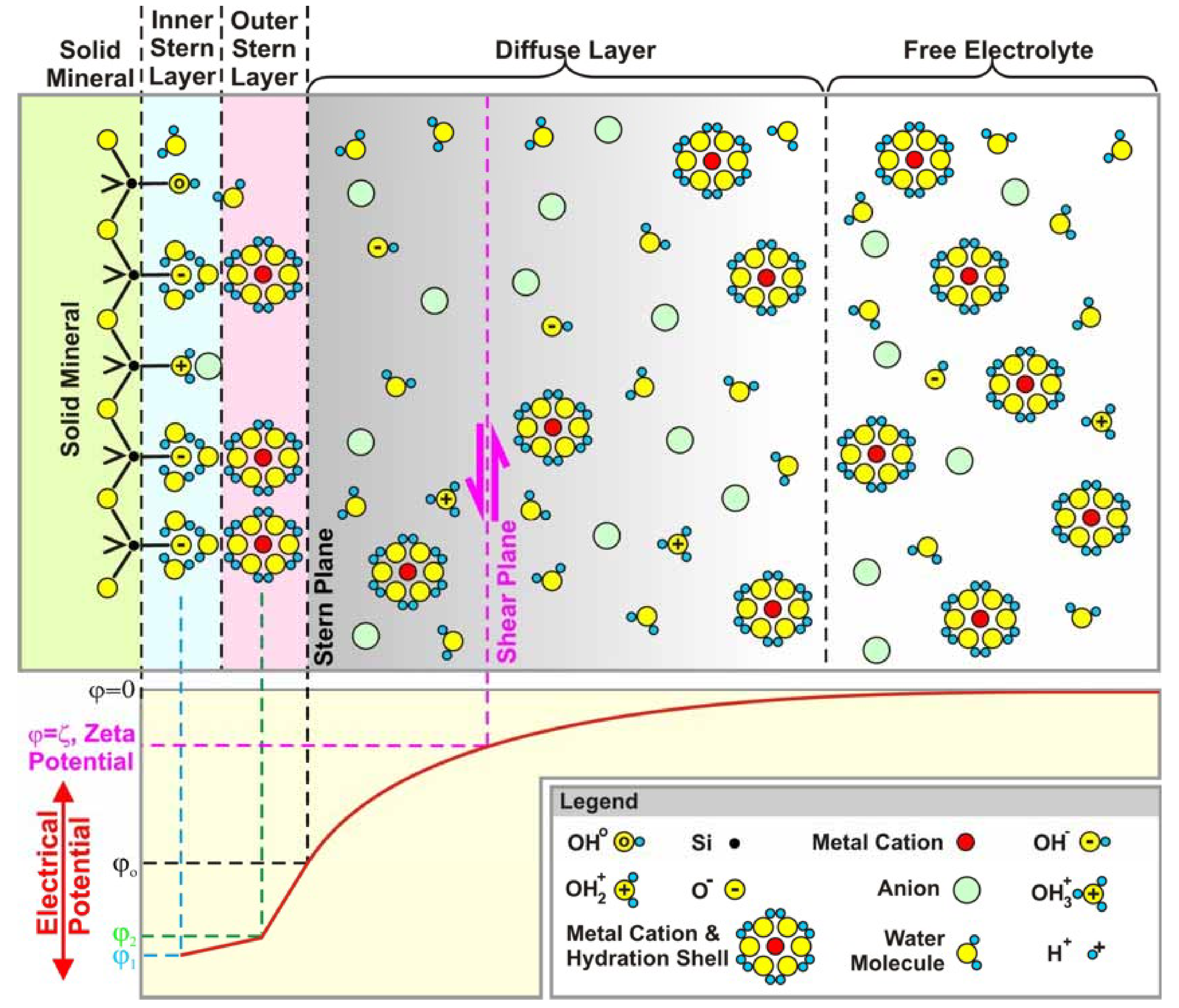
- ➢ Electro-seismic phenomena
  - ✓Hydrocarbon exploration & production
  - ✓Water reservoir management
  - ✓Volcano prediction
  - ✓Earthquake prediction

Origins

Origin

- The electrical “double” layer
- Debye thickness
- Surface conduction
- Electro-seismic conversion

Origin - The electrical double layer



Plan

Introduction

Origin

Theory

Apparatus

Laboratory determination

Applications

Conclusions

Future directions

Origin - The electrical double layer

There exists:

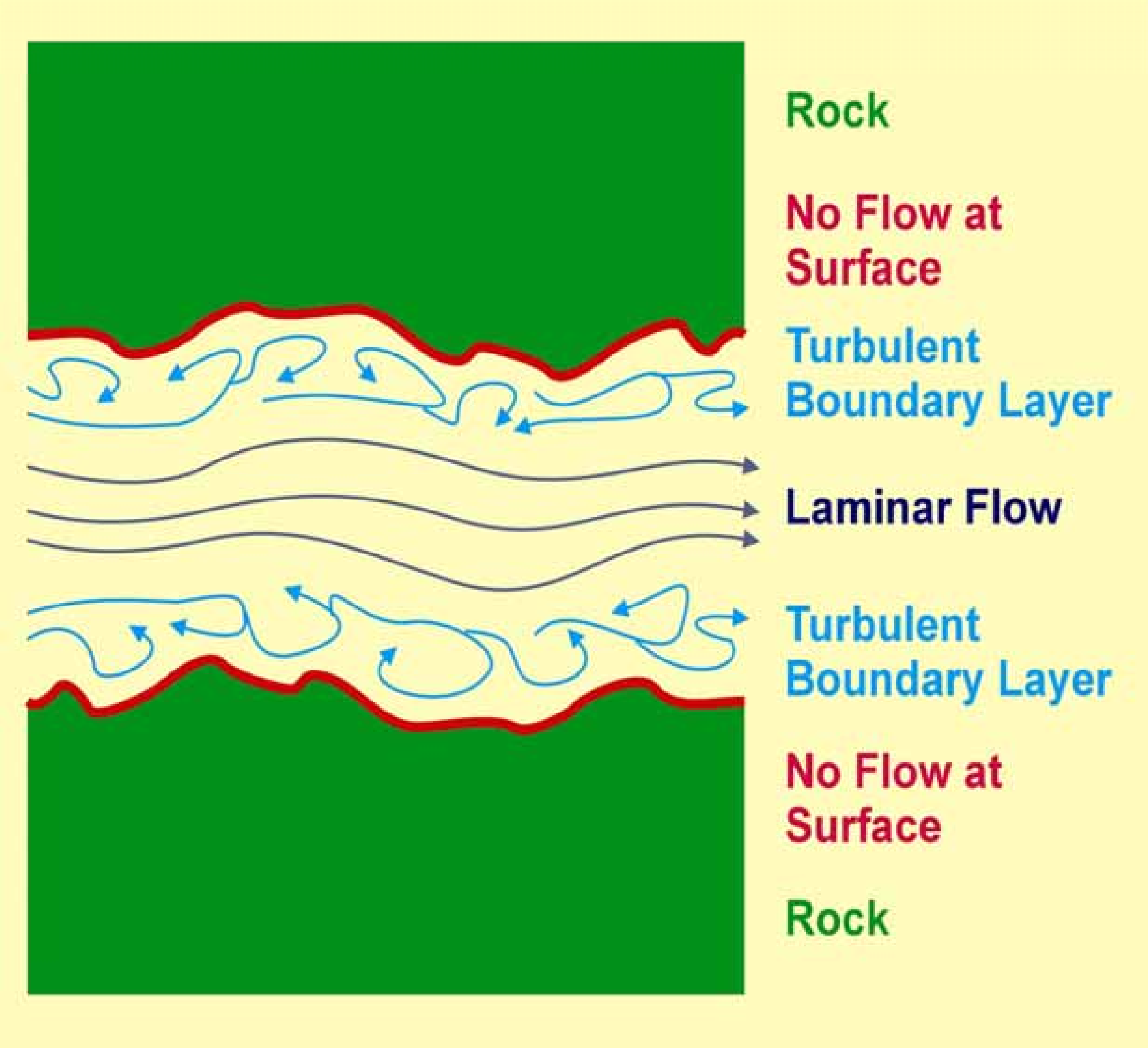
An undisturbed central zone of laminar flow,

and

A surface boundary layer of turbulent flow,

and

Zero flow at the rock surface



Origin - The electrical double layer

There exists:

A -ve charged rock surface,

and

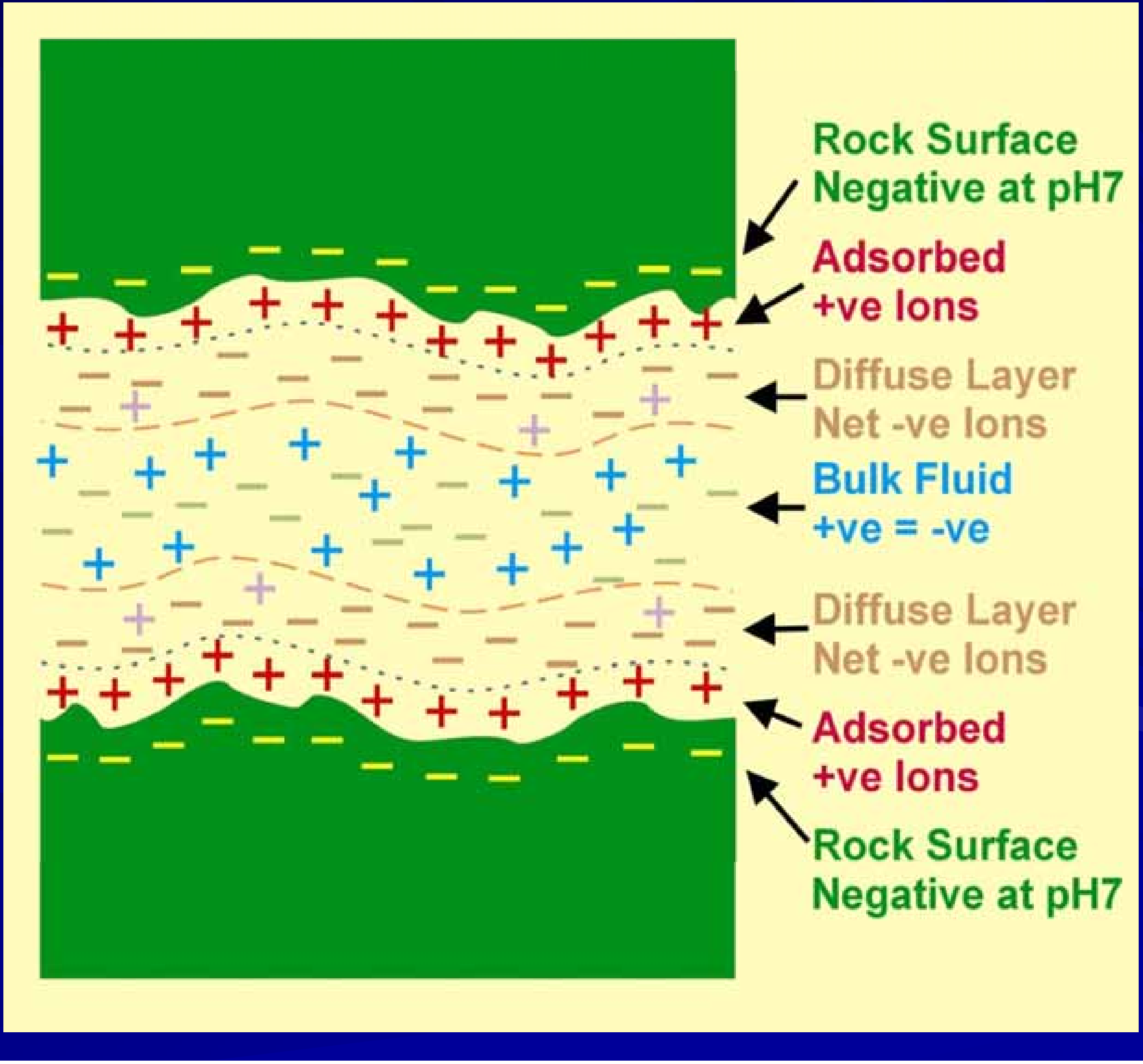
A layer of +ve adsorbed ions,

and

A net –ve diffuse layer [thickness *f*(salinity)]

and

Net neutral bulk fluid



Origin - The electrical double layer

Boundary of moveable fluids is in diffuse layer

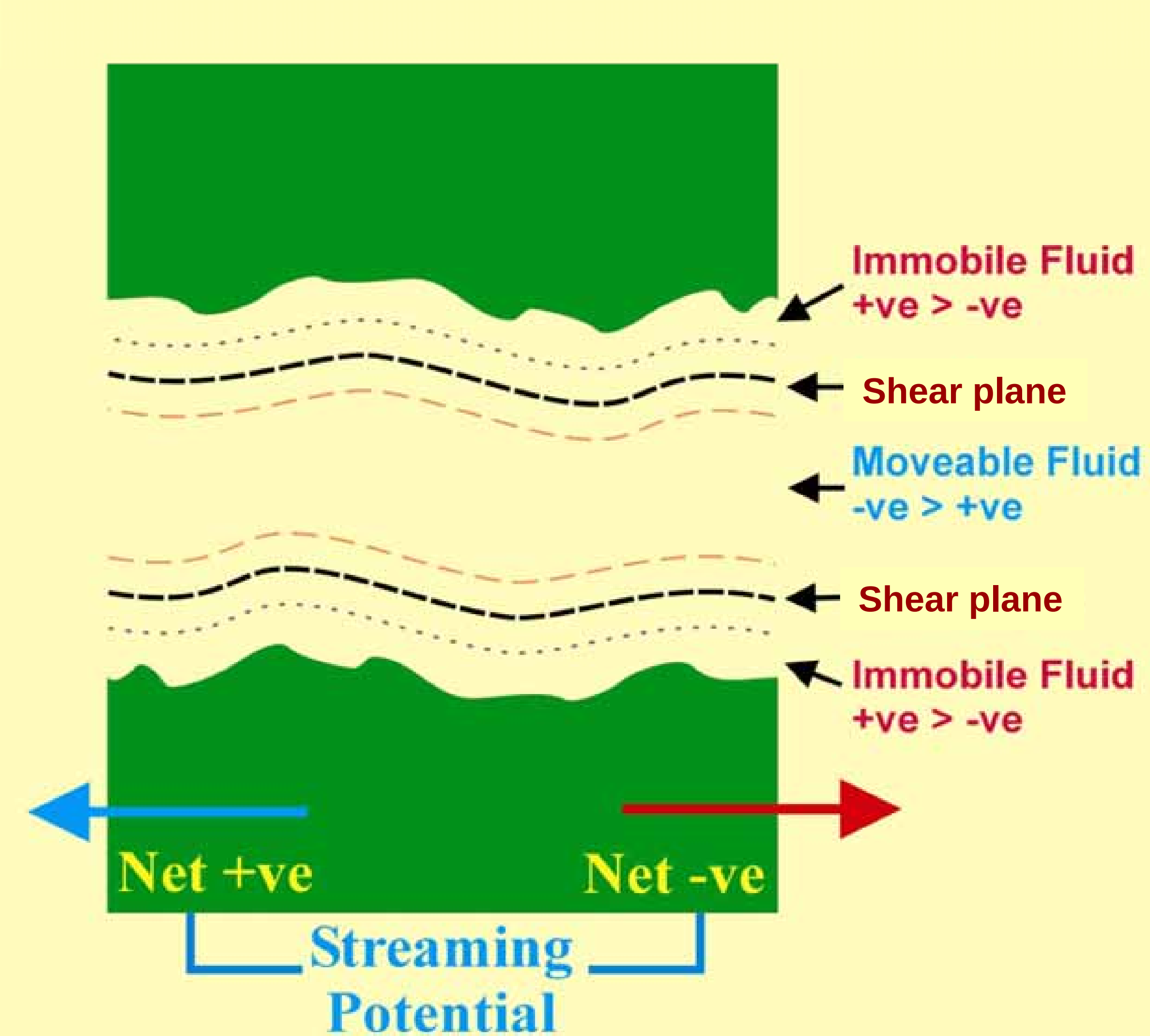
Flow separates –ve charges to the right

and

+ve charges are left behind

this

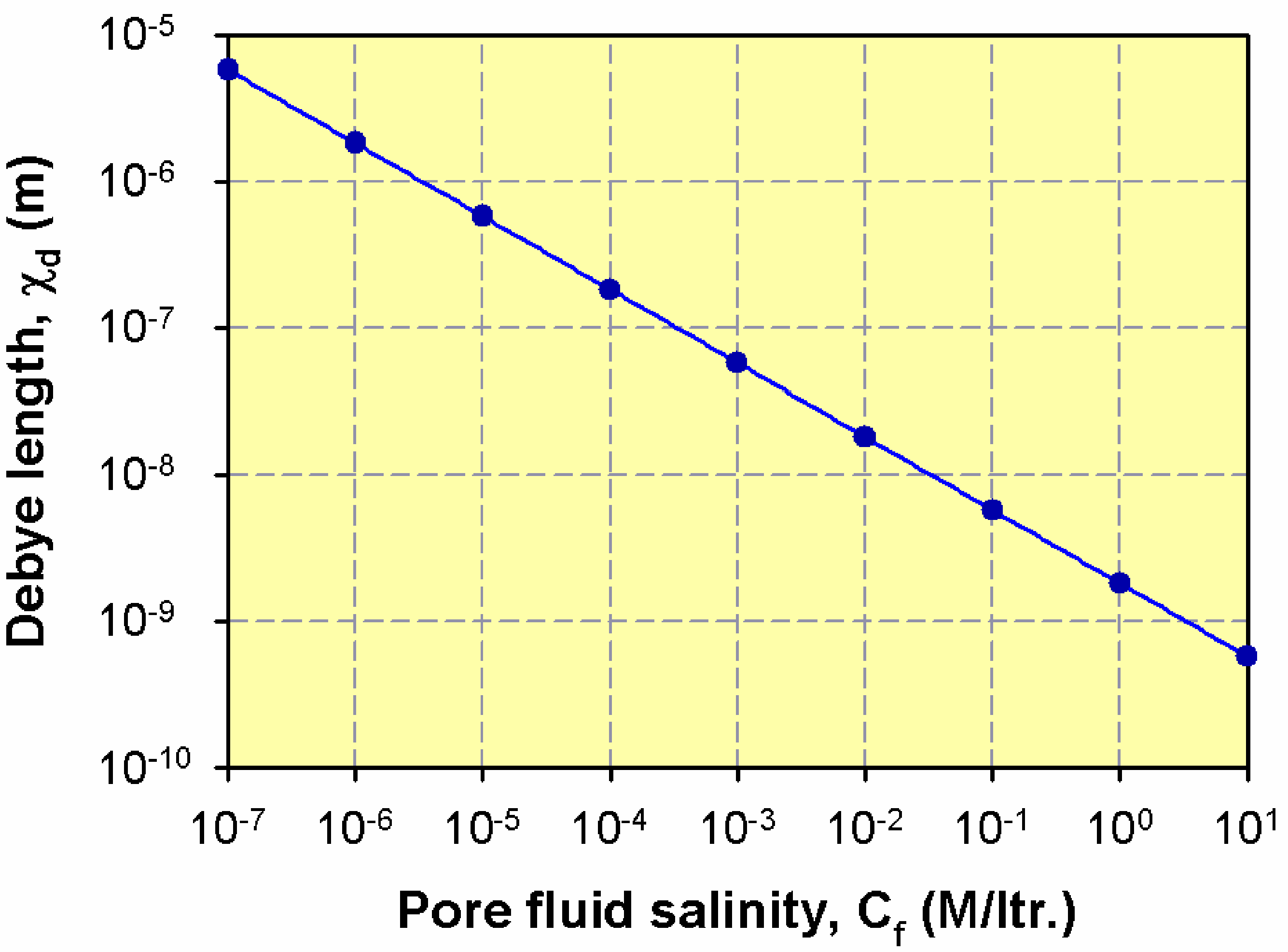
generates a potential difference called the **STREAMING POTENTIAL**



