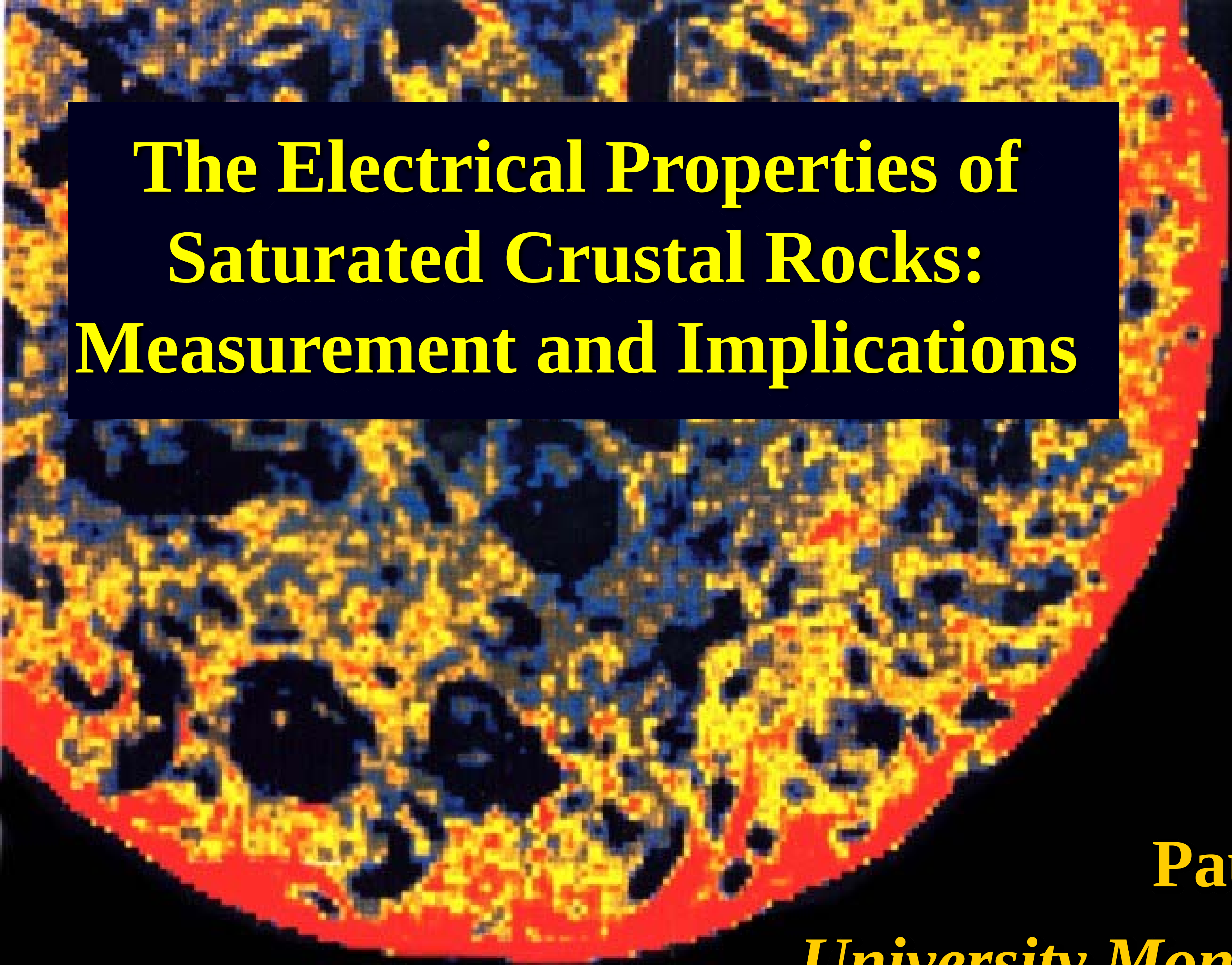


The Electrical Properties of Saturated Crustal Rocks: Measurement and Implications