Origin

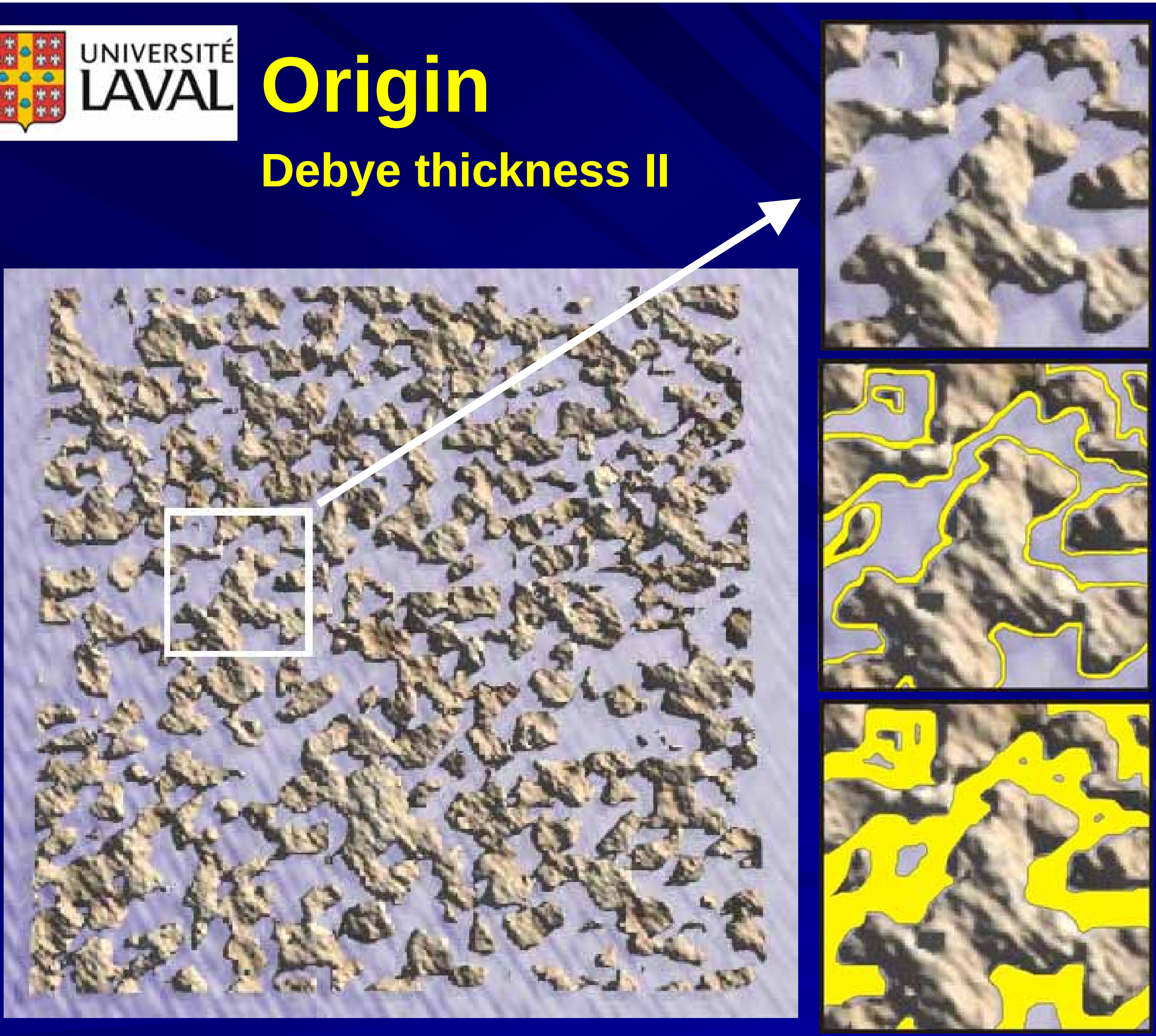
Debye thickness I

$$\chi_d = \sqrt[2]{\frac{\varepsilon_f \, k_b T \, N_A}{2000\, e^2 \, C_f}}$$



Origin

Debye thickness II



Plan

Introduction

Origin

Theory

Apparatus

Laboratory determination

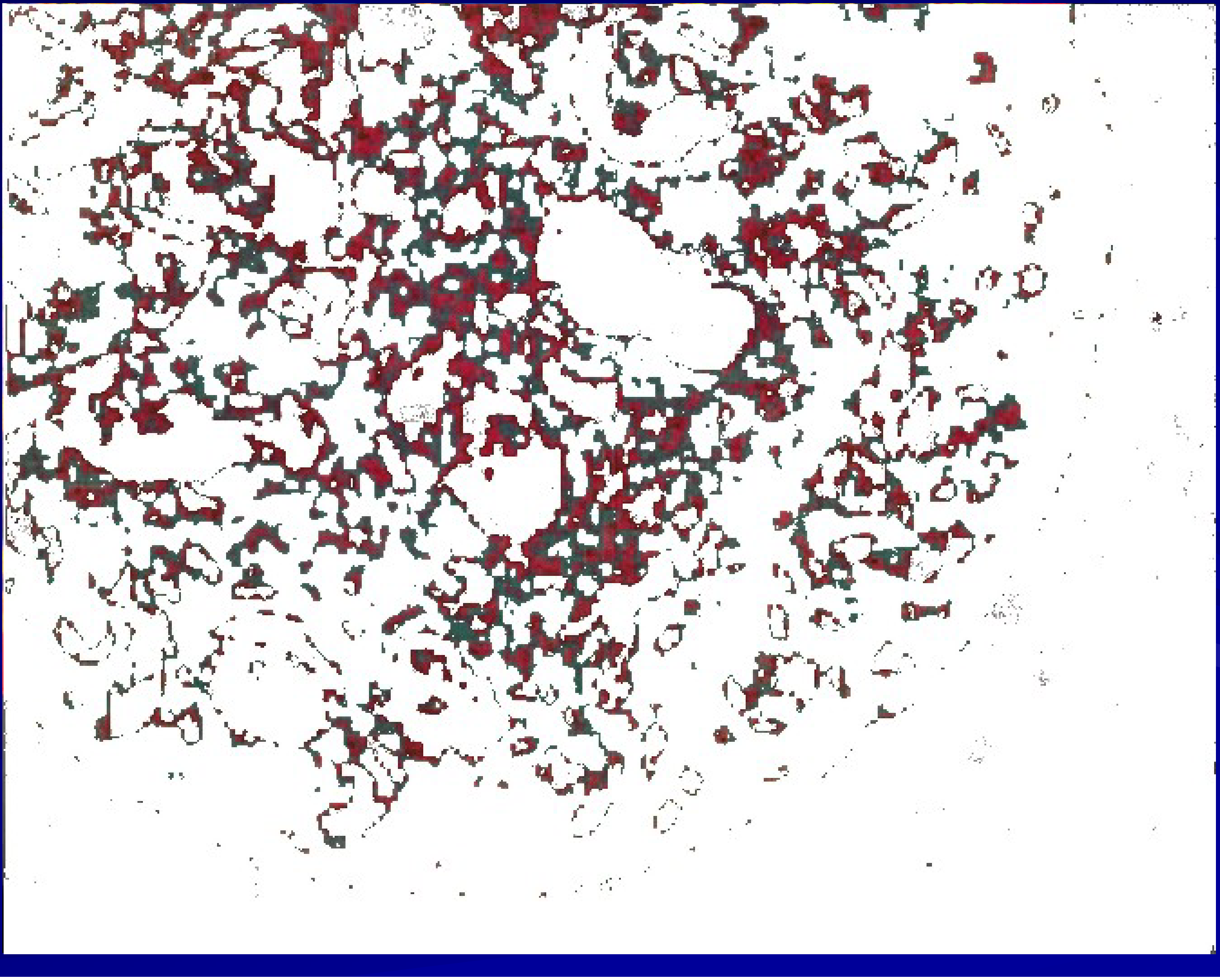
Applications

Conclusions

Future directions

Origin

PET Visualisation of the electrical double layer



Origin

Surface conduction

Two conduction mechanisms

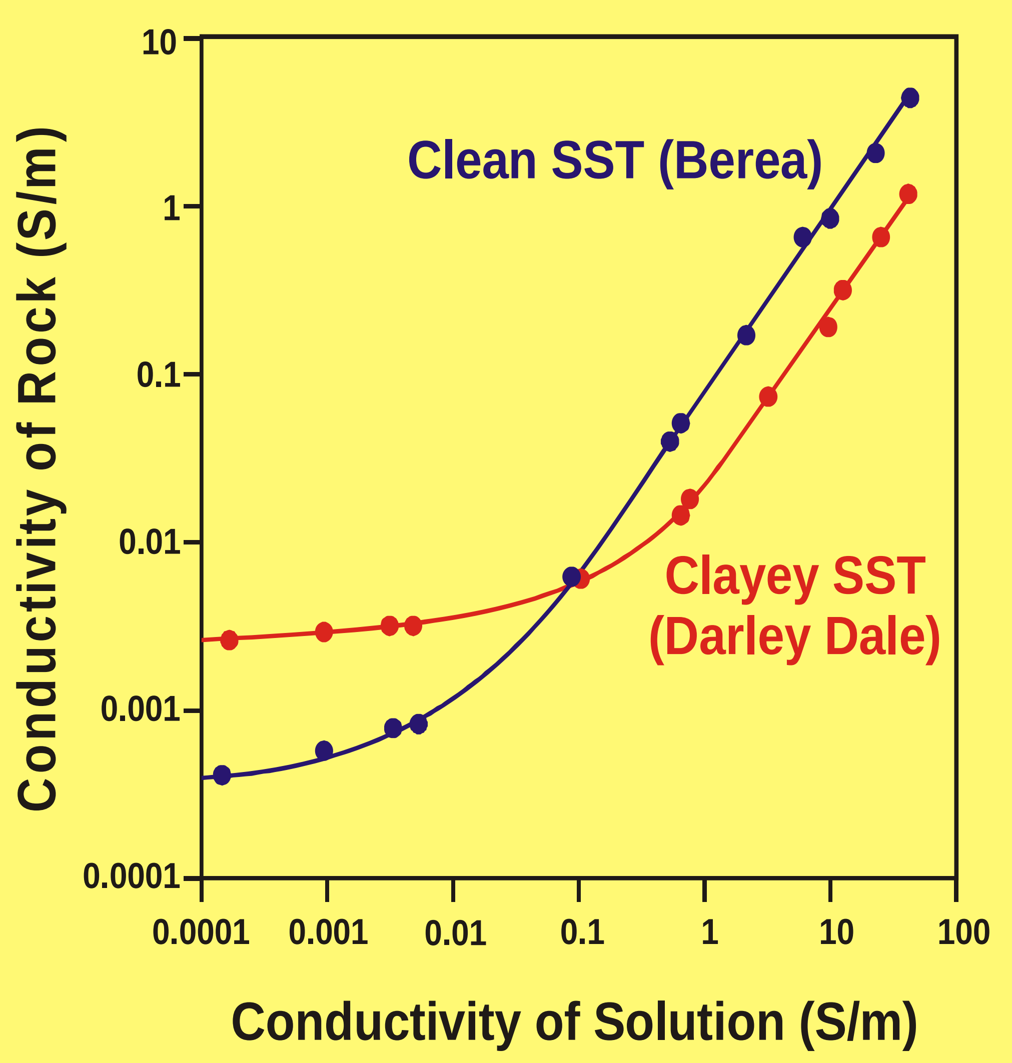
A. via the bulk fluid

B. via the diffuse and Stern layers

The latter is surface conduction

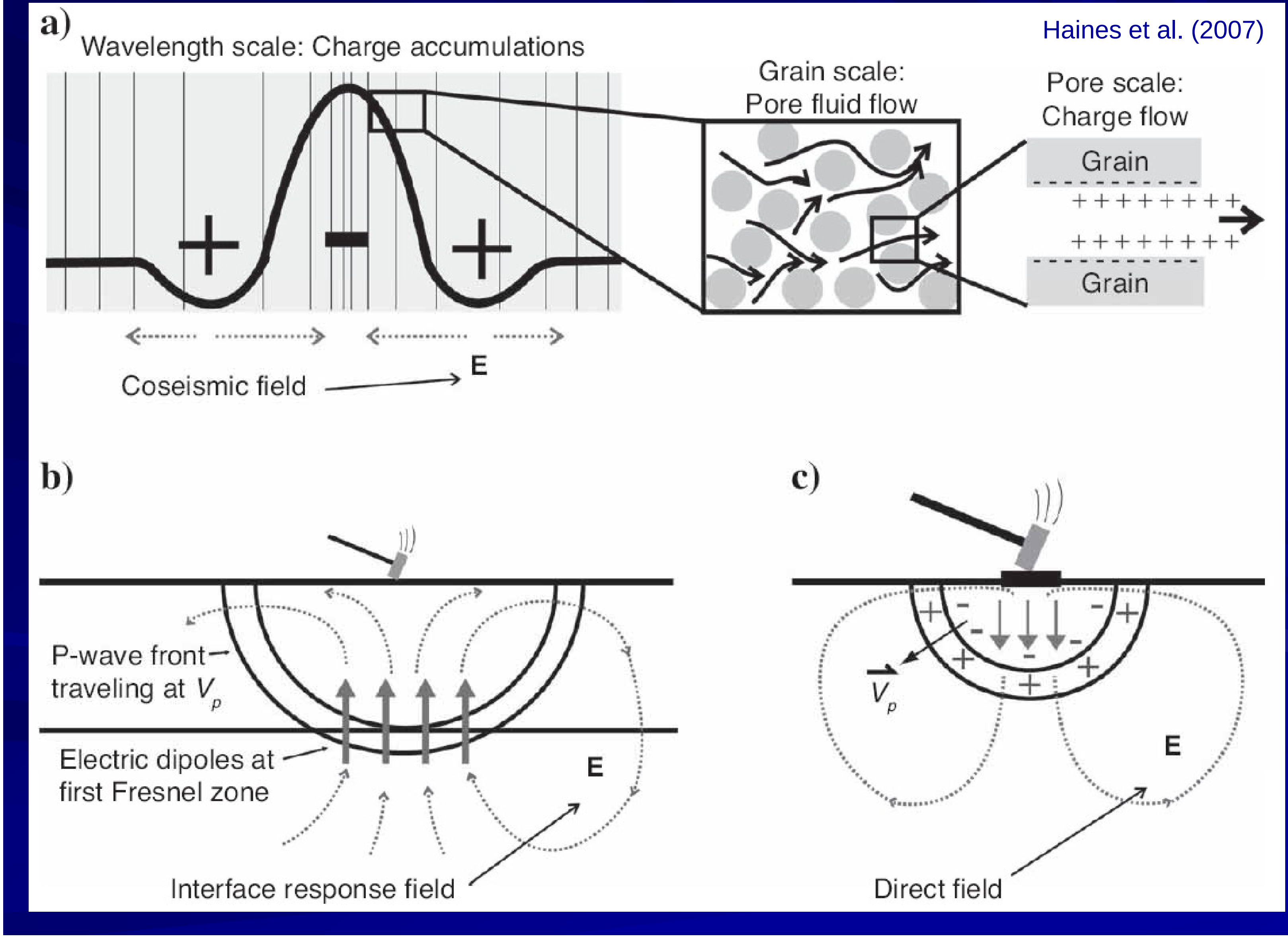
Surface conduction more effective than bulk fluid conduction

At low salinities – the EDL is thick – Surface conductivity dominates

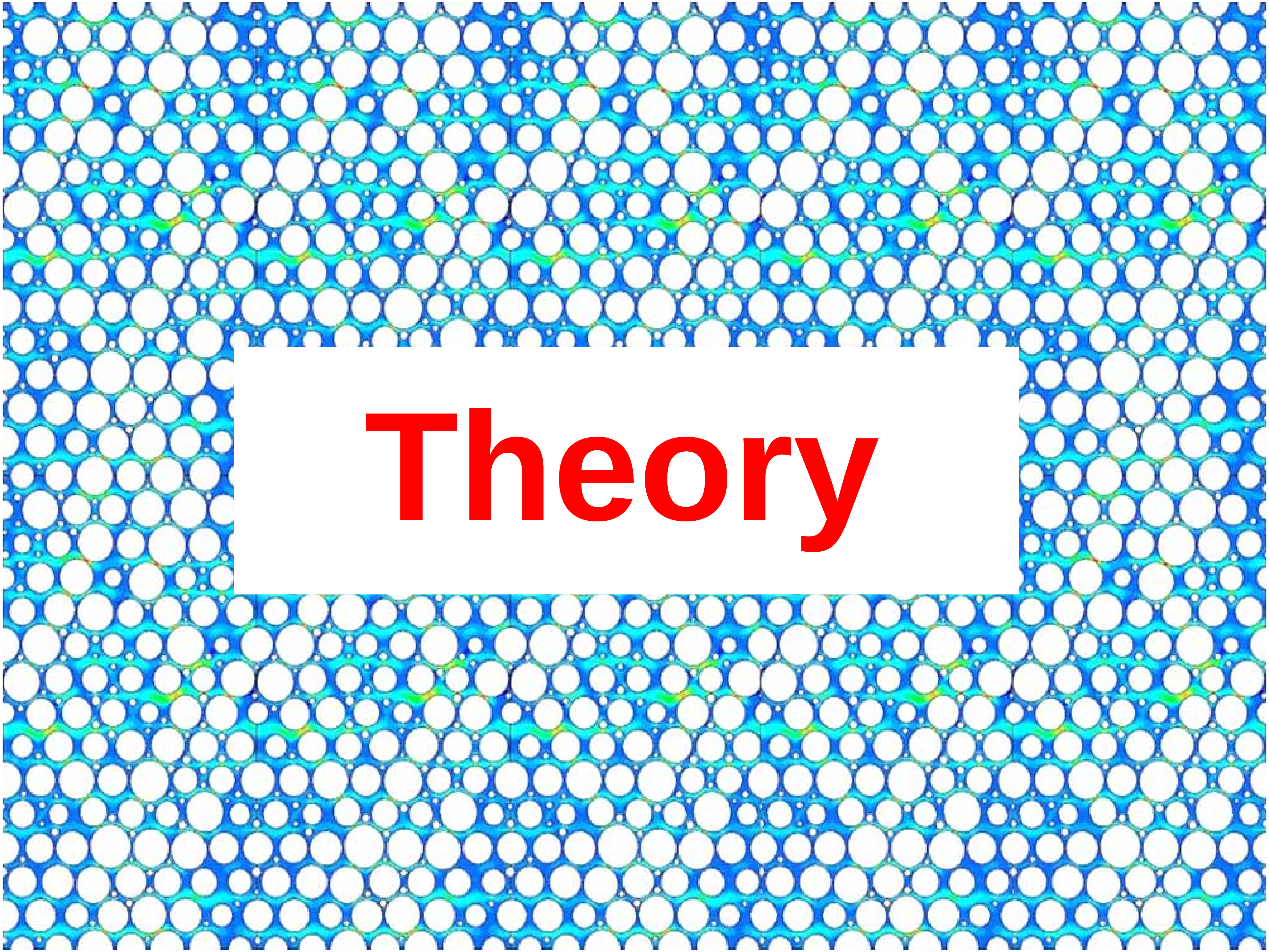


Origin

Electro-seismic conversion



Haines et al. (2007)



Theory

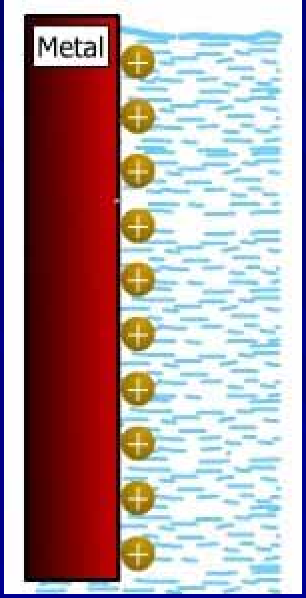
Theory

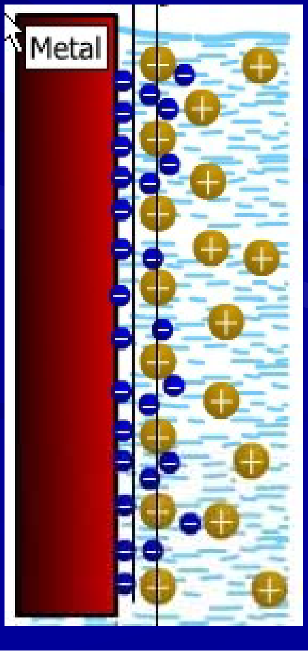
- DC Theory
- The Helmholtz-Smoluchowski equation
- Formulation in continuous media
- What controls the zeta potential?
- AC Theory

Theory

DC theory - Historical

➢ **Helmholtz (1879)**	Simple mineral surface neutralized by a monolayer of counterions from the fluid
➢ **Gouy (1910) & Chapman (1913)**	Replaces monolayer with a diffuse layer composed of counterions and coions (monolayer affected by thermal agitation)
➢ **Stern (1924)**	Proposes amalgamation of the two previous models





Plan

Introduction

Origin

Theory

Apparatus

Laboratory determination

Applications

Conclusions

Future directions

Theory

The Helmholtz-Smoluchowski equation

By equating the convective and conductive currents (Overbeek, 1952)

$$\Delta V = -\frac{\varepsilon\zeta}{\eta\left(\sigma_f + \frac{2\Sigma_s}{\Lambda}\right)}\Delta P$$

C_s is the electro-kinetic coupling coefficient is defined as the ratio of the streaming potential to the fluid pressure difference that created it (V/Pa)

$$C_s = \frac{\Delta V}{\Delta P} = \frac{\varepsilon\varsigma}{\eta\sigma^*}$$

where

$$\sigma^* = \sigma_f + \frac{2\Sigma_s}{\Lambda}$$

Sources of error

1. Not including surface conduction
2. Using $\varepsilon = 80$ at low fluid salinities
3. Using bulk fluid pH (zeta potential is a strong function of pH)

Plan

Introduction

Origin

Theory

Apparatus

Laboratory determination

Applications

Conclusions

Future directions

Theory

Formulation in continuous media

Darcy's law, $L_{11} = k/\eta$

$$\begin{bmatrix} Q \\ J \end{bmatrix} = -\begin{bmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{bmatrix} \begin{bmatrix} \nabla P \\ \nabla \varphi \end{bmatrix}$$

Electro-kinetic phenomena
$L_{21} = L_{12} = \varepsilon\zeta/\eta$

Ohm's law,
$L_{22} = \sigma_f$

k	permeability (m²)
σ_f	fluid conductivity (S/m)
ε	fluid dielectric constant
ζ	zeta potential (V)
η	fluid viscosity (Pa.s)
P	fluid pressure (Pa)
φ	electrical potential (V)
Q	fluid flow (L/m²),
J	electric current density (A/m²)

or $J = \dfrac{\varepsilon\zeta}{\eta}\nabla P - \sigma_f \nabla\varphi$ and $Q = -\dfrac{k}{\eta}\nabla P + \dfrac{\varepsilon\zeta}{\eta}\nabla\varphi$

✓ OK for capillaries ✘ To be verified for rocks

Plan

Introduction

Origin

Theory

Apparatus

Laboratory determination

Applications

Conclusions

Future directions

Theory

What controls the zeta potential?

The streaming potential depends upon 4 parameters

- Fluid* dielectric constant
- Fluid* viscosity
- Fluid* conductivity
- Zeta potential

Therefore any control of the streaming potential exercised by the rock rests in the zeta potential

What controls the zeta potential?

Theory

Controls on the zeta potential

- Salinity
- pH
- Porosity
- Pore microstructure – connectedness G
- Flow rate
- Fluid viscosity
- Pore/fracture surface roughness
- Saturation
- Temperature, applied, pore and effective pressure
- Chemical composition of mineral and fluid

Theory - AC Theory I

We propose

$$\frac{\Delta V}{\Delta P} = f^*(\omega)\frac{\varepsilon_f \zeta}{\eta_f \sigma_f^*}$$

Glover (2007)

For the hydraulic coupling coefficient

$$\frac{\nu(\omega)}{\Delta P(\omega)} = \frac{1}{\eta l k^2}\left[\frac{2}{ka}\frac{J_1(ka)}{J_0(ka)} - 1\right]$$

Packard (1953)

The streaming potential coupling coefficient becomes

$$C(\omega) = \frac{\Delta V(\omega)}{\Delta P(\omega)} = \frac{\varepsilon_f \zeta}{\eta_f \sigma_f^*}\left[-\frac{2}{ka}\frac{J_1(ka)}{J_0(ka)}\right]$$

Packard (1953)

$$C(\omega) = \frac{\Delta V(\omega)}{\Delta P(\omega)} = \frac{\varepsilon_f \zeta}{\eta_f \sigma_f^*}\left[1 - \frac{2}{a}\sqrt{\frac{\eta_f}{\omega \rho_f}}\left(\frac{1}{\sqrt{2}} - \frac{1}{\sqrt{2}}i\right)\right]$$

Reppert & Morgan (2001)