Paul Glover

University Montpellier II

Structure

- Basics – Ignoring the difficult mathematics
- Past Experiments
  - Benchtop Multisalinity
  - Confining Pressure
  - Deformation
- Developments in Montpellier
- Application to the Pyrennees

Basic Theory

Causes in Rocks

Cause		Medium		Examples / Conduction
Matrix	→	Rock Forming Minerals	→	Hydrated Amphiboles & Clay Minerals Electronic
	→	Minor Minerals	→	Metal Oxides & Sulphides, & Graphite Electronic
Fluid	→	Electrolyte	→	Natural Brines Ionic
Surface	→	Double Layer	→	+ve ions on mineral surfaces Ionic
Melt	→	Molten Rock	→	ions in melt Ionic

Fundamentals of Measurement

- Electrical properties are incredibly sensitive to changes in the rock microstructure
- Therefore, ideally suited as a probe
- In-phase and out-of-phase components
- Vary with frequency (Impedance Spectroscopy)
- Can vary with AC amplitude (AC Voltammetry)

Related Measured Variables

Measured	Specific
In-phase impedance, Z’	In-phase resistivity, ρ’
Out of phase impedance, Z”	Out of phase resistivity, ρ”
In-phase admittance, Y’	In-phase conductivity, σ’
Out of phase admittance, Y”	Out of phase conductivity, σ”
Scaled real permittivity, e’	Real permittivity, ε’
Scaled imaginary permittivity, e”	Imaginary permittivity, ε”
Length, L	Real realtive permittivity, K’
Diameter, D	Imag. relative permittivity, K”
Permeability, k	Phase angle, θ
Porosity, f	Electrical properties of fluids
Electrical properties of fluids	

Basic Equations I

$$Z^* = Z' + i\,Z''$$

$$Y^* = Y' + i\,Y'' \quad where \quad Y^* = \frac{1}{Z^*}$$

$$\sigma^* = \sigma' + i\,\sigma'' \quad where \quad \sigma^* = \frac{1}{\rho^*} \quad and \quad \sigma^* = \frac{Y^* L}{A}$$

$$\rho^* = \rho' + i\,\rho'' \quad where \quad \rho^* = \frac{1}{\sigma^*} \quad and \quad \rho^* = \frac{Z^* A}{L}$$

Basic Equations II

$$\varepsilon^* = \varepsilon' + i\,\varepsilon'' \quad where \quad \varepsilon^* = \frac{\sigma^*}{i\,\omega}$$