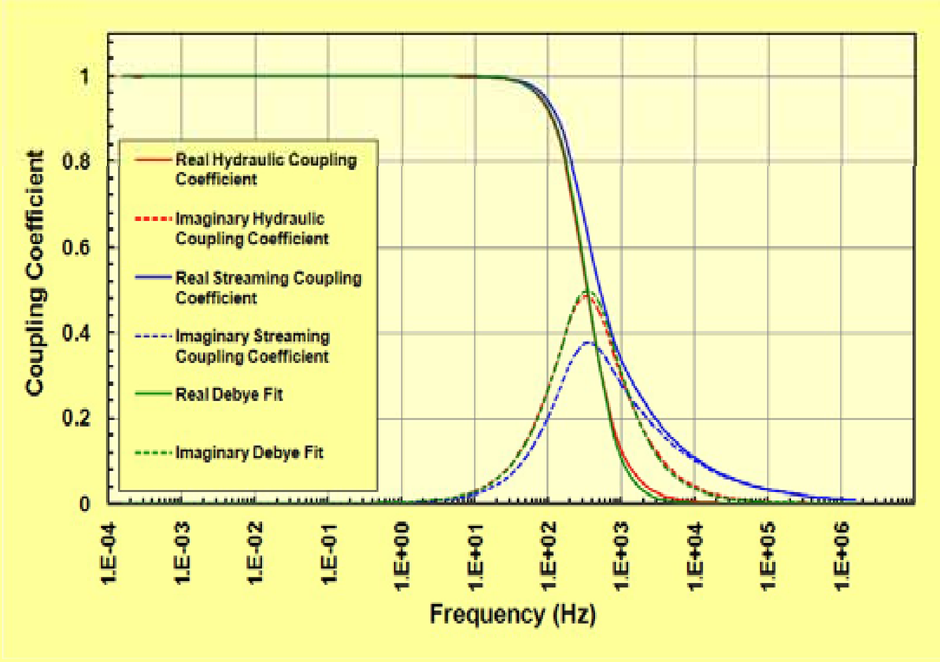
Theory

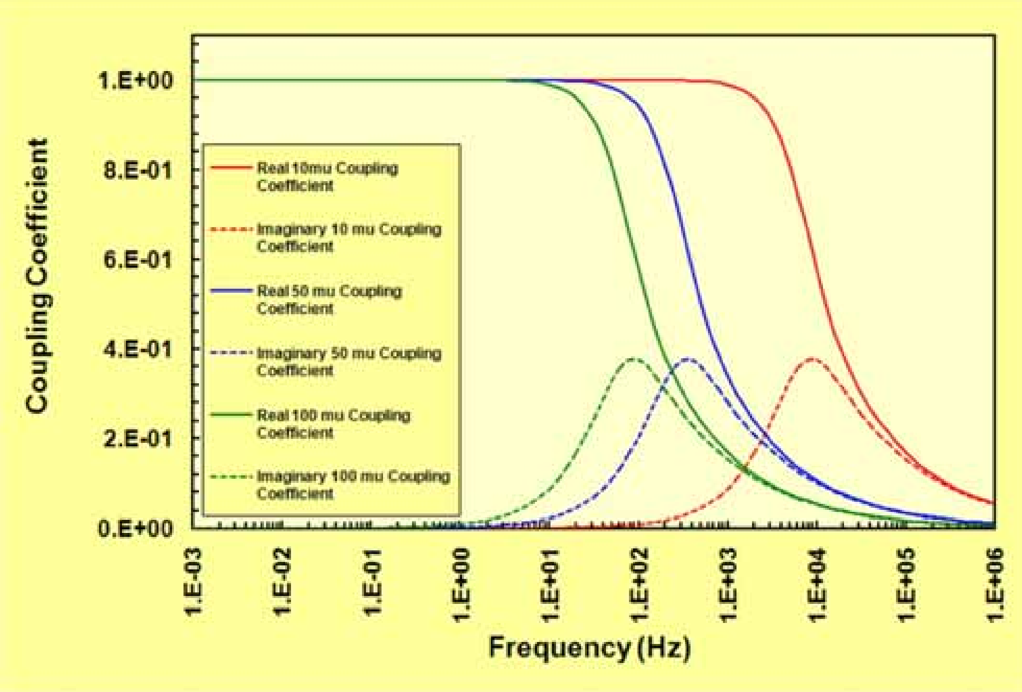
AC Theory II

Hydraulic coupling coefficient is almost Debye-like

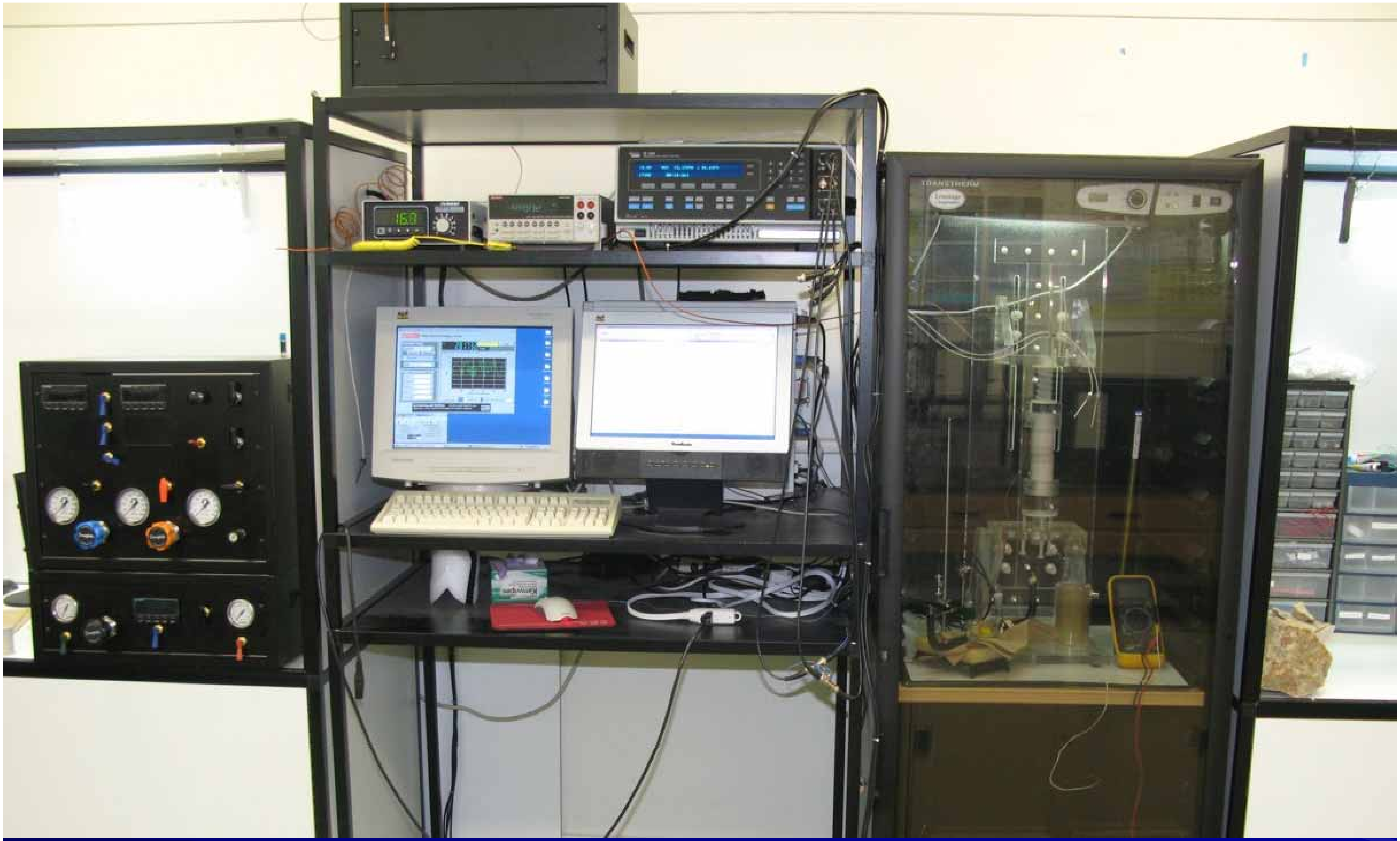
Streaming coupling coefficient is not Debye-like

The smaller the grain size the higher the frequency of the dispersion





Plan
Introduction
Origin
Theory
Apparatus
Laboratory determination
Applications
Conclusions
Future directions



Apparatus

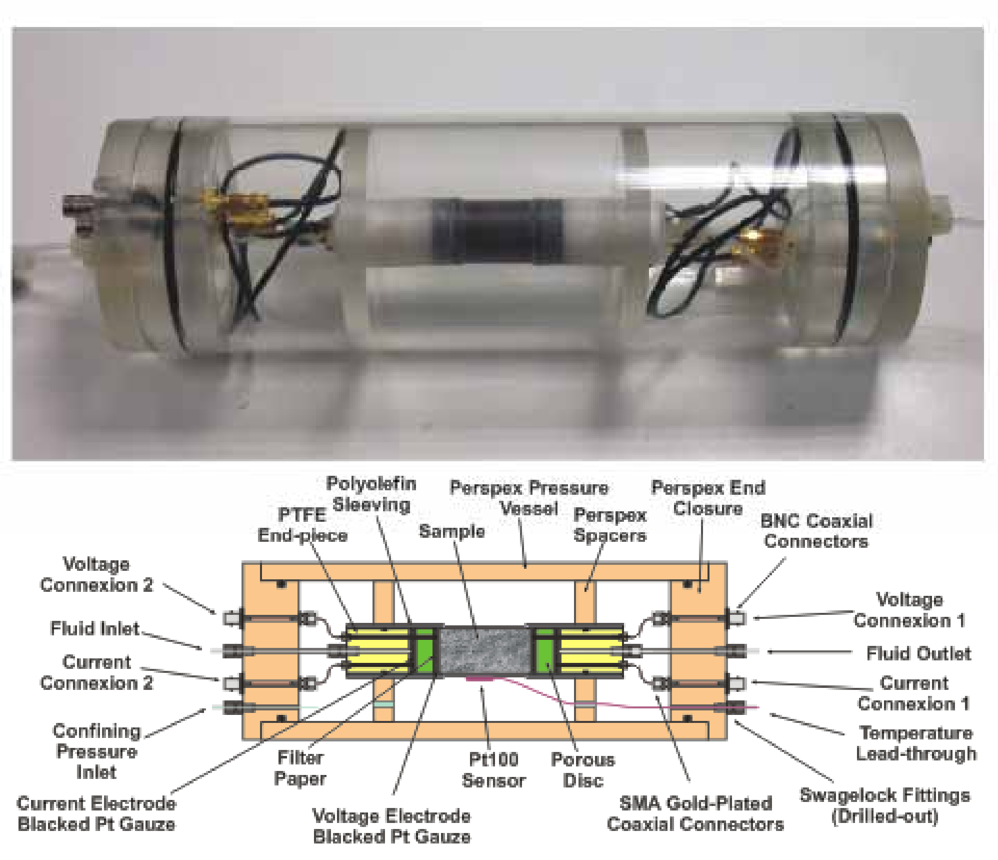
Apparatus

- Early DC measurement cells
- DC measurement cells at ULaval
- Early AC measurement cells
- AC measurement cells at ULaval

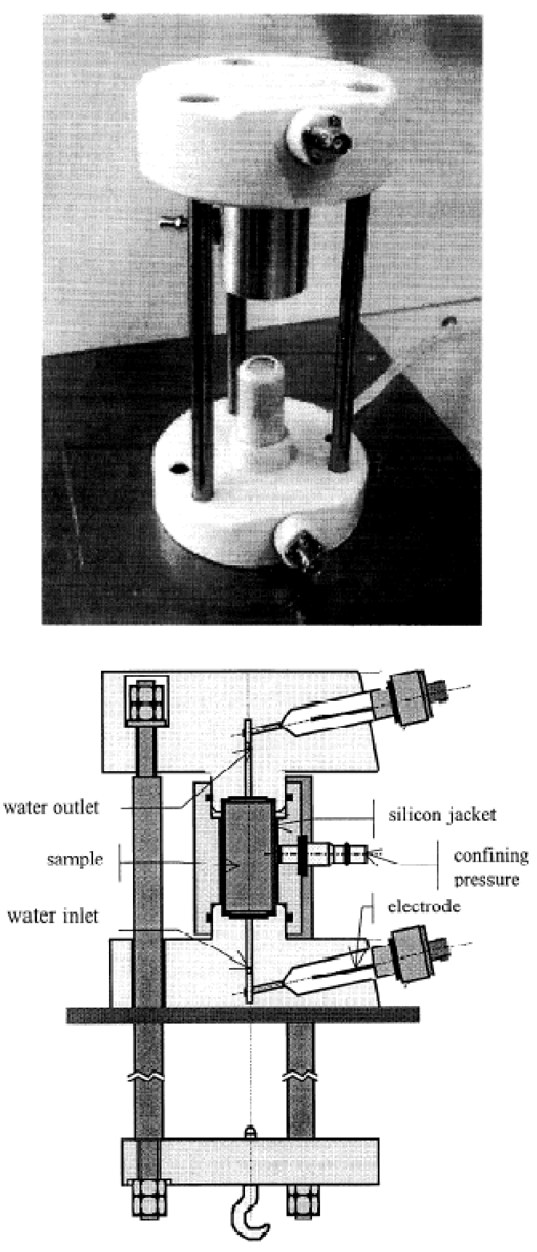
Apparatus

Early DC cells

- From two existing cells:
  - →Jouniaux et al. (2000)
  - → Glover (2001)



Glover (2001)

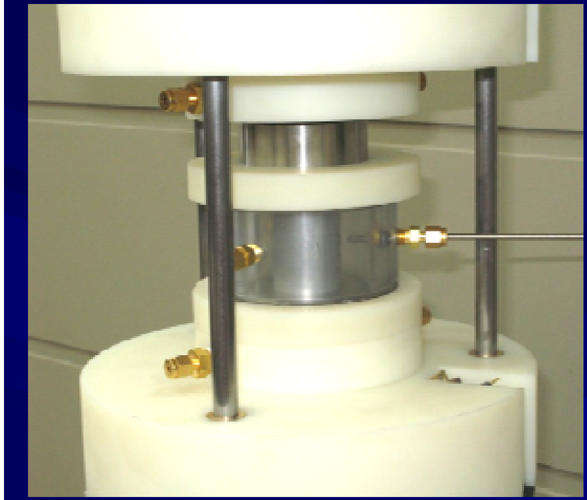


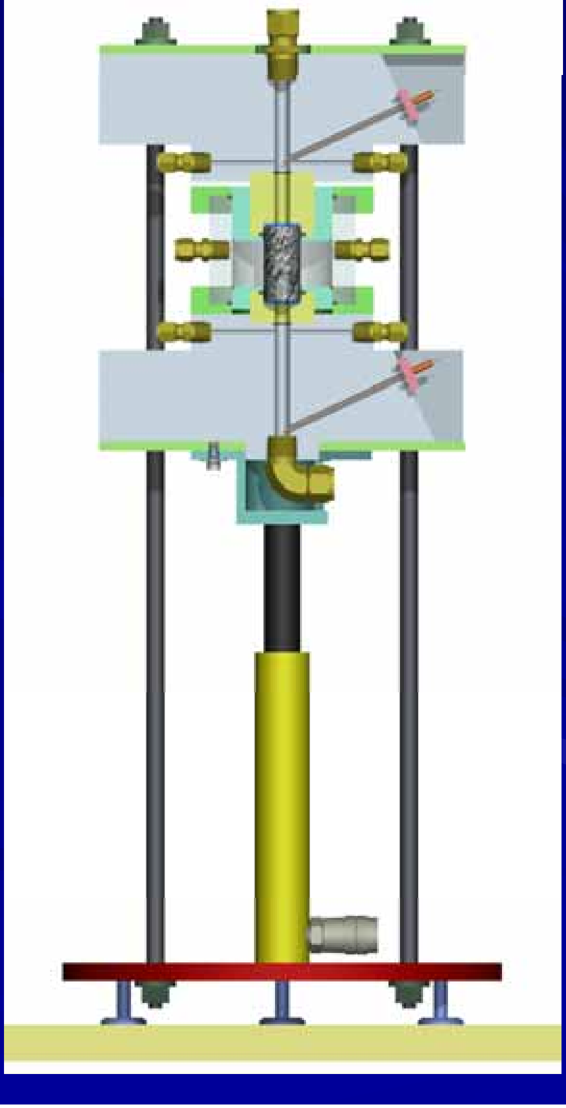
Jouniaux et al. (2000)

Plan
Introduction
Origin
Theory
Apparatus
Laboratory determination
Applications
Conclusions
Future directions

Apparatus

DC measurement cells





Plan

Introduction

Origin

Theory

Apparatus

Laboratory determination

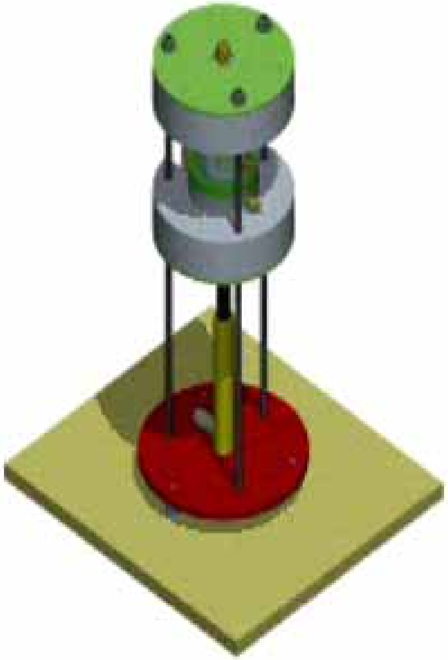
Applications

Conclusions

Future directions

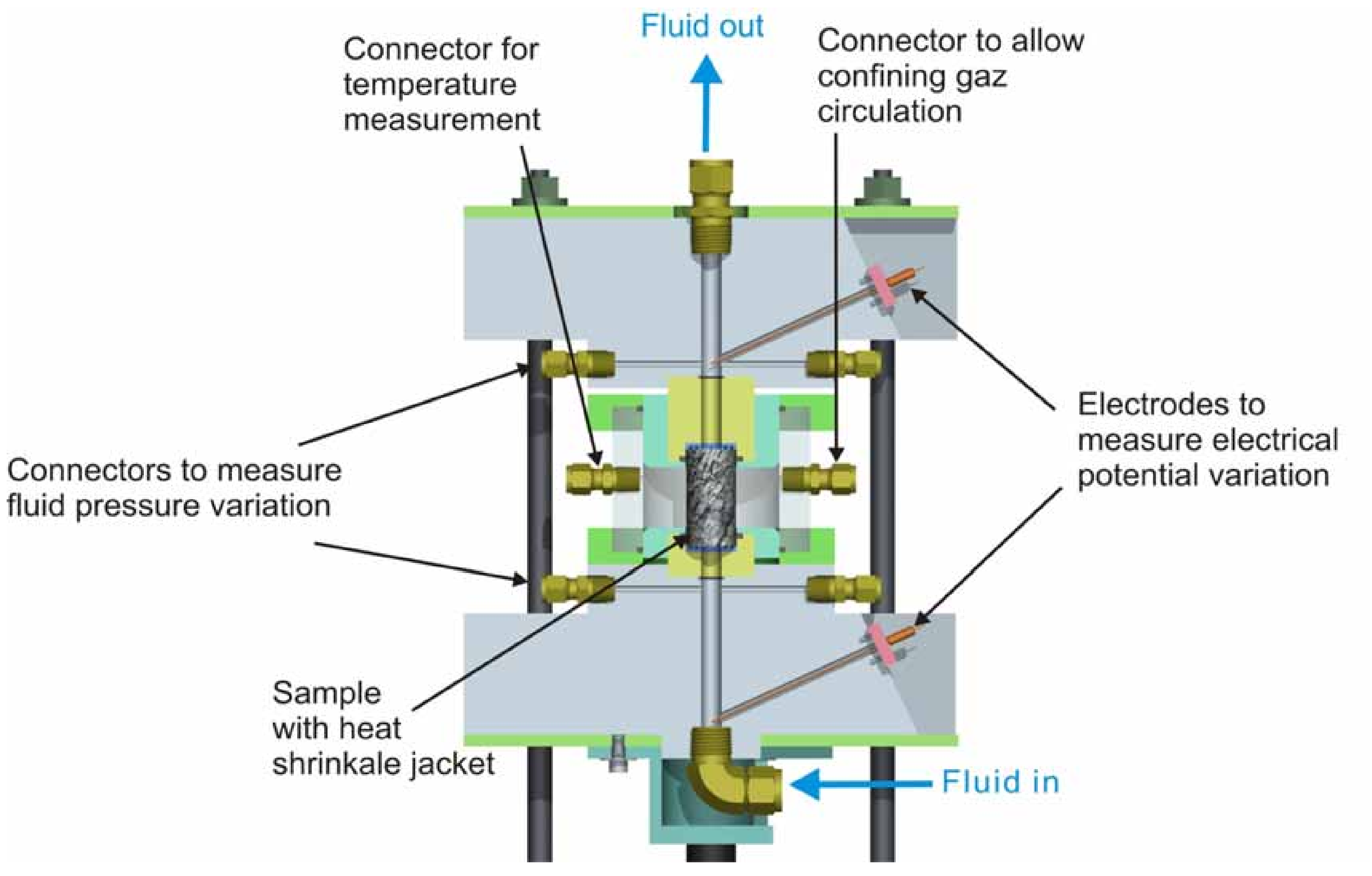
Apparatus

DC measurement cells



Apparatus

DC measurement cells



Fluid out

Connector for temperature measurement

Connector to allow confining gaz circulation

Electrodes to measure electrical potential variation

Connectors to measure fluid pressure variation

Sample with heat shrinkale jacket

Fluid in

Apparatus

DC measurement cells

Mark 3 cell can be used at higher Confining pressures within the same hydraulic press

Plan

Introduction

Origin

Theory

Apparatus

Laboratory determination

Applications

Conclusions

Future directions

Apparatus

Early AC measurement cells

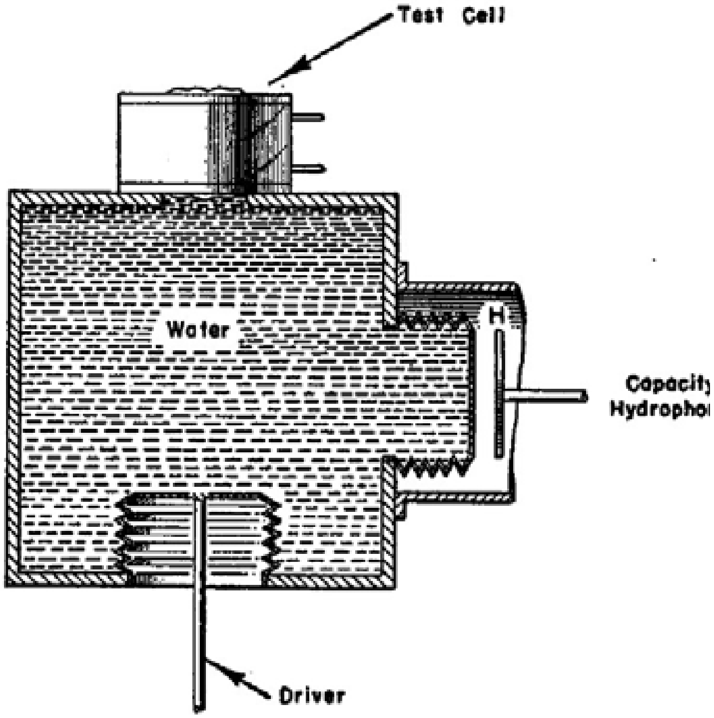


FIG. 2. Cross-sectional view of main test chamber with test cell attached.

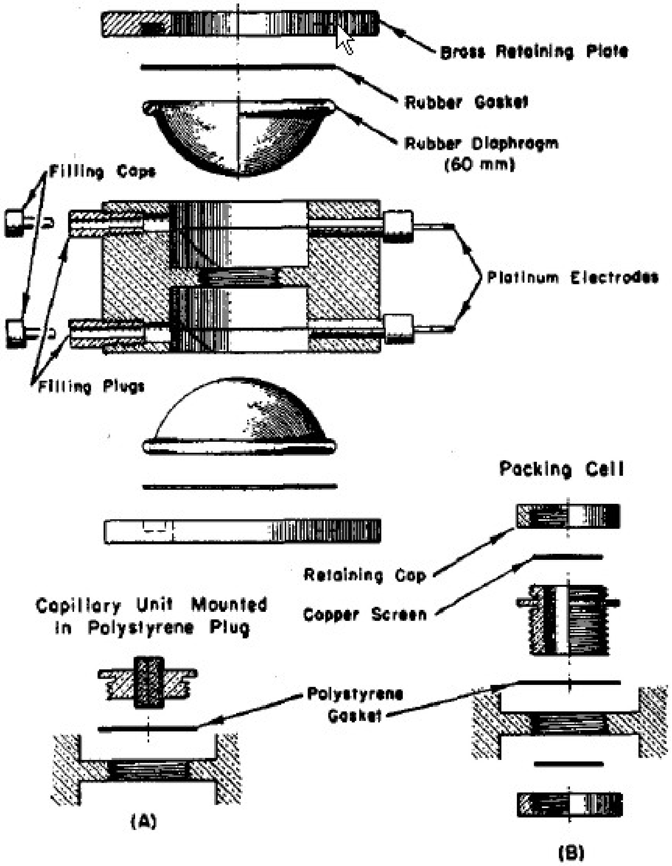


FIG. 3. Diagrammatic view of test cell, showing capillary unit. Dimensions of test cell: internal diameter: 1.75 in.; outer diameter: 3.00 in.; height polystyrene body: $1\frac{7}{8}$ in.; distance between electrodes: $1\frac{1}{4}$ in.; length platinum electrodes: $1\frac{1}{2}$ in.; diameter platinum electrodes: 0.016 in.; thickness threaded section: $\frac{3}{8}$ in.; diameter threaded section: $\frac{7}{8}$ in.

Packard (1953)

Plan

Introduction

Origin

Theory

Apparatus

Laboratory determination

Applications

Conclusions

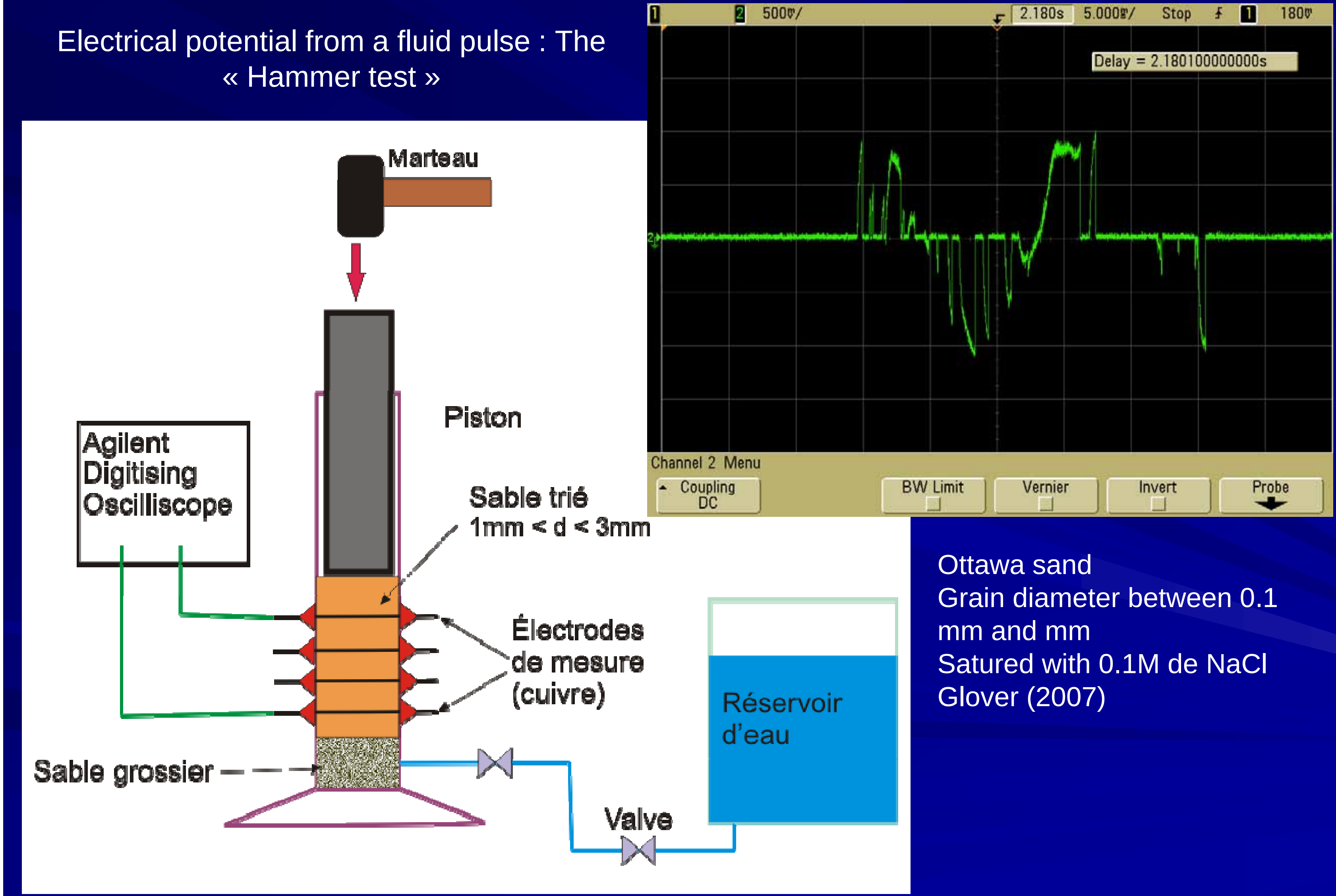
Future directions

Apparatus

Early AC measurement cells

Vertical scale: 1 square = 1 V
Horizontal scale: 1 square = 5 ms

Electrical potential from a fluid pulse : The « Hammer test »



Ottawa sand
Grain diameter between 0.1 mm and mm
Satured with 0.1M de NaCl
Glover (2007)

Plan

Introduction

Origin

Theory

Apparatus

Laboratory determination

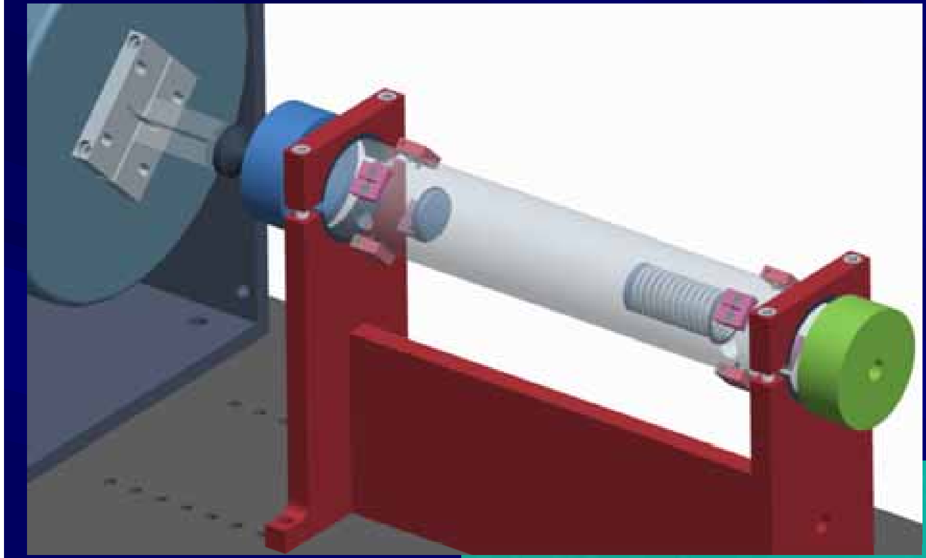
Applications

Conclusions

Future directions

Apparatus

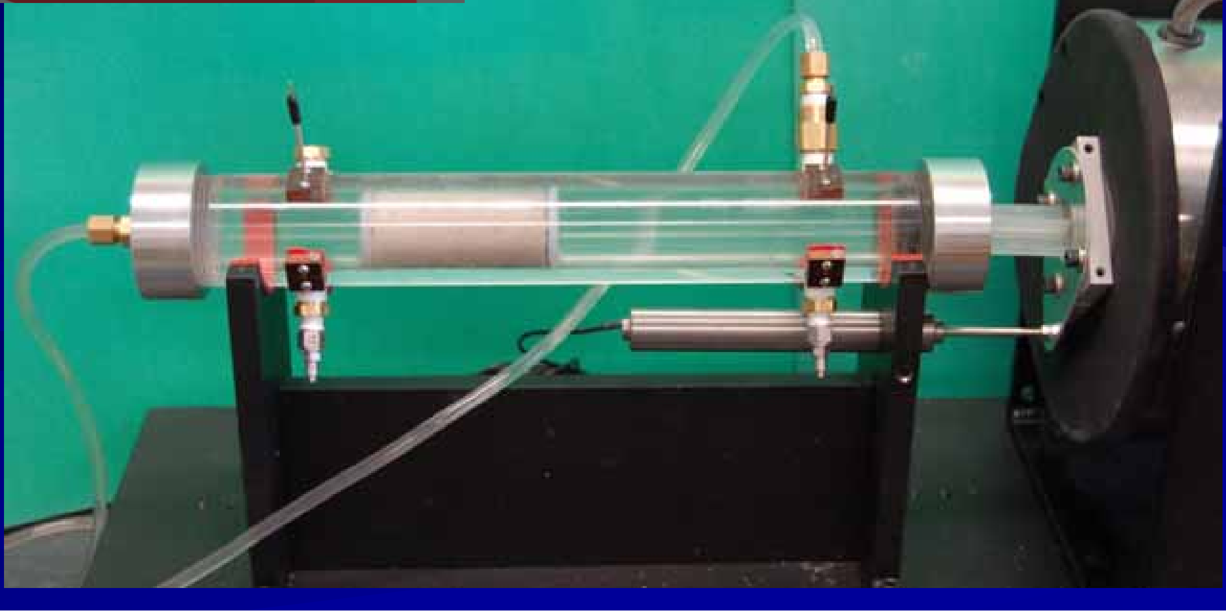
AC measurement cells



The design takes a piston or a rubber membrane

An LVDT allows a servo-locked amplifier to control the shaker with precision

Measurements can be made with or without an imposed DC fluid flow



Plan

Introduction

Origin

Theory

Apparatus

Laboratory determination

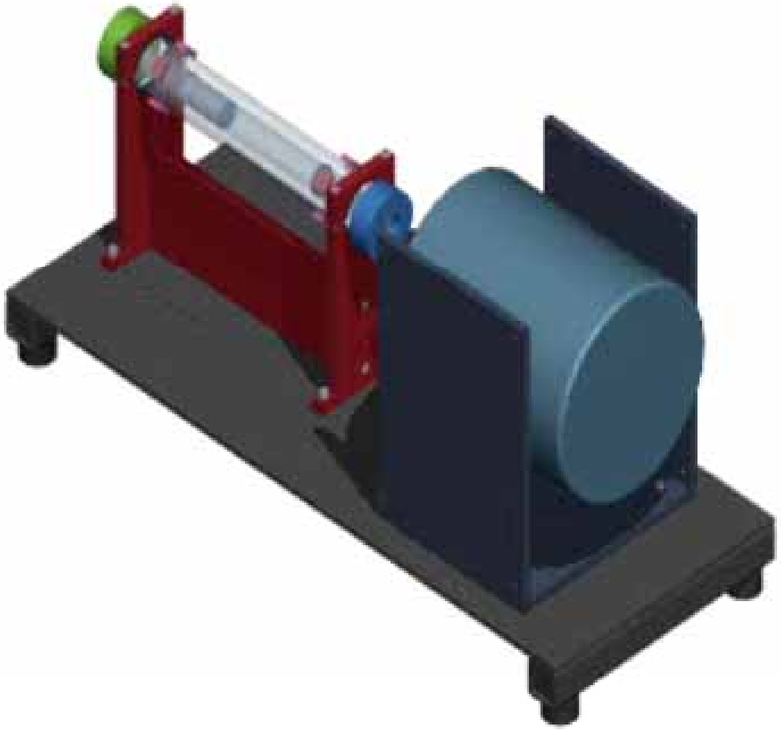
Applications

Conclusions

Future directions

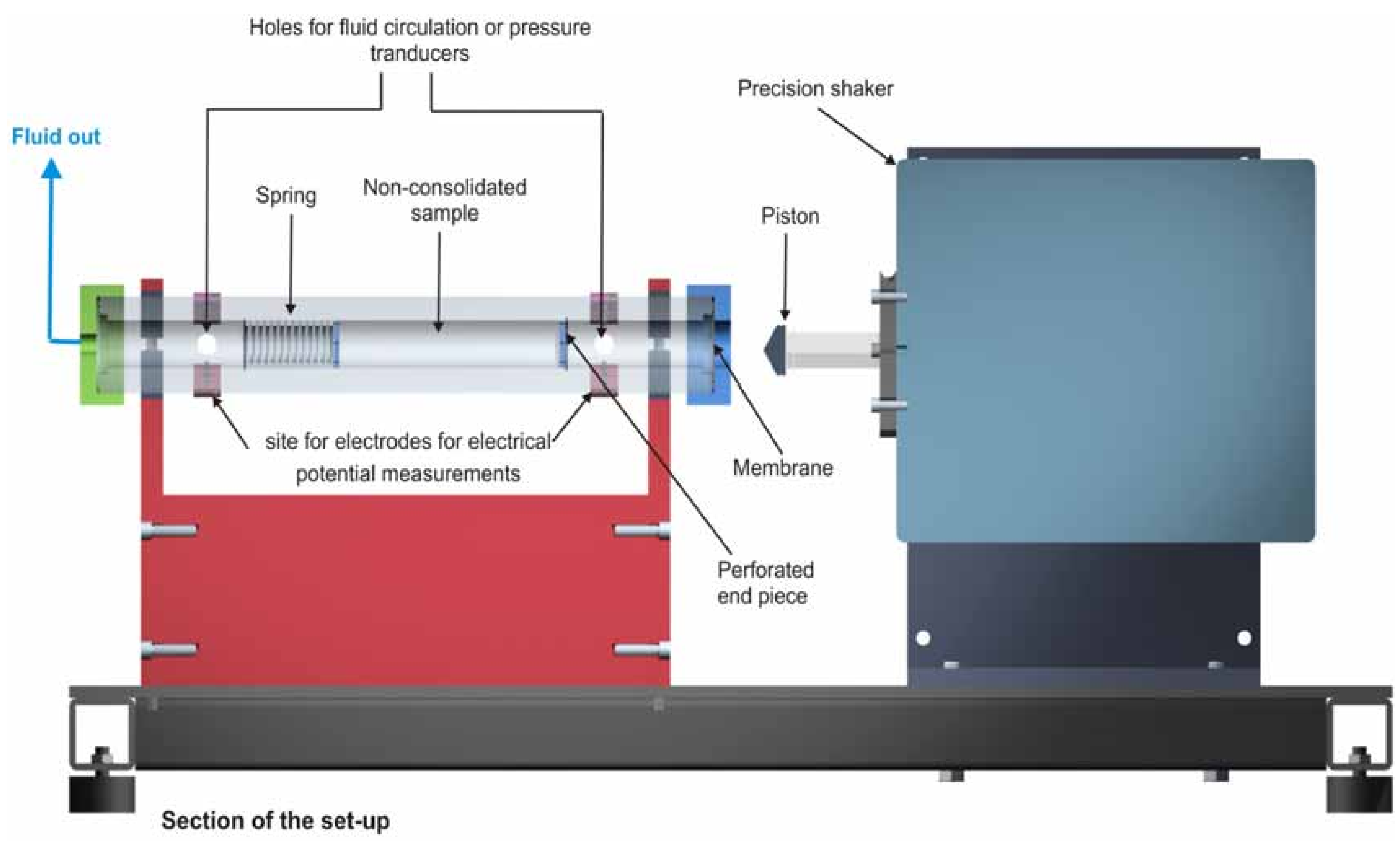
Apparatus

AC measurement cells



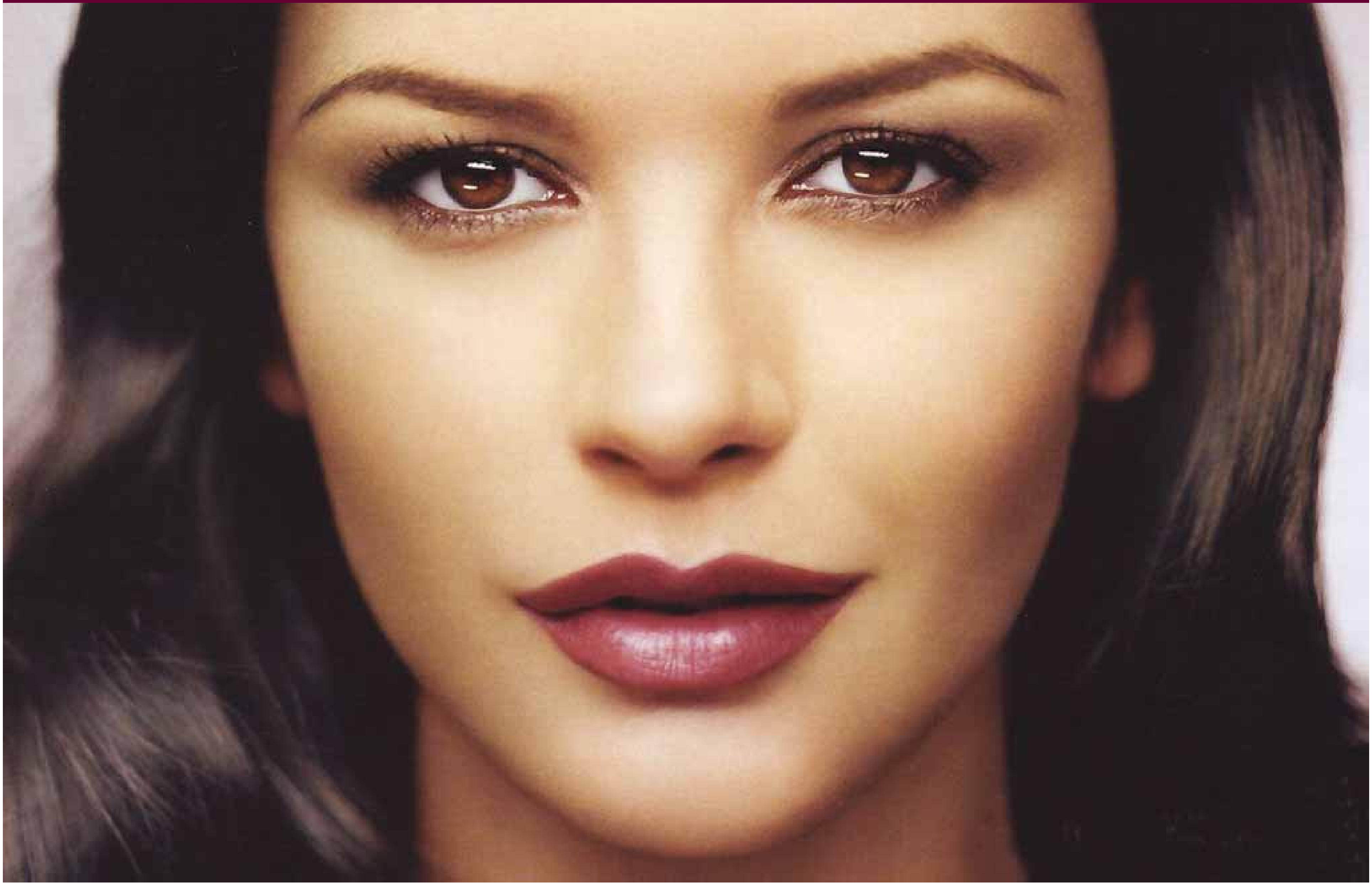
Apparatus

AC measurement cells



Section of the set-up

Laboratory determinations

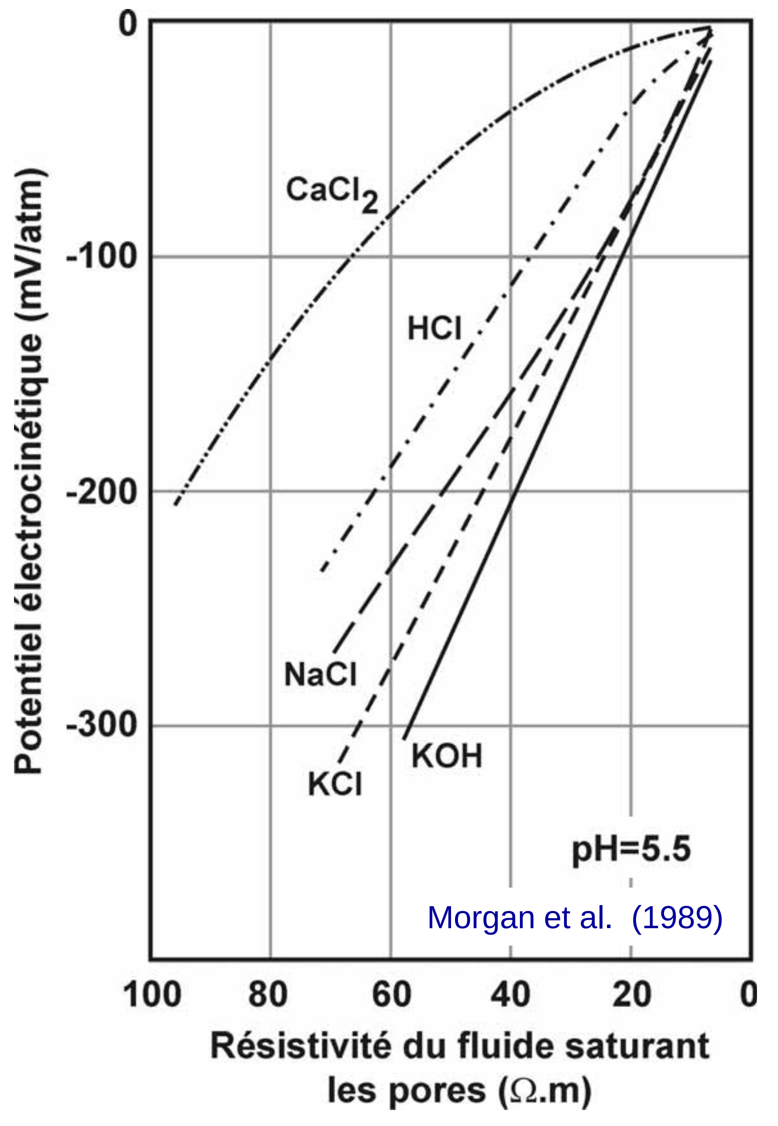


Laboratory determinations

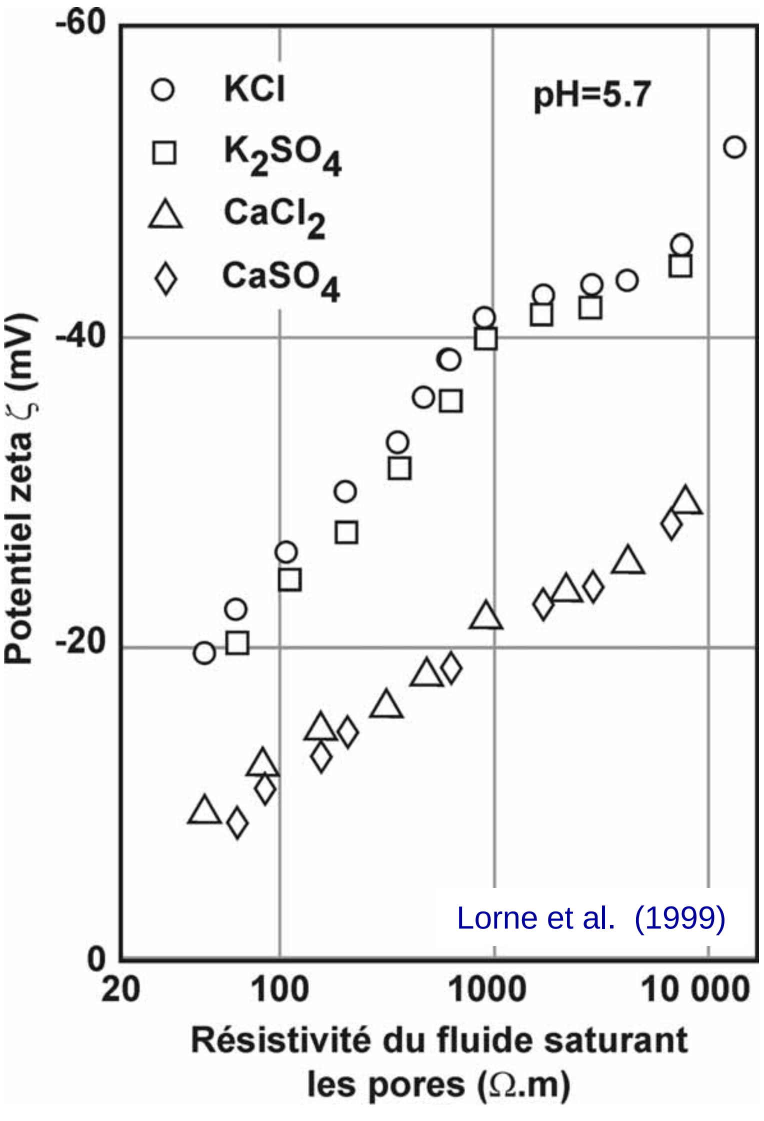
- Pore fluid chemistry
- Pore fluid salinity
- Pore fluid pH
- Mineralogy
- Grain size
- Temperature
- Saturation
- Frequency

Laboratory determinations

Pore fluid chemistry



Morgan et al. (1989)

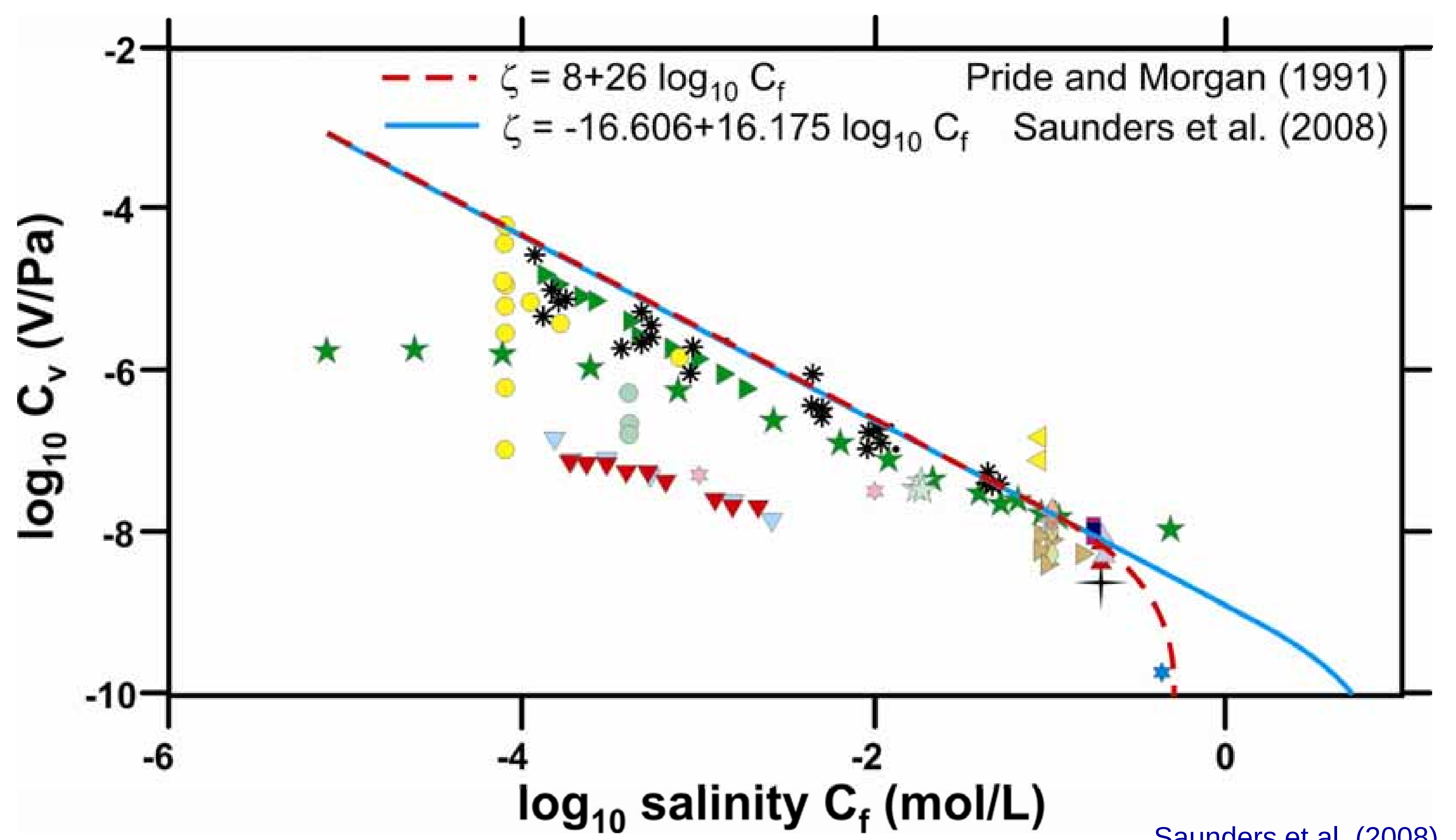


Lorne et al. (1999)