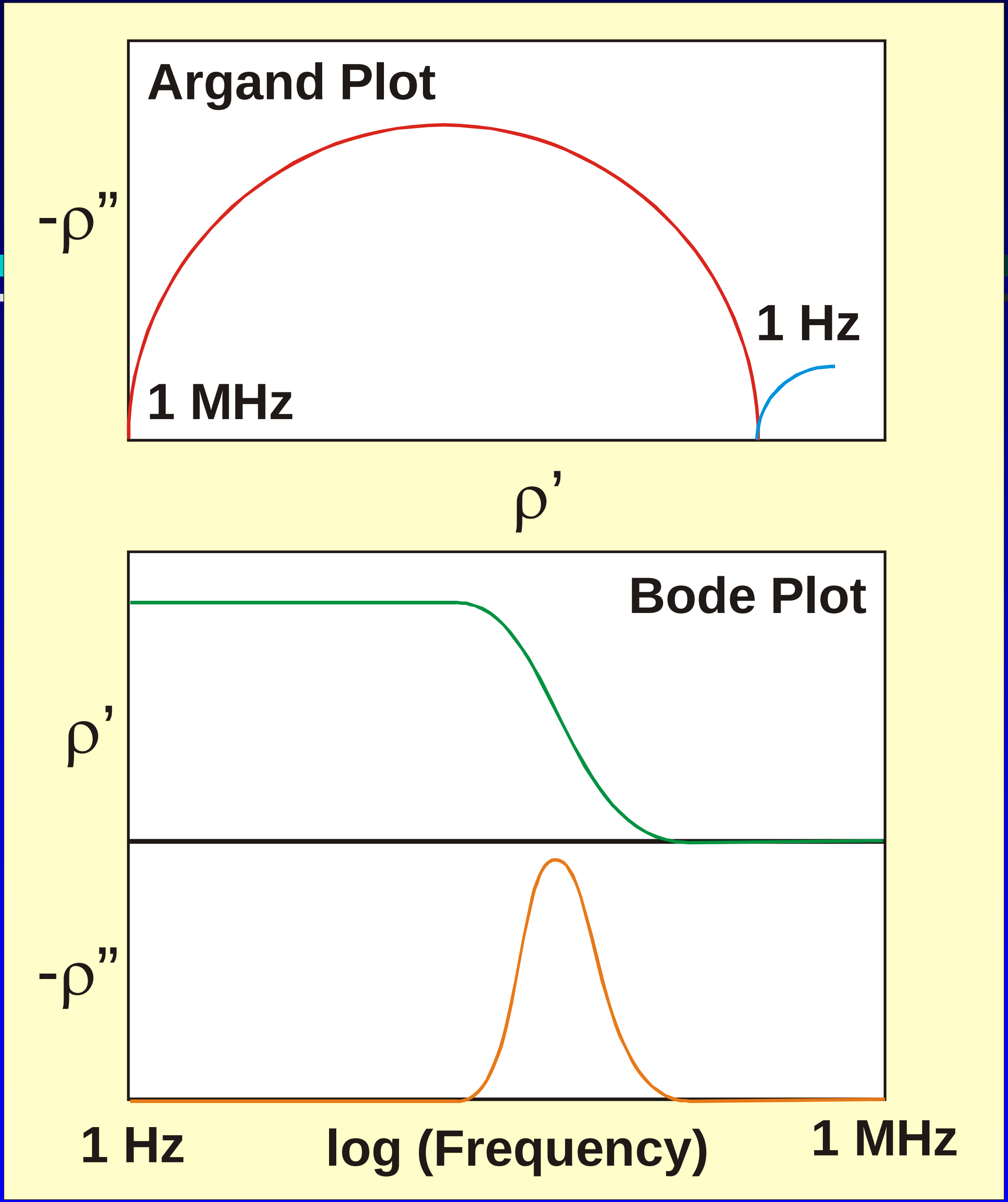
$$K^* = K' + i\,K'' \quad where \quad K^* = \frac{\varepsilon^*}{\varepsilon_\circ}$$