Plan
Introduction
Origin
Theory
Apparatus
Laboratory determination
Applications
Conclusions
Future directions

Laboratory determinations

Pore fluid salinity I



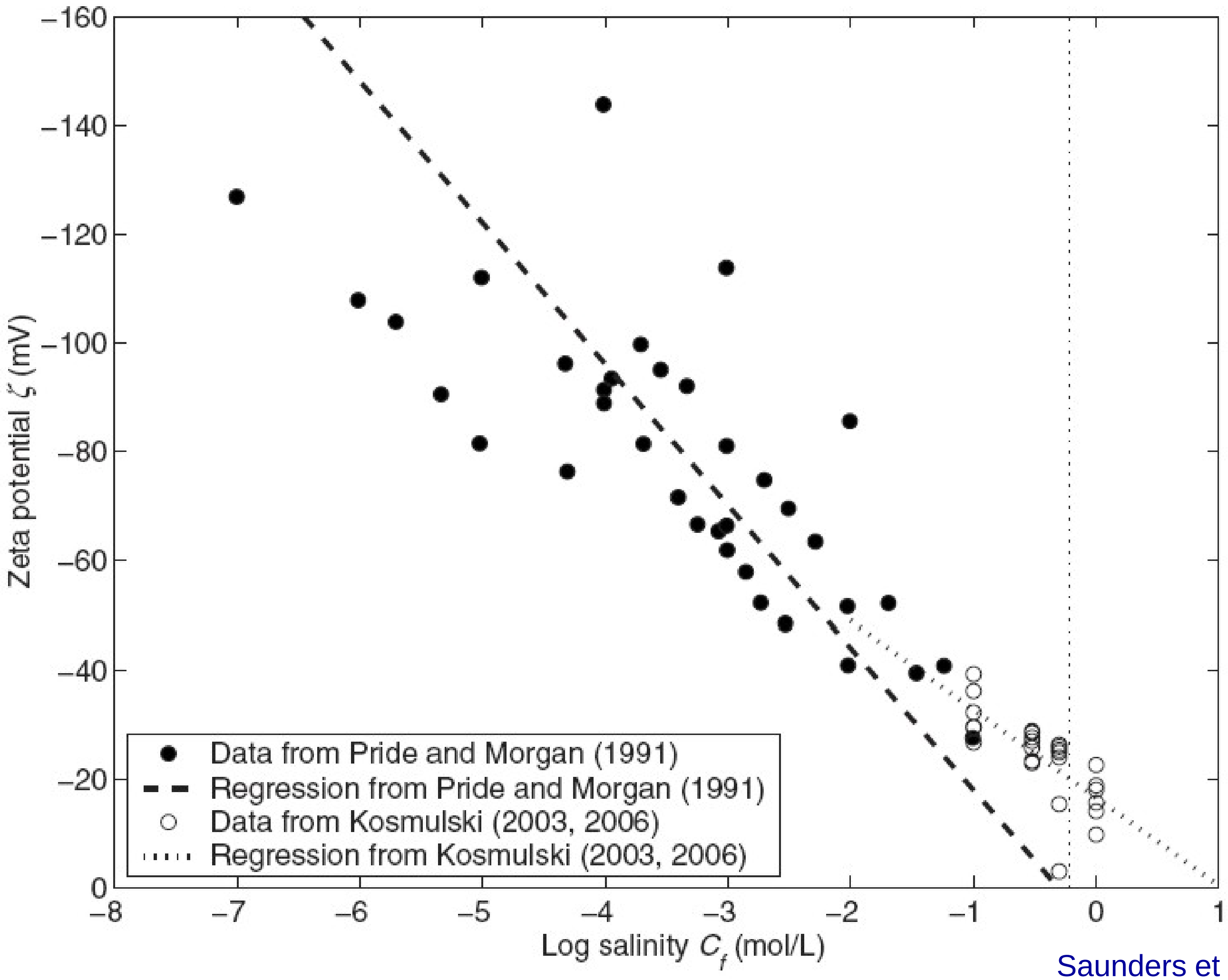
Saunders et al. (2008)

Plan

- Introduction
- Origin
- Theory
- Apparatus
- Laboratory determination
- Applications
- Conclusions
- Future directions

Laboratory determinations

Pore fluid salinity II



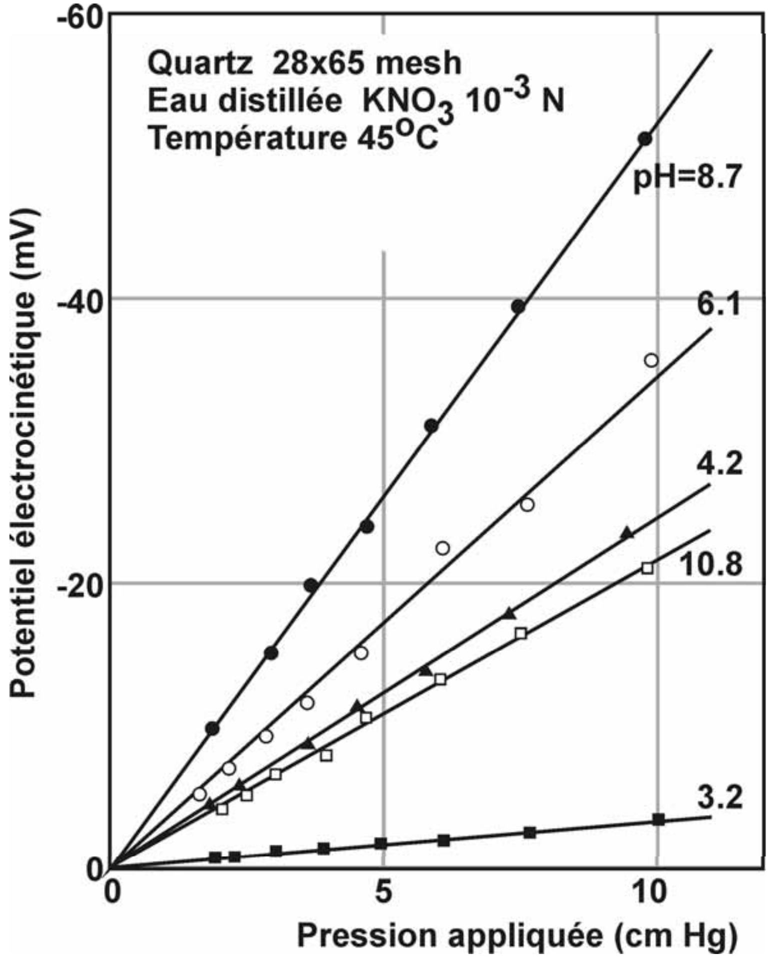
Saunders et al. (2008)

Plan

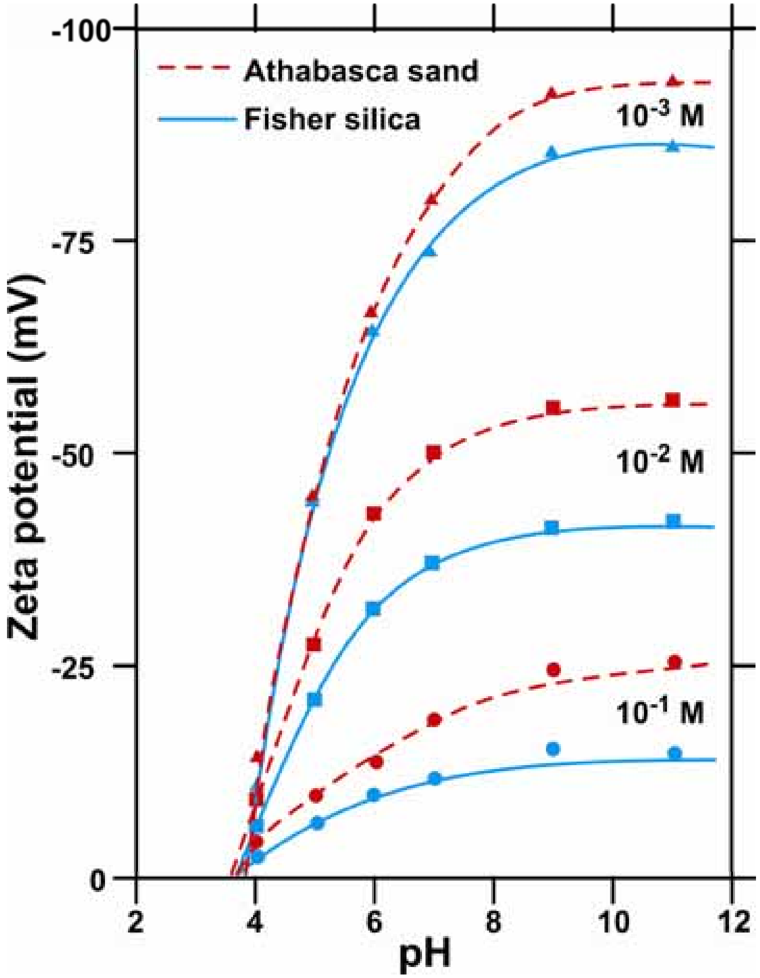
- Introduction
- Origin
- Theory
- Apparatus
- Laboratory determination
- Applications
- Conclusions
- Future directions

Laboratory determinations

Pore fluid pH I



Ishido et Mizutani (1981)



Cerda & Non-Chhom (1989)

Plan

Introduction

Origin

Theory

Apparatus

Laboratory determination

Applications

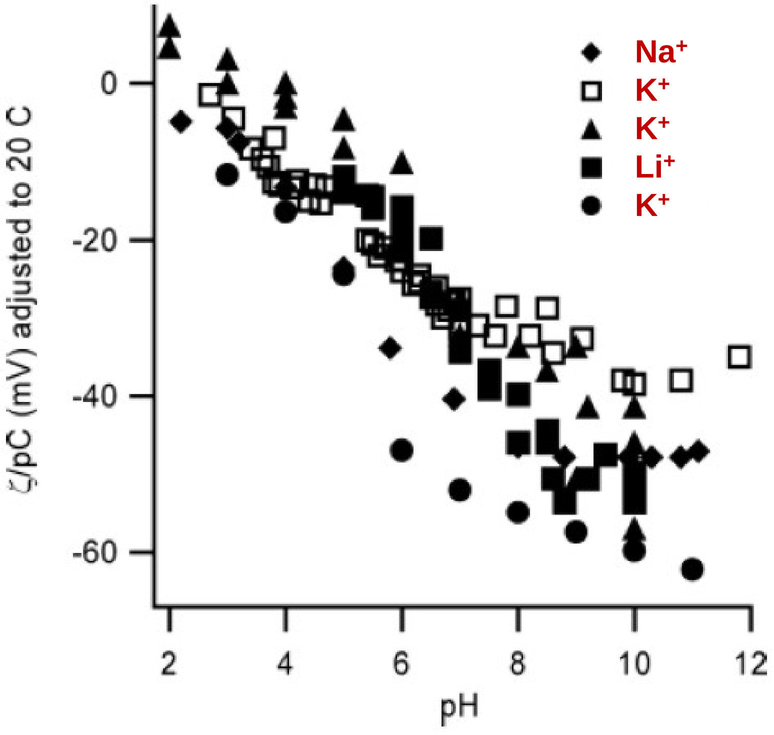
Conclusions

Future directions

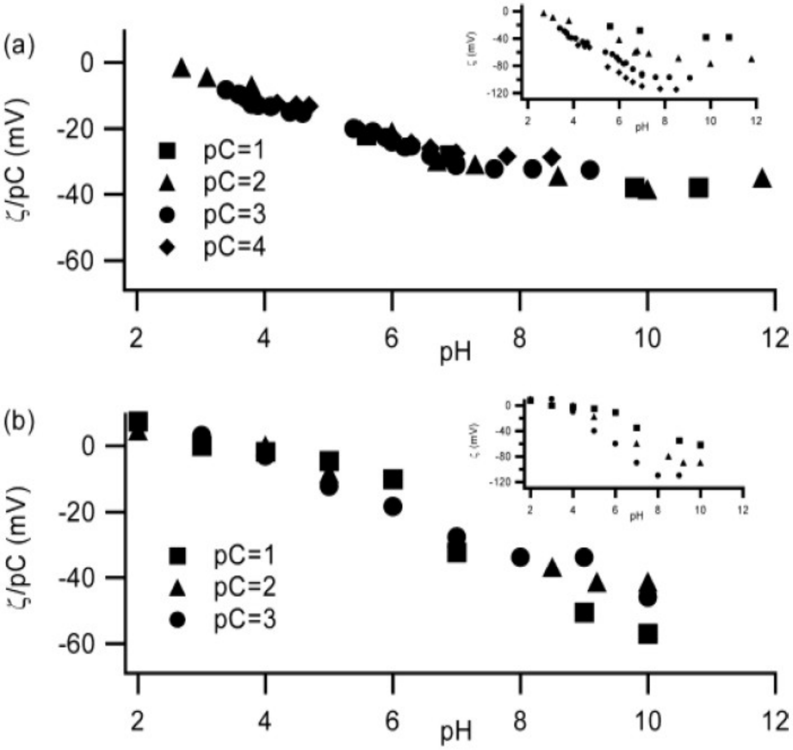
Laboratory determinations

Pore fluid pH II

Scales et al.(1992)
Kosmulski & Matijevic (1992)
Kirby & Hasselbrink (2004)



pH dependence of temperature-corrected (20°C), normalized zeta potential



Zeta potential measured as a function of pH and counterion concentration

Plan

Introduction

Origin

Theory

Apparatus

Laboratory determination

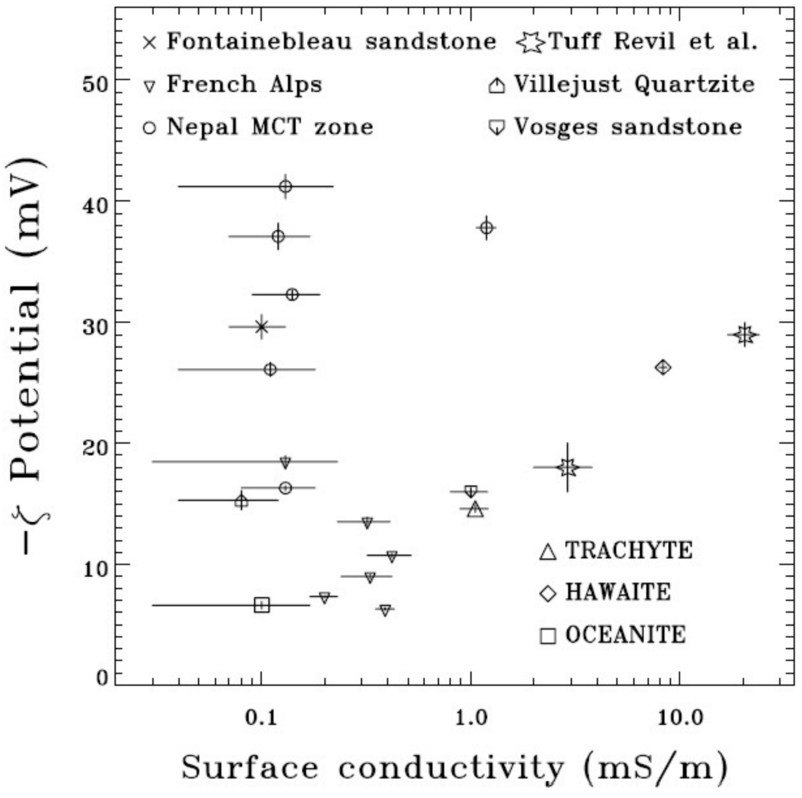
Applications

Conclusions

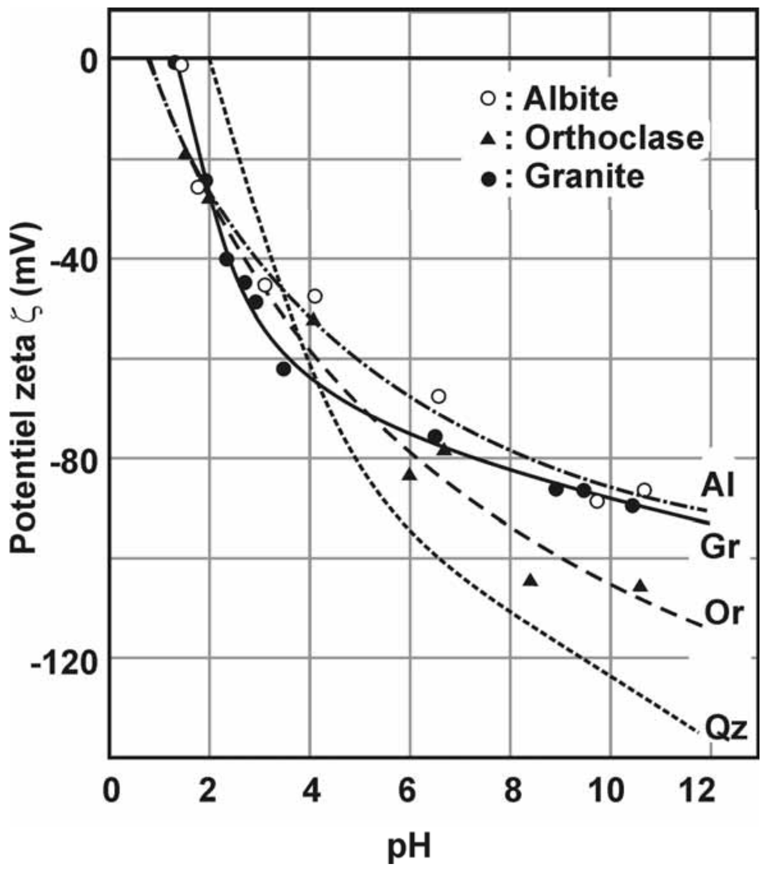
Future directions

Laboratory determinations

Mineralogy I



Perrier and Froidefond (2003)

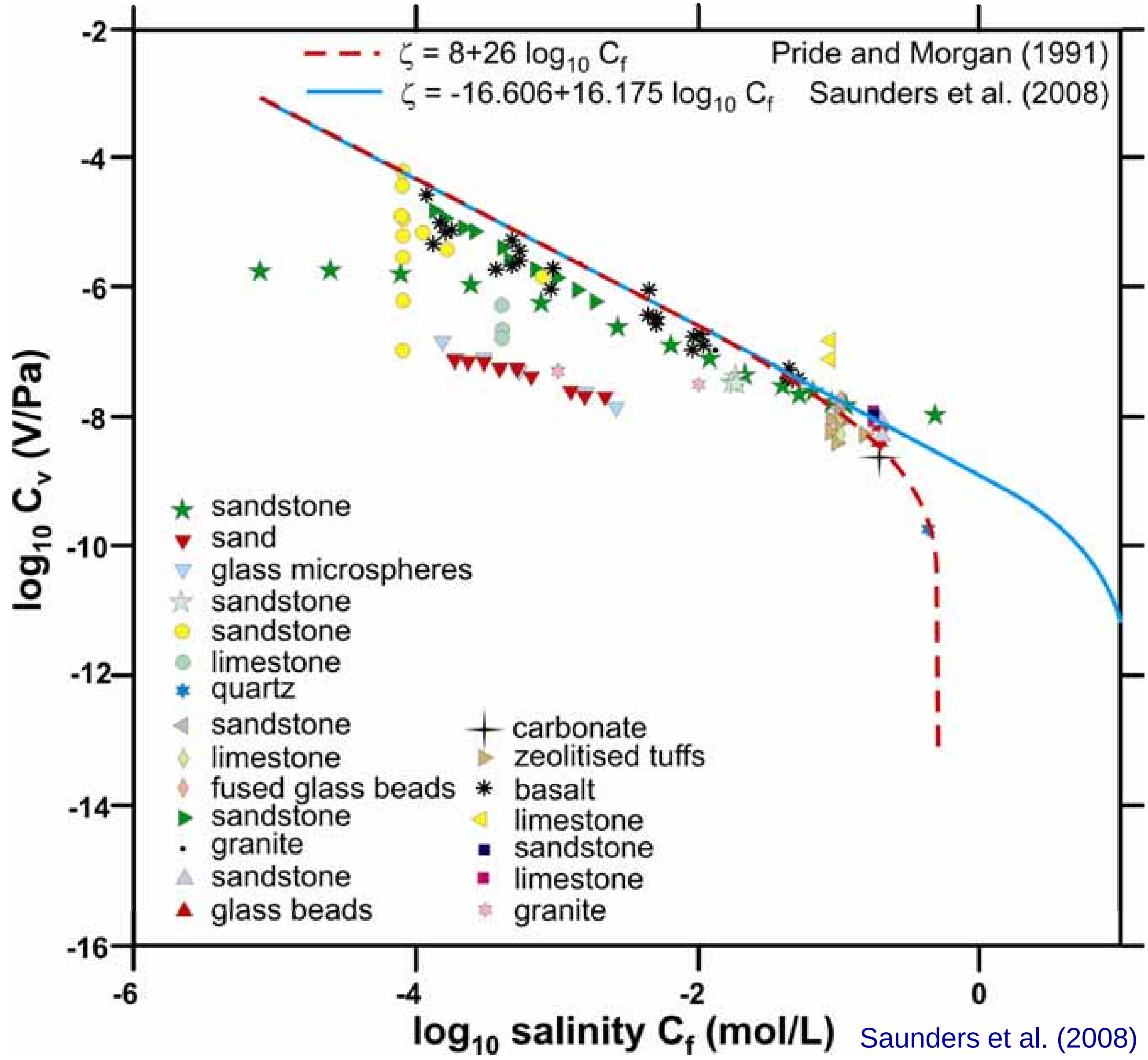


Ishido et Mizutani (1981)

Plan
Introduction
Origin
Theory
Apparatus
Laboratory determination
Applications
Conclusions
Future directions

Laboratory determinations

Mineralogy II



Saunders et al. (2008)