$$\theta = \tan^{-1}\left(\frac{\sigma'}{\sigma''}\right) - \frac{\pi}{2}$$

$$\left|\sigma^*\right| = n\,e\,\mu$$

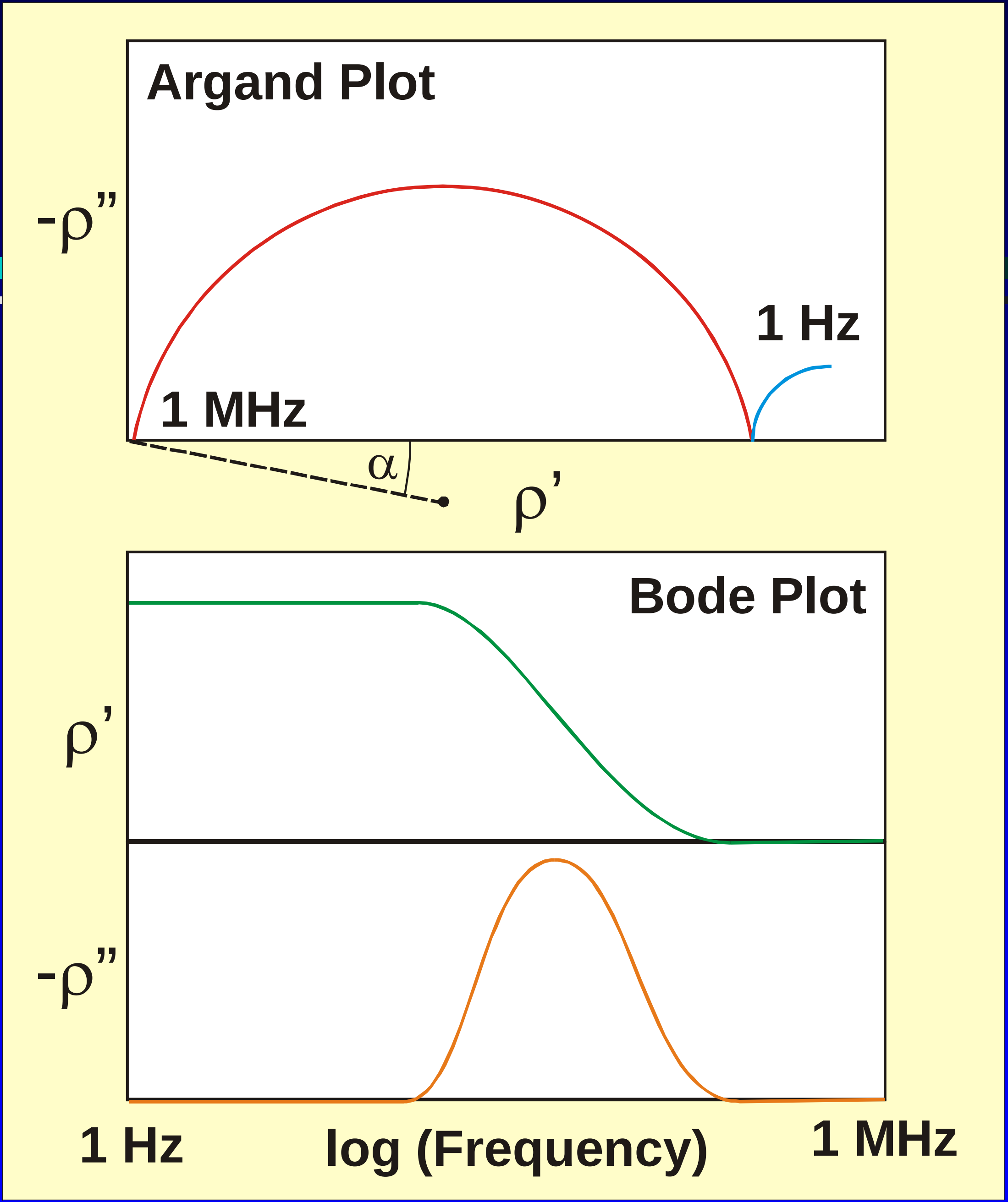
Response Functions: Debye

$$\rho = \rho_\infty + \frac{\rho_o - \rho_\infty}{1 + i\,\omega\,\tau}$$



Response Functions: Cole & Cole

$$\rho = \rho_\infty + \frac{\rho_o - \rho_\infty}{1 + (i\,\omega\,\tau)^{(1-\alpha)}}$$



Rocks – Basic Constant Frequency

Archie's Law (Archie, 1942)