Plan

Introduction

Origin

Theory

Apparatus

Laboratory determination

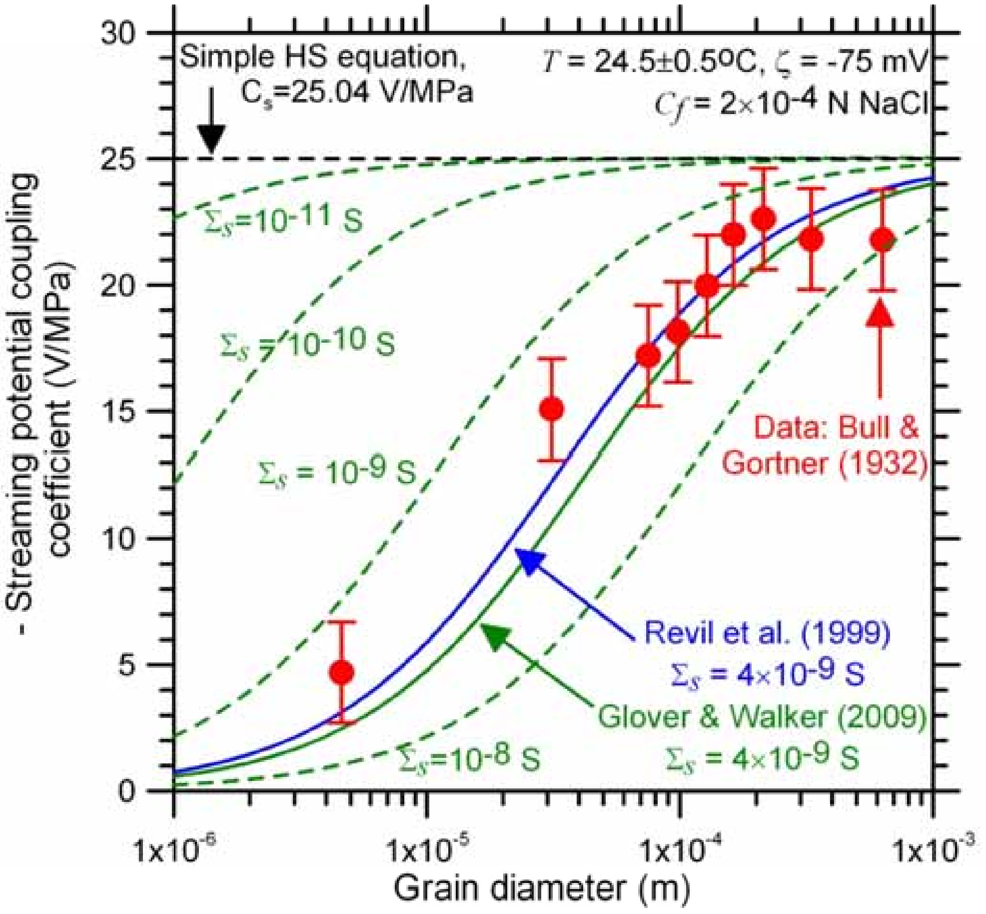
Applications

Conclusions

Future directions

Laboratory determinations

Grain size



$$C_s = -\frac{d\,\varepsilon_f\,\zeta}{\eta_f\left(d\,\sigma_f + 6\Sigma_s\left(F-1\right)\right)},$$

$$\Lambda = \frac{d}{3\left(F-1\right)}$$

Revil et al. (1999)

$$C_s = -\frac{d\,\varepsilon_f\,\zeta}{\eta_f\left(d\,\sigma_f + 4\Sigma_s mF\right)},$$

$$\Lambda = \frac{d}{2mF}$$

Glover et al. (2006)

$$C_s = -\frac{r\,\varepsilon_f\,\zeta\sqrt{a}}{\eta_f\left(r\,\sigma_f\sqrt{a} + 4\Sigma_s\sqrt{2}\right)},$$

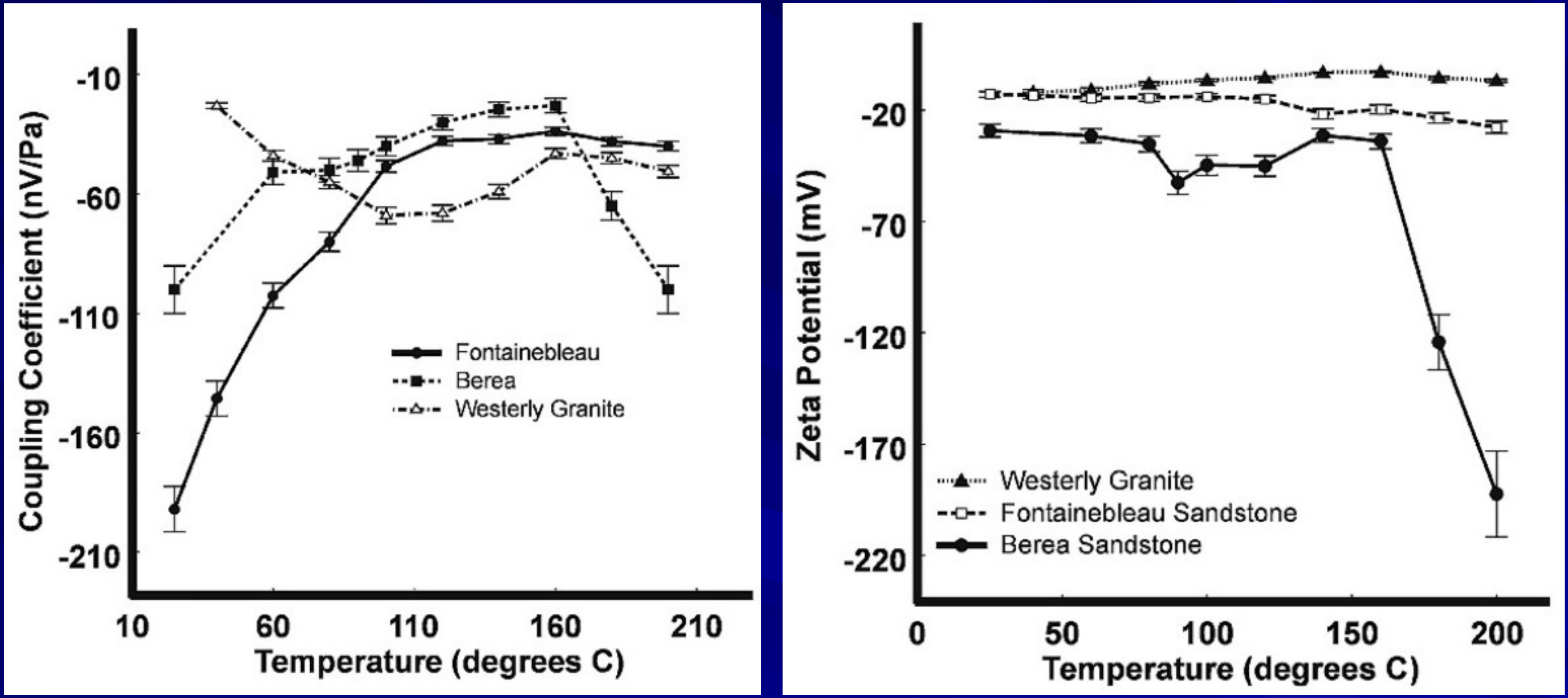
$$\Lambda = r\sqrt{\frac{a}{8}}$$

Glover and Walker (2009)

Laboratory determinations

Temperature

Reppert and Morgan (2003)



The coupling coefficient varies significantly, but erratically with temperature

Stability is the main experimental problem

$$\zeta = \frac{\Delta V}{\Delta P}\frac{\eta_f \sigma_f^*}{\varepsilon_f} = \frac{C_s \eta_f \sigma_f^*}{\varepsilon_f}$$

The calculated zeta potential may be a function of temperature

However, its form is controlled by the effect of temperature on the fluid conductivity

Laboratory determinations

Saturation I

$$J_i = -\sigma\sigma_{ri} C C_{ri} \nabla P_i$$

$$\sigma_{ri} = S_i^n$$

$$C_{ri} = ?$$

Many attempts at finding a solution

$$C_r = \frac{1}{S_w^{n+1}}\left(\frac{S_w - S_w^r}{1 - S_w^r}\right)^{(2+3\lambda)/\lambda}$$

Revil et al. (2007)

$$C_r = \frac{Q_w}{\mu_w}\frac{k_{rw}}{\sigma_r} \quad where \quad C = \frac{k}{\sigma}$$

Jackson (2008)

$$C_r = S_w^{n+2}\left(\frac{S_w - S_w^r}{1 - S_w^r}\right)^{1/\lambda}$$

Glover (2009)

Jackson (2008)

$$C_r = \frac{\frac{Q_w}{\mu_w}k_{rw} + \frac{Q_o}{\mu_o}k_{ro}}{\sigma_r}$$

Plan

Introduction

Origin

Theory

Apparatus

Laboratory determination

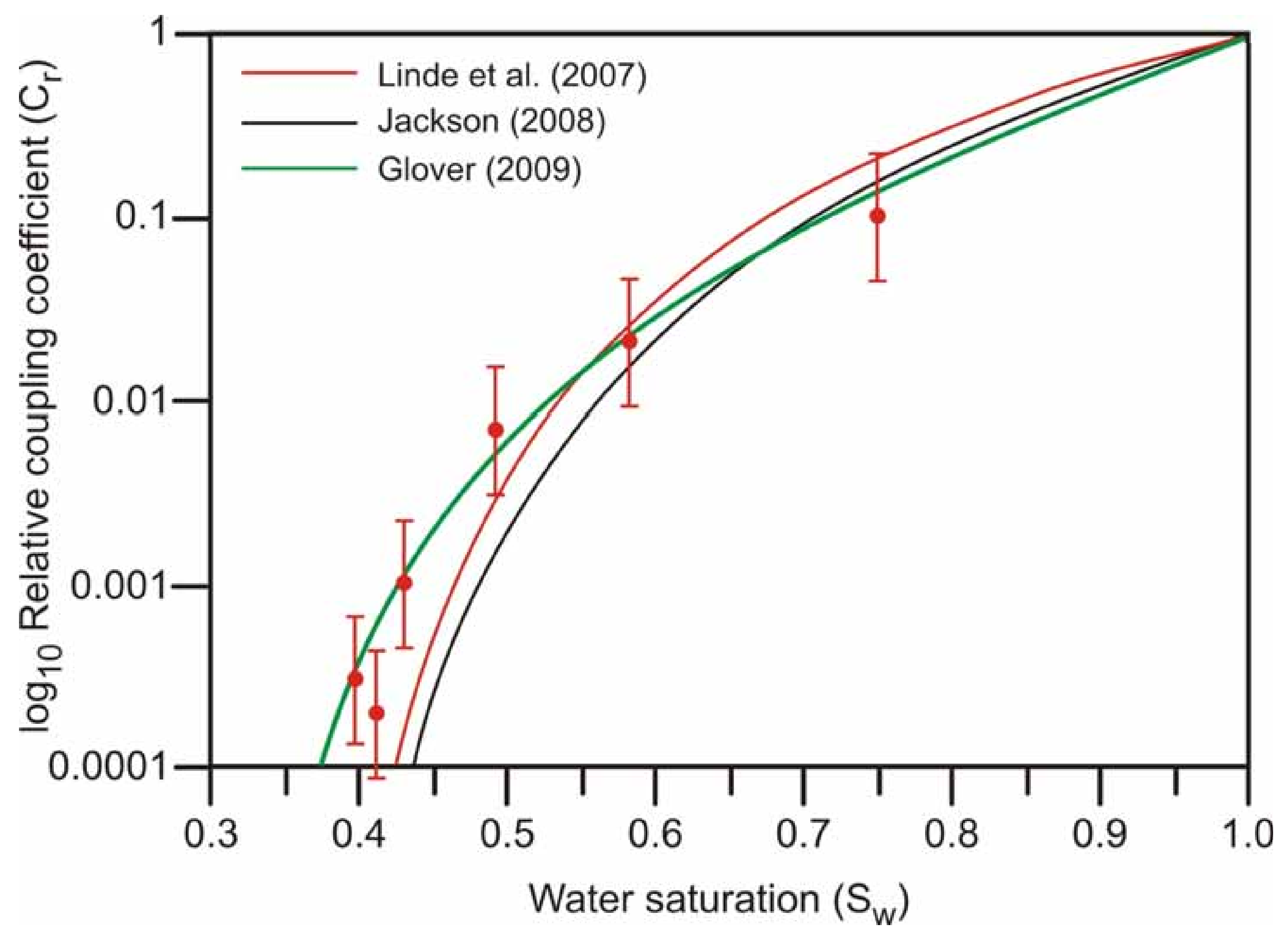
Applications

Conclusions

Future directions

Laboratory determinations

Saturation II

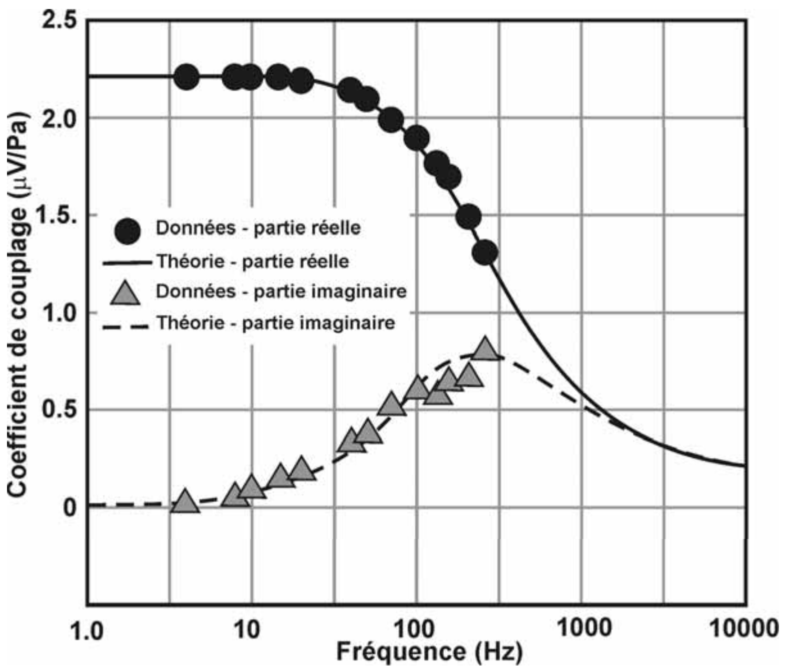


Laboratory determinations

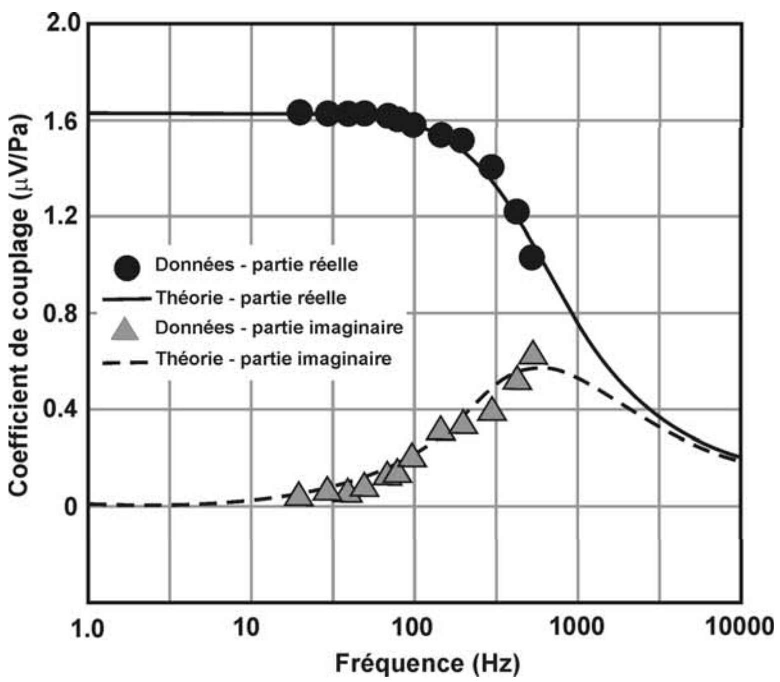
Frequency (AC measurements) I

No reliable data exists for rocks in the public domain

Here is the best data made on silica filters



Filter A (72.5-87 µm). Modelled transition frequency (269 Hz) corresponds to a pore radius of 65 µm.

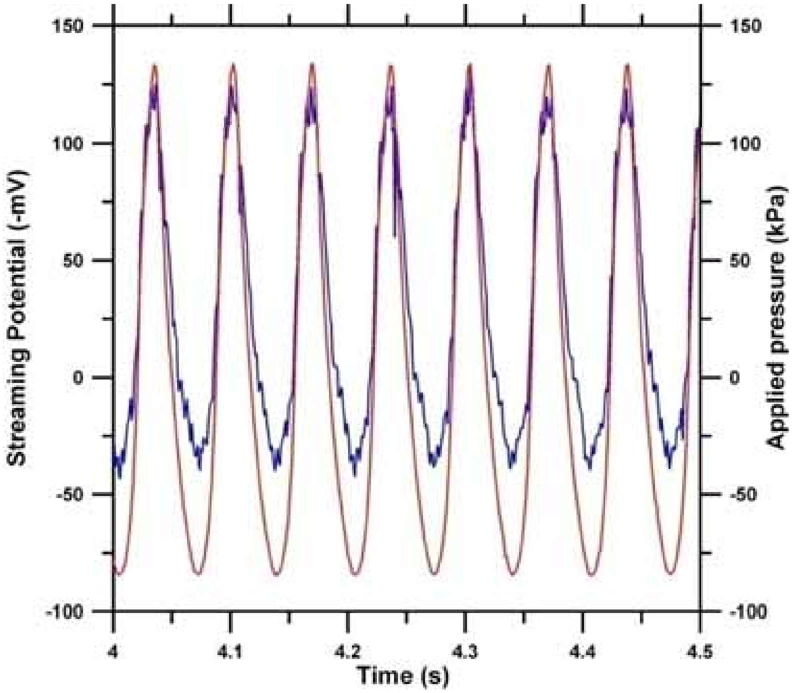


Filter B (35-50 µm). Modelled transition frequency (710 Hz) corresponds to a pore radius of 40 µm.

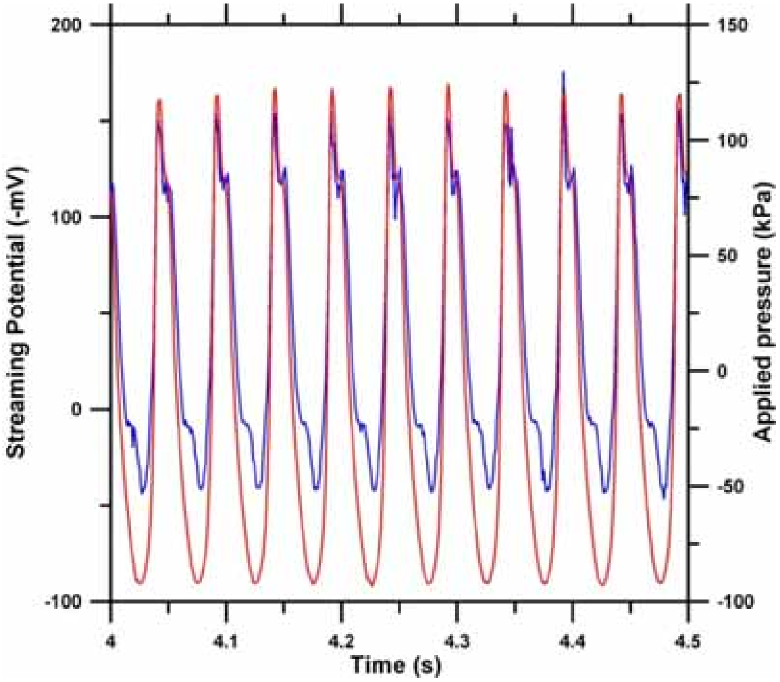
Laboratory determinations

Frequency (AC measurements) II

First data available for ottawa sand using the Université Laval Petrophysics AC cell Mk 2



15 Hz – some improvement of S/N ratio required



20 Hz – Problems with cavitation. Calculations have been carried out to avoid this phenomenon.

Applied pressure difference in red

Streaming potential in blue

Plan

Introduction

Origin

Theory

Apparatus

Laboratory determination

Applications

Conclusions

Future directions

Applications

Applications

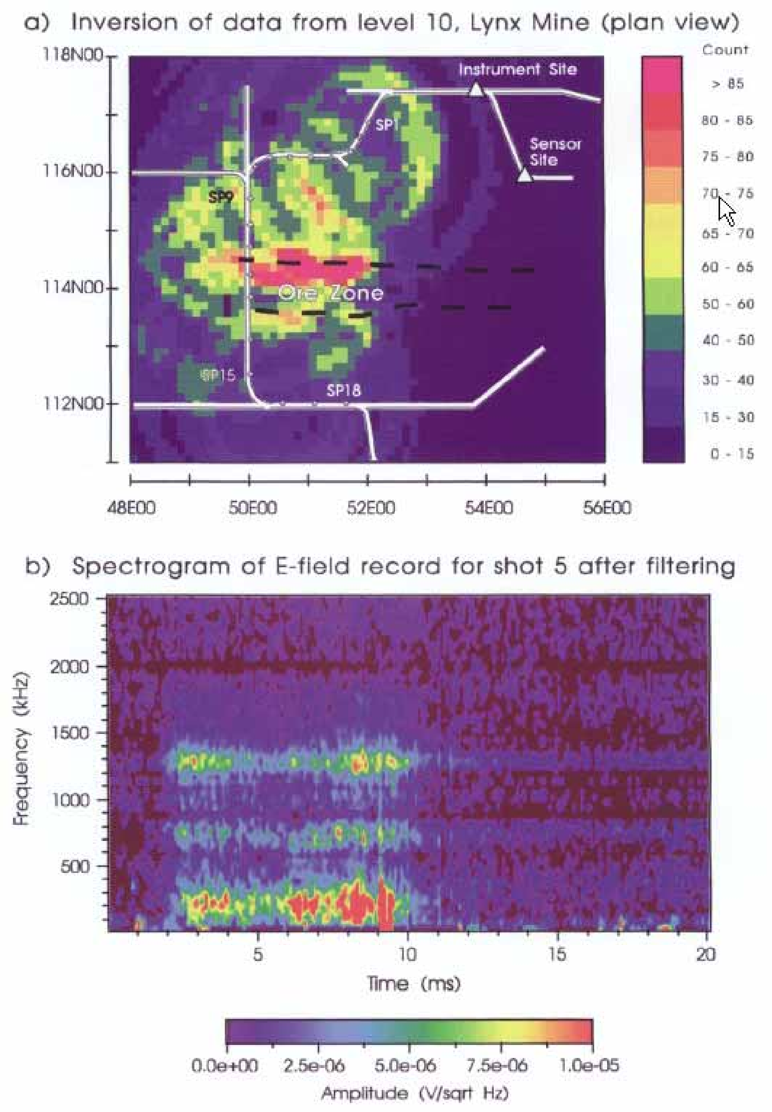
- Hydrocarbon exploration & production
- Water reservoir management
- Remediation of polluted soils
- Permafrost monitoring
- Acid mine drainage monitoring
- Volcano prediction
- Earthquake prediction
- Synthetic earthquakes
- Geothermal HDR reservoir monitoring
- Monitoring of CO_2 sequestering
- Soil stabilisation

…many others

Applications

Hydrocarbon exploration & production I

Saunders et al. (2008)



There are many impressive examples of the use of seismoelectric and electro-kinetic prospection of hydrocarbon reservoirs

All are impossible to publish!!!

Here is an application to mining instead – the discovery of zinc ore by electroseismics

Plan

Introduction

Origin

Theory

Apparatus

Laboratory determination

Applications

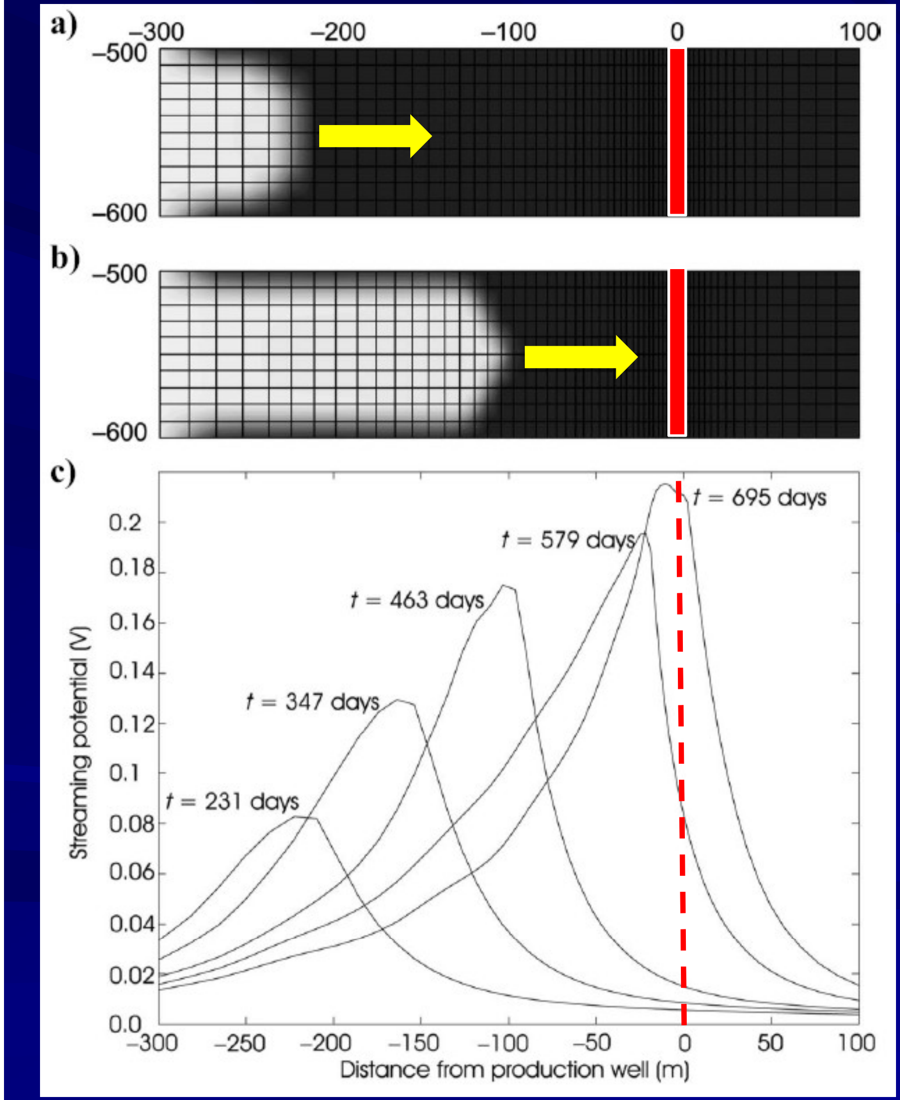
Conclusions

Future directions

Applications

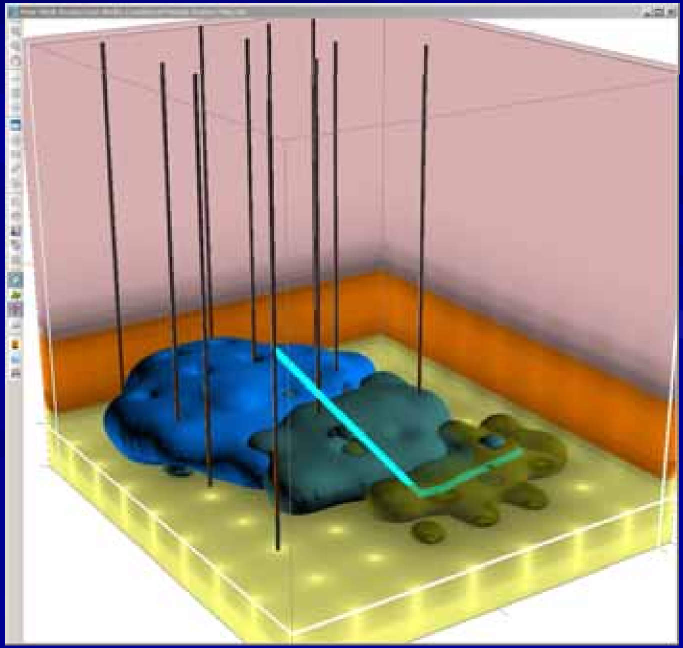
Hydrocarbon exploration & production II

Saunders et al. (2008)



As water approaches the borehole it may be predicted by measuring the increasing streaming potential

The well can be shut to improve the reservoir production



Plan
Introduction
Origin
Theory
Apparatus
Laboratory determination
Applications
Conclusions
Future directions

Applications

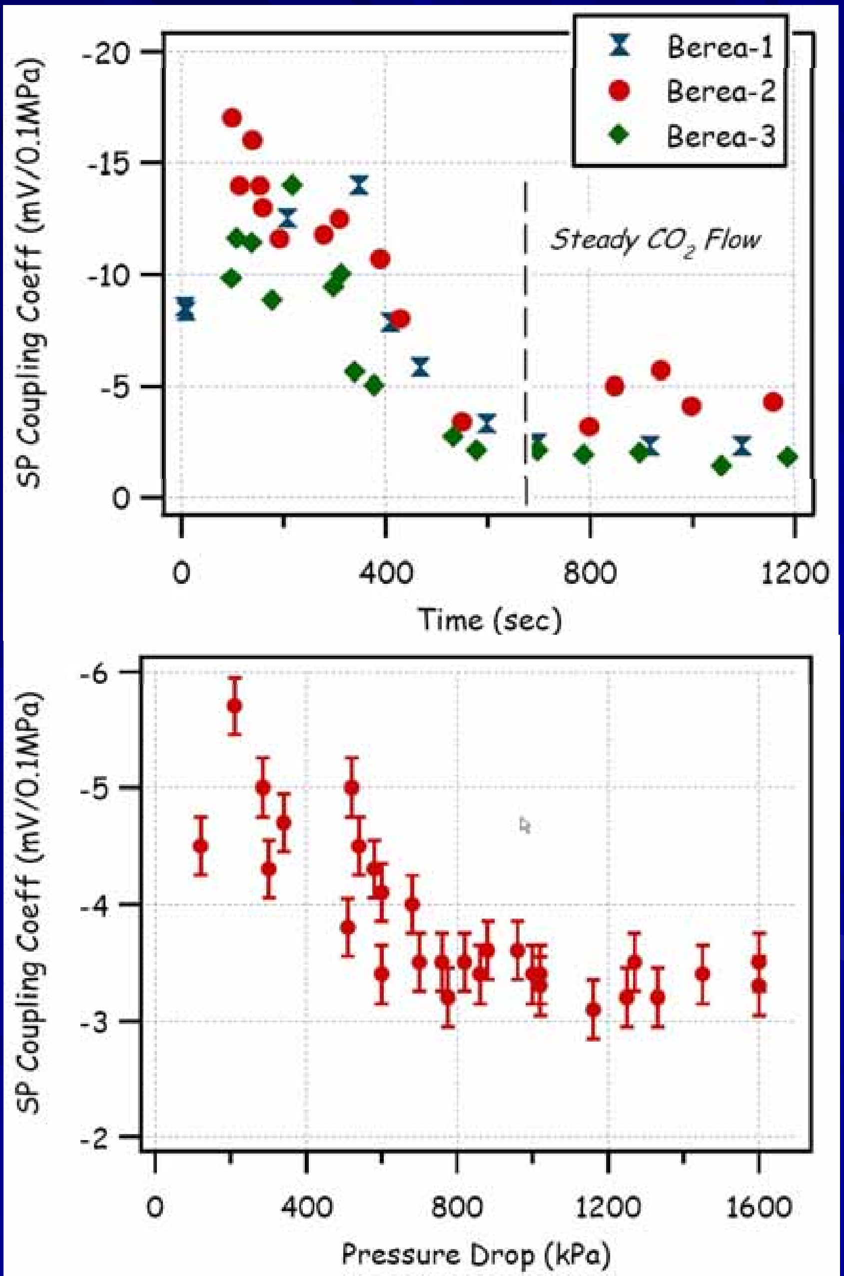
CO$_2$ Sequestration

Injection of CO2 produces a dramatic decrease in the coupling coefficient

-300 mV/MPa ➡ -30 mV/MPa

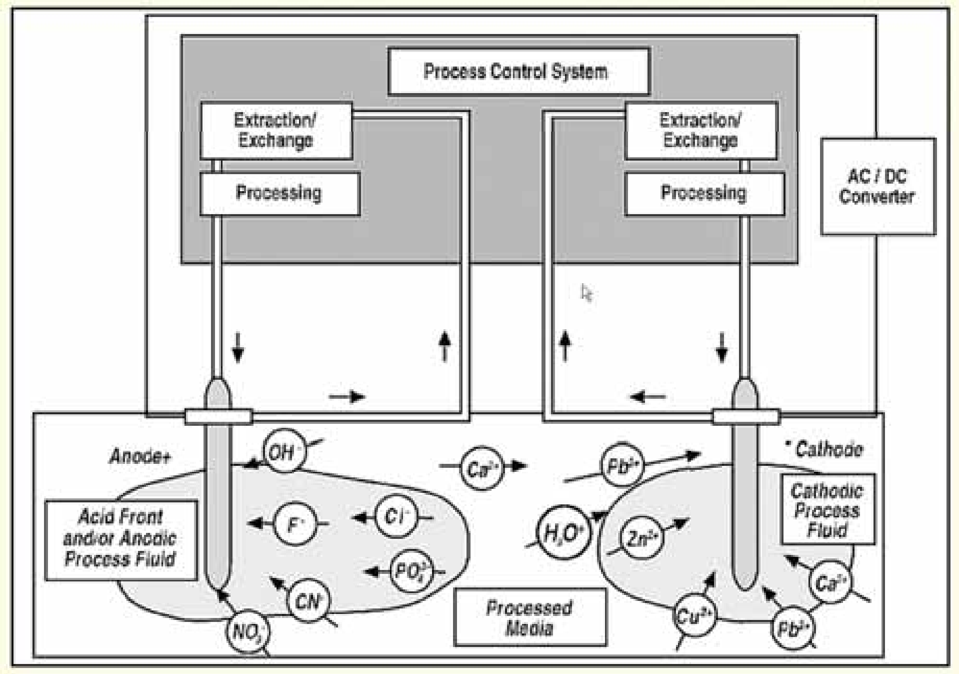
These differences would be easily detectable by measuring surface SP

- ❖ Progressive injection of a reservoir with CO2 could be monitored
- ❖ CO2 leaking from a sequestration reservoir may also be detected before it appears at the surface



Applications

Remediation of polluted soils



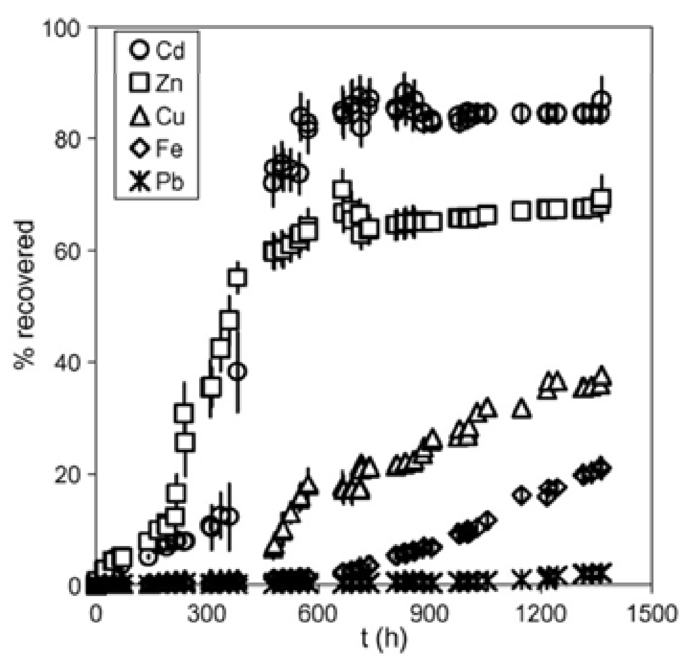
Electro-kinetic processes are used to

A. Extract polluted fluids and ions, or
B. Move polluted fluids into contact with bioremediation or other active agents

Active from ppt upwards

Electrolysis	ions
Electo-osmosis	water
Electrophoresis	colloids

Electro-kinetic water extraction Is also used to strengthen soils



Plan
Introduction
Origin
Theory
Apparatus
Laboratory determination
Applications
Conclusions
Future directions

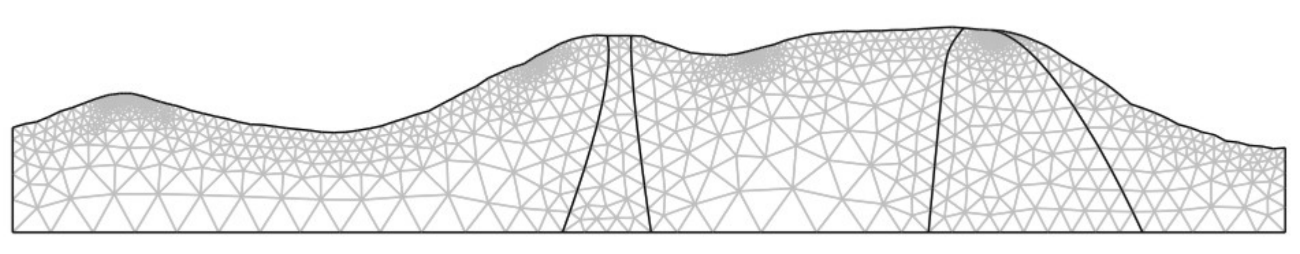
Applications

Volcano prediction I


© Google Earth


© John Freeman

First create a 2D finite element model in Comsol Multiphysics



Plan

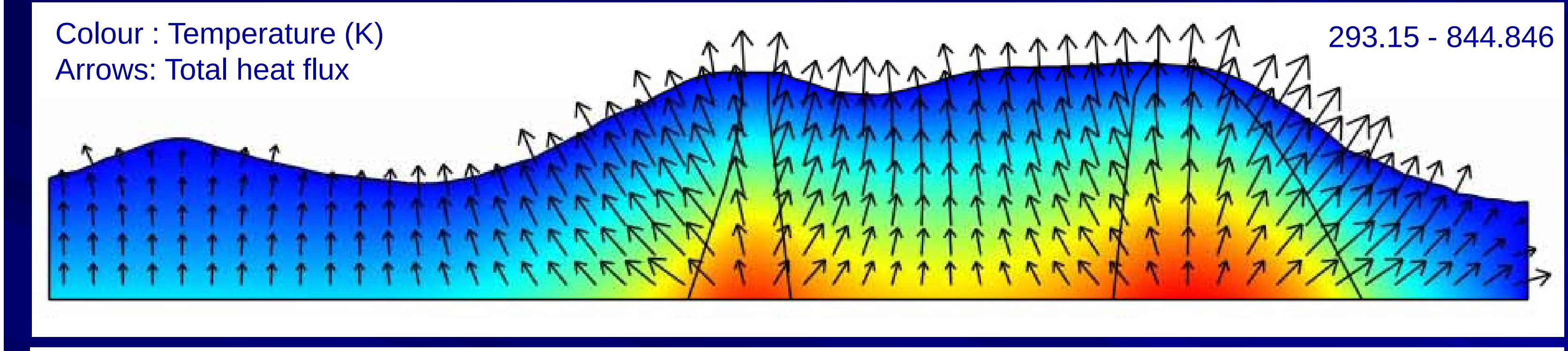
- Introduction
- Origin
- Theory
- Apparatus
- Laboratory determination
- Applications
- Conclusions
- Future directions

Applications

Volcano prediction II

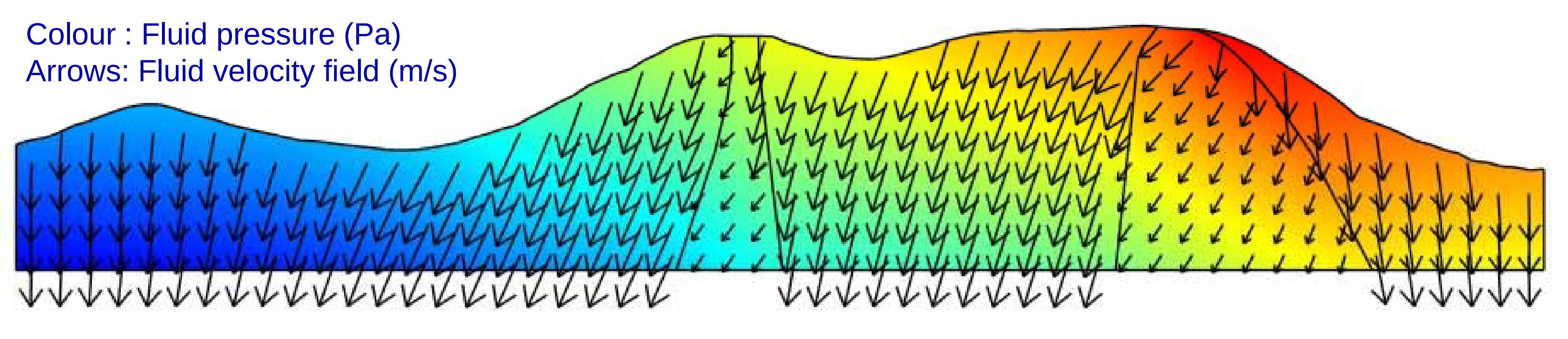
First create a 2D finite element model in Comsol Multiphysics

Courtesy of Emile Walker

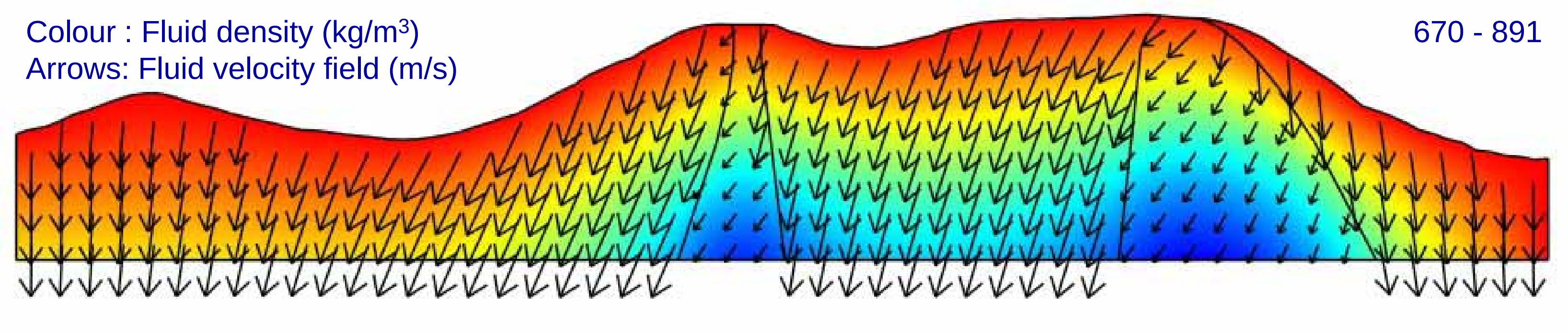


Colour : Temperature (K)
Arrows: Total heat flux

293.15 - 844.846



Colour : Fluid pressure (Pa)
Arrows: Fluid velocity field (m/s)



Colour : Fluid density (kg/m^3)
Arrows: Fluid velocity field (m/s)

670 - 891

Plan

Introduction

Origin

Theory

Apparatus

Laboratory determination

Applications

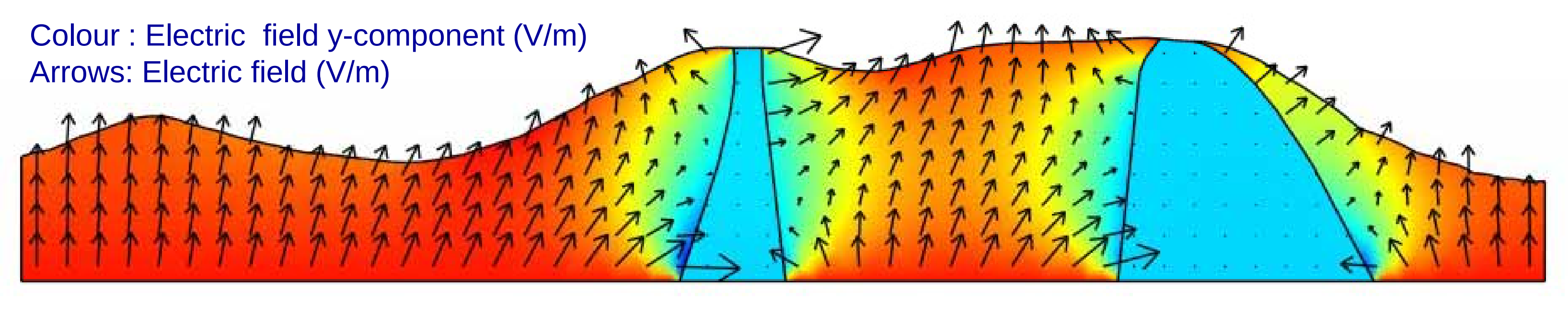
Conclusions

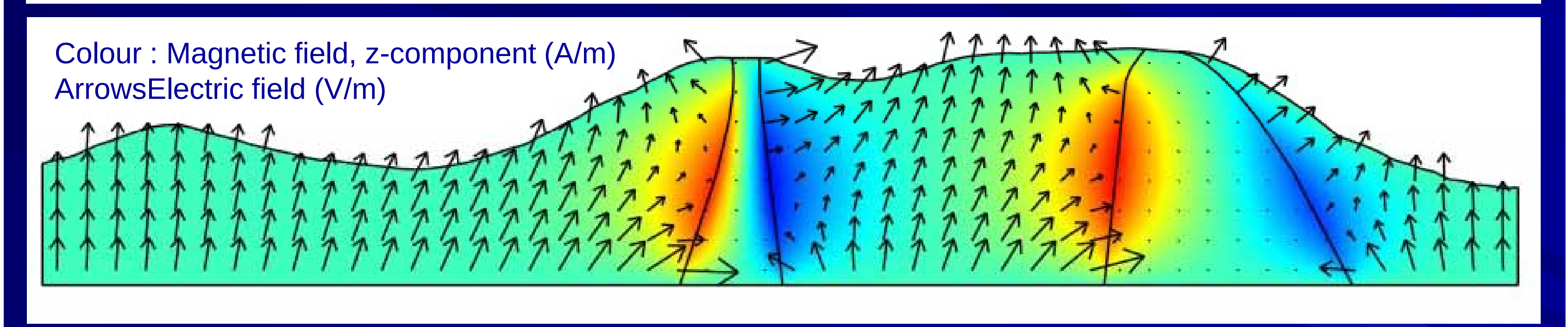
Future directions

Applications

Volcano prediction III

Courtesy of Emile Walker


Colour : Electric field y-component (V/m)
Arrows: Electric field (V/m)


Colour : Magnetic field, z-component (A/m)
ArrowsElectric field (V/m)

Colour: Fluid density (kg/m³)
Arrows: Fluid velocity field (m/s)

Modelling is still at an early stage. Need to develop convective flow.
A map of the electric potential across the surface will then be compared to
The measured SP values.

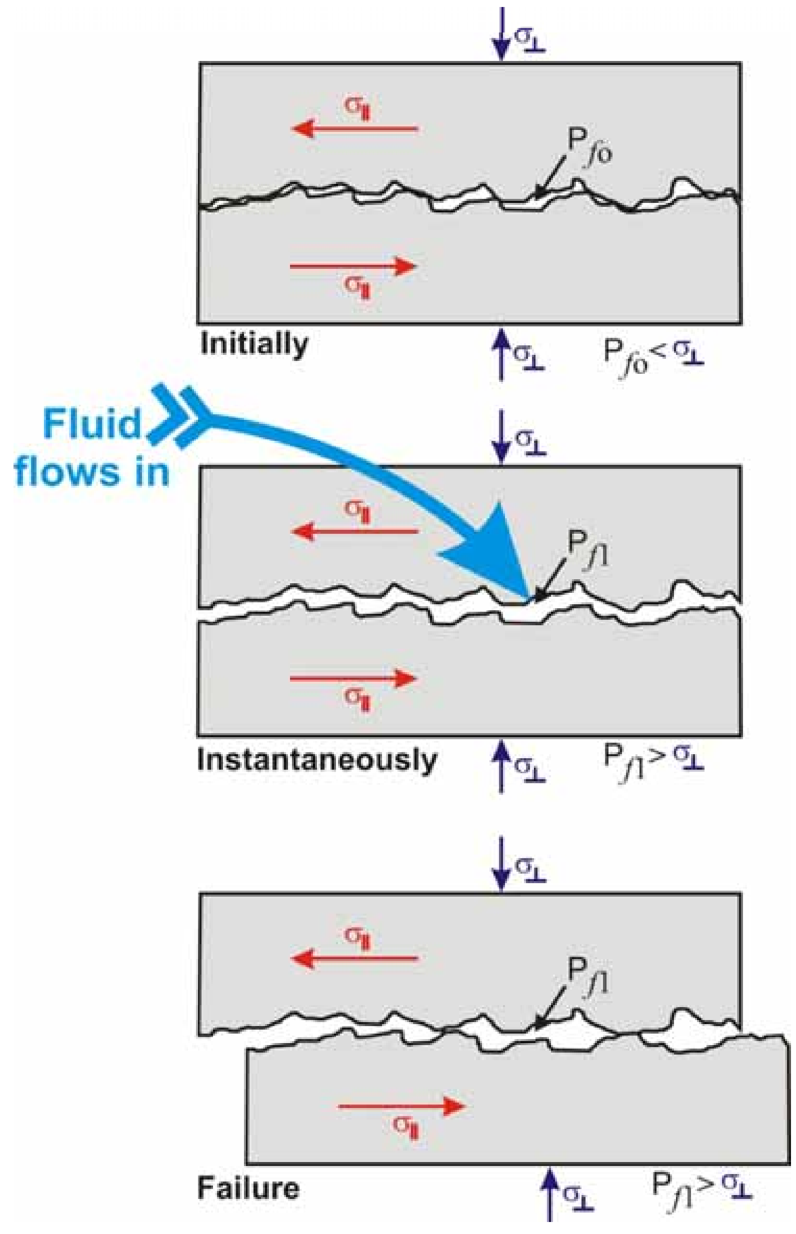
Time dependent injection of magma will then be modelled
to see the SP values change with time.

Plan
Introduction
Origin
Theory
Apparatus
Laboratory determination
Applications
Conclusions
Future directions

Applications - Earthquake prediction I

- Initial fault is submitted to a shear stress
- However, it is locked
  - by its surface geometry and
  - by the effective stress perpendicular to the fault
- Fluid flowing into a fault increases the fluid pressure
- It decreases the effective stress on the fault
- Unlocks the fault for it to fail
- Lubricates the faulting process

What causes the fluid flow?
What can the fluid flow cause?



Plan
Introduction
Origin
Theory
Apparatus
Laboratory determination
Applications
Conclusions
Future directions

Applications

Earthquake prediction II

- The inflow may cause an electrical potential difference
  hence generating a streaming current
  and hence a magnetic field
  by electro-kinetic processes
  generating electro-magnetic and SP precursors

$\Delta P \rightarrow \Delta V$

- The fluid flow can be caused by electrical potential differences within the crust
  associated with natural telluric currents
  induced by ionospheric currents
  by electro-osmosis

$\Delta V \rightarrow \Delta P$

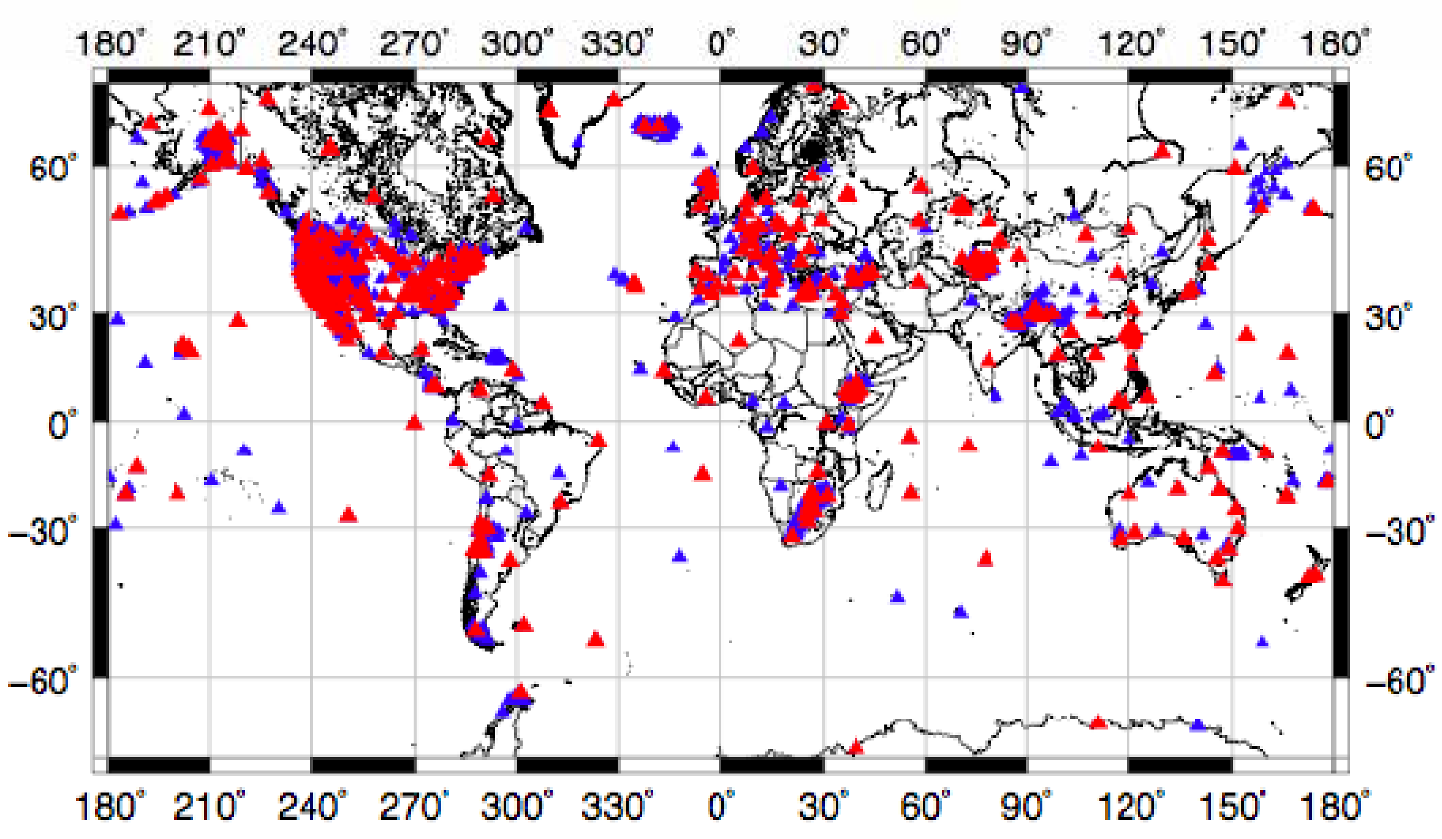
- The fluid flow may be caused by elastic waves set in motion by other earthquakes

Understanding these links may lead to improvement in our ability to predict the time of earthquakes

Plan
Introduction
Origin
Theory
Apparatus
Laboratory determination
Applications
Conclusions
Future directions

Applications

Earthquake prediction III



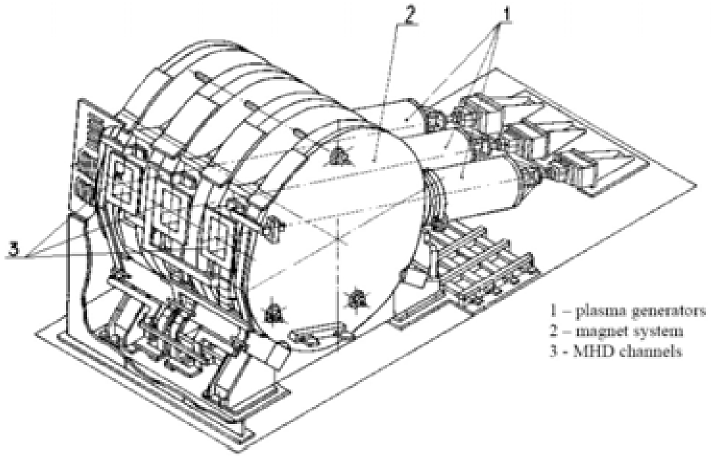
Red seismic stations received arrivals from small local earthquakes that was triggered by a large distant earthquake (those in blue did not)

Independent of tectonic province – mediated by surface waves!

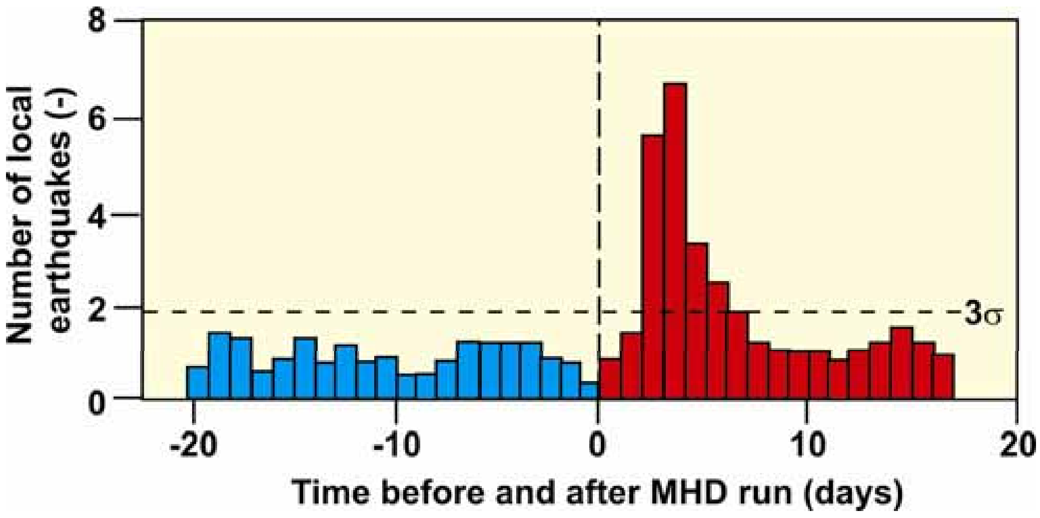
Applications

Synthetic earthquakes I

MHD Generators – The Earthquake machine



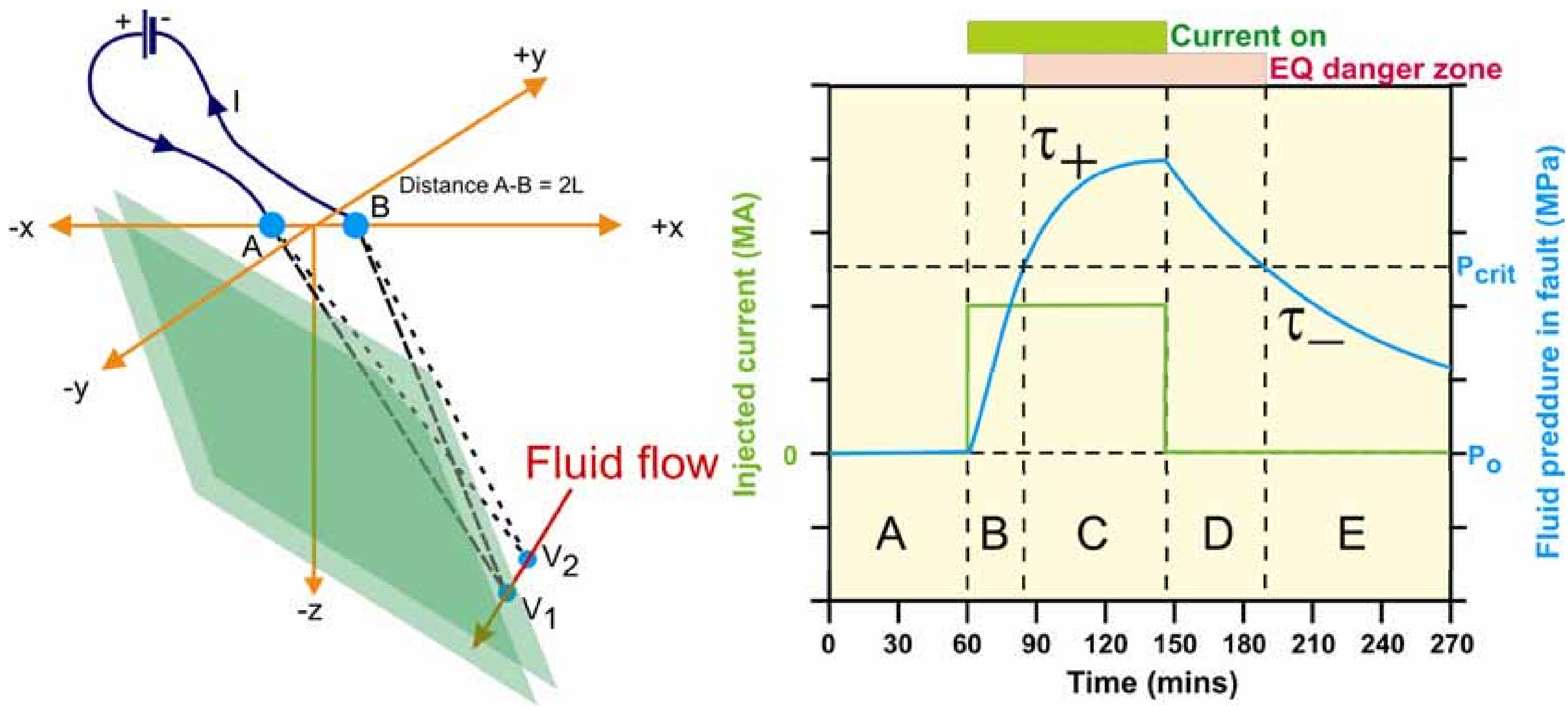
Weight 18,000 kg
Maximum power 15 MW
Runtime 2 & 7 seconds
Output 1.5 kA at 1350 V



Plan
Introduction
Origin
Theory
Apparatus
Laboratory determination
Applications
Conclusions
Future directions

Applications

Synthetic earthquakes II

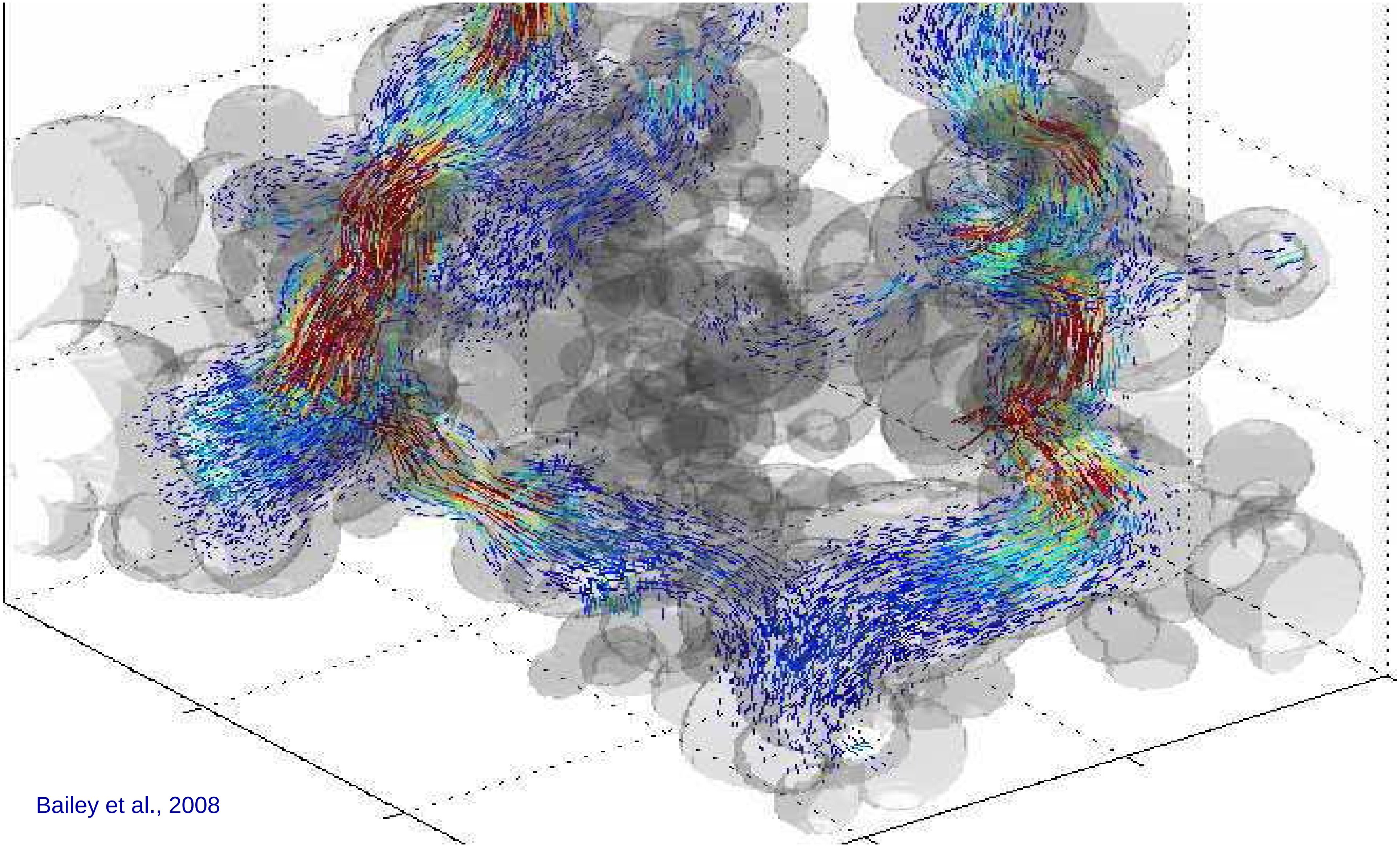


Fluid flow into the fault reduces the effective pressure, triggering the earthquake

Pressure in the fault increases at one rate and decreases at another. Fracture fluid pressure may be over a critical level for several days after current injection

Plan
Introduction
Origin
Theory
Apparatus
Laboratory determination
Applications
Conclusions
Future directions

Conclusions



Bailey et al., 2008

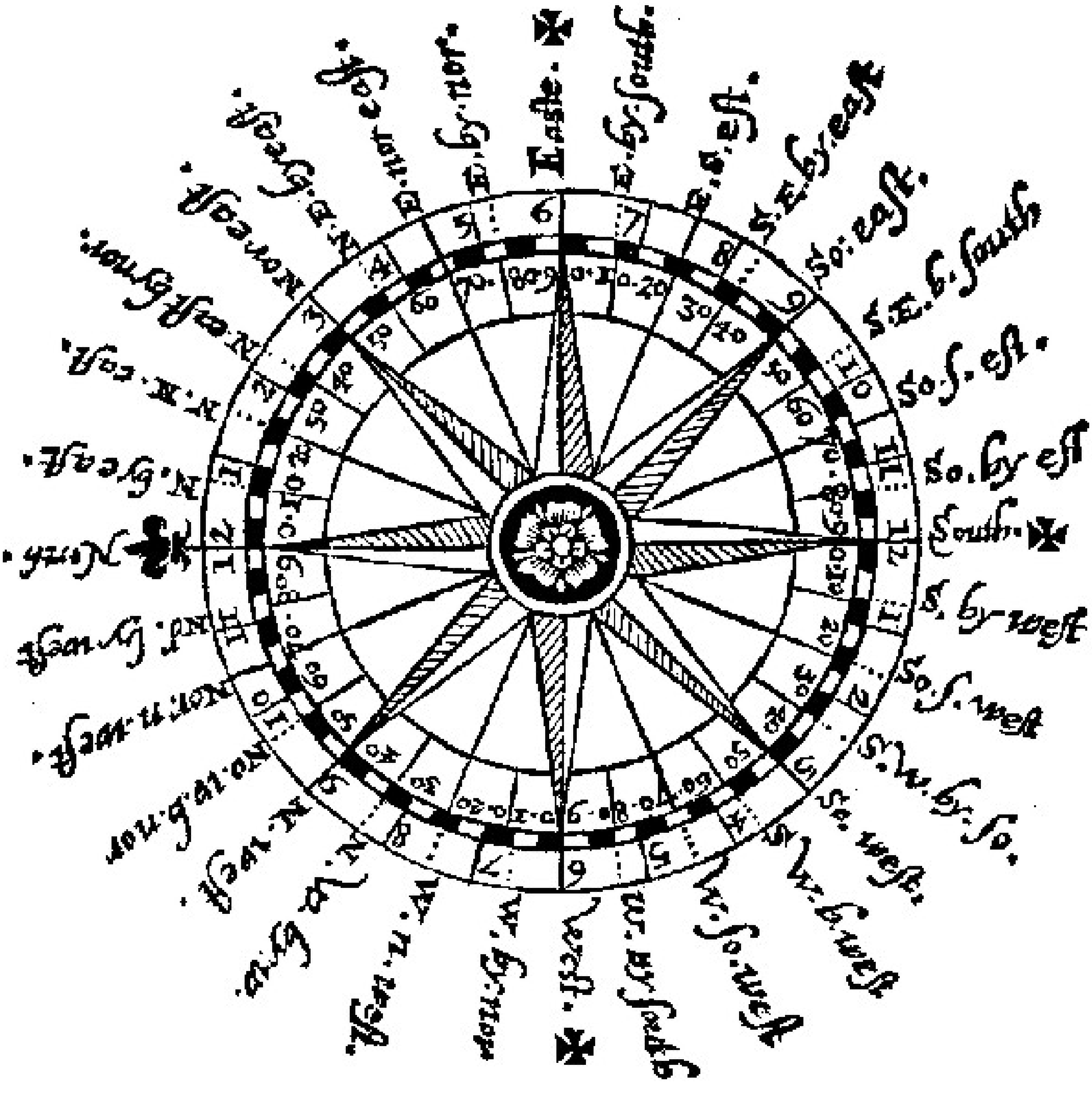
Conclusions I

- The electro-kinetic and (seismo-electric) phenomena are well understood conceptually and qualitatively
- Unfortunately we do not have a sufficient database of measurements to fully understand quantitatively these phenomena in rocks
- Despite this fundamental lack both phenomena have been pressed into practical application

Conclusions II

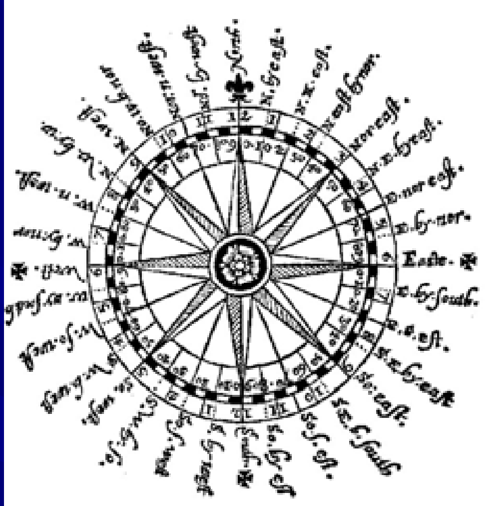
- However, high quality apparatus is being developed in a number of laboratories worldwide
- Future data should give us a better quantitative basis for the phenomena
- Applications for the phenomena are huge with a potential market amounting to billions of euros
- The properties as a function of frequency and saturation are particularly important

Future directions



Future directions

- Development of AC electrical theory in rocks
- Development of AC electro-kinetic and seismo-electric theory
- Better basic measurements made over a large range of rocks and parameters
- Particular importance given to AC measurements and saturation measurements
- Open research with industry
- Ensure applications use the latest evelopments and data



UNIVERSITÉ LAVAL

Acknowledgments

Canada	Emilie Walker & Eric Tardif, Jean Ruel, John Hadjigeorgiou & Tom Ransford, Guillaume Lalande, Melissa Jodouin, Marc Blouin, Nicholas Déry & Simon Marcil
Scotland	Steven Ogilvie, Evgeny Isakov, Malcolm Hole & Colin Taylor, Ibrahim Al-Zadjali, Kellie Frew, Steven Cuddy & Hesham Al-Qassab, Peter Bormann & Gregor Bächle
Hungary	Antal Adám
Spain	Jaume Pous & Javier Gomez
Japan	Koji Matsuki, Kazuo Hayashi & Toshiyuki Hashida
France	André Revil, David Mainprice, Philippe Pezard, Benoît Iledefonse, Yves Guéguen, Yves Bernabé, Michel Darot, Thierry Reuschlé & Patrick Baud
UCL	Philip Meredith, Stan Murrell & Steve Boon
UEA & Newcastle upon Tyne	Fred Vine FRS, Keith Runcorn & Russell Ross

GASTEM

Plan
Introduction
Origin
Theory
Apparatus
Laboratory determination
Applications
Conclusions
Future directions