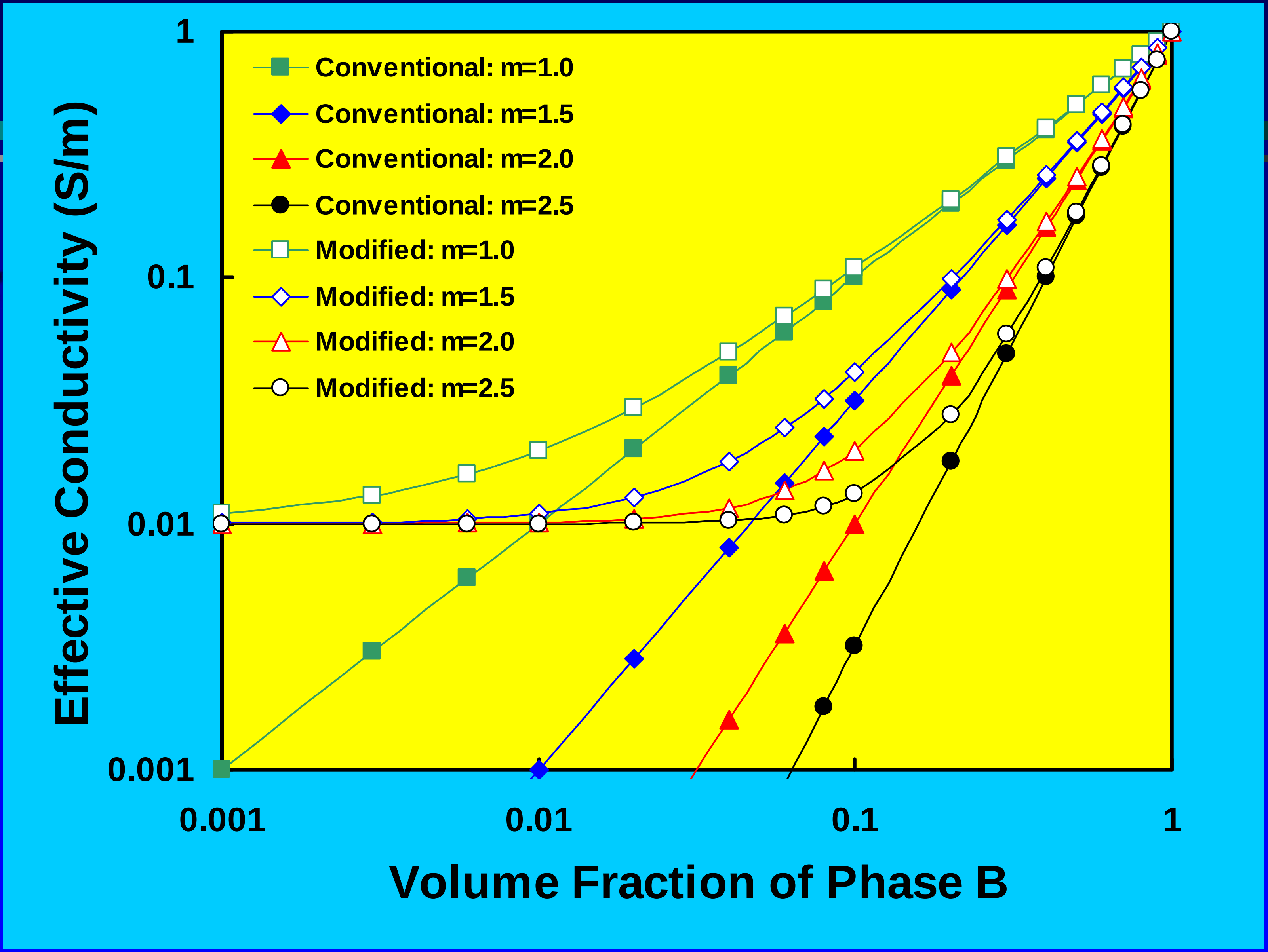
$$\sigma_{eff} = \sigma_f \chi_f^m \quad hence \quad \tau = \chi^{(1-m)}$$

Simple mixing laws to account for only the conductivity of the fluid saturating the pores of the rocks

Modified Archie's Law (Glover *et al.*, 2000)

$$\sigma_{eff} = \sigma_{mat} (1-\chi_f)^{(\log(1-\chi_f^m)/\log(1-\chi_f))} + \sigma_f \chi_f^m$$

Archie's Law Old & New



Rocks – Added Constant Frequency

Bussian (1983)

$$\sigma_{eff} = \frac{1}{F}\left(\sigma_f + m\left(F-1\right)\sigma_s\right)$$

Complex theory containing surface conduction BUT still no frequency dependence

Revil & Glover (1998)

$$\sigma = \frac{\sigma_f}{F}\left[F\xi + \frac{1}{2}\left(1-\xi\right)\left(1-\xi+\sqrt{\left(1-\xi\right)^2+4F\xi}\right)\right], \text{for } 0 \le \xi \le 1,$$

Fluid Flow in Rocks

There exists:

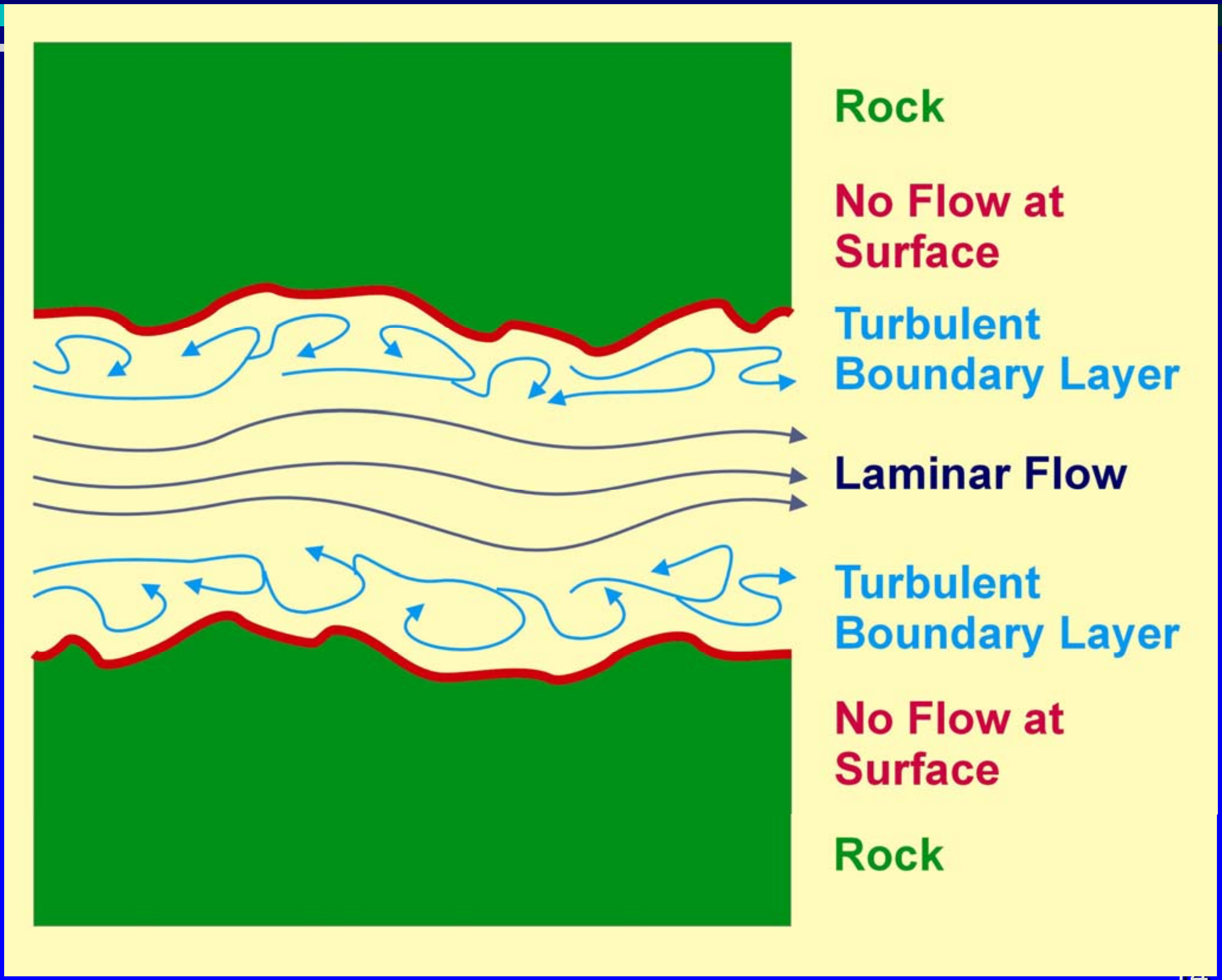
An undisturbed central zone of laminar flow,

and

A surface boundary layer of turbulent flow,

and

Zero flow at the rock surface



Electrical Conduction in Rocks

There exists:

A -ve charged rock surface,

and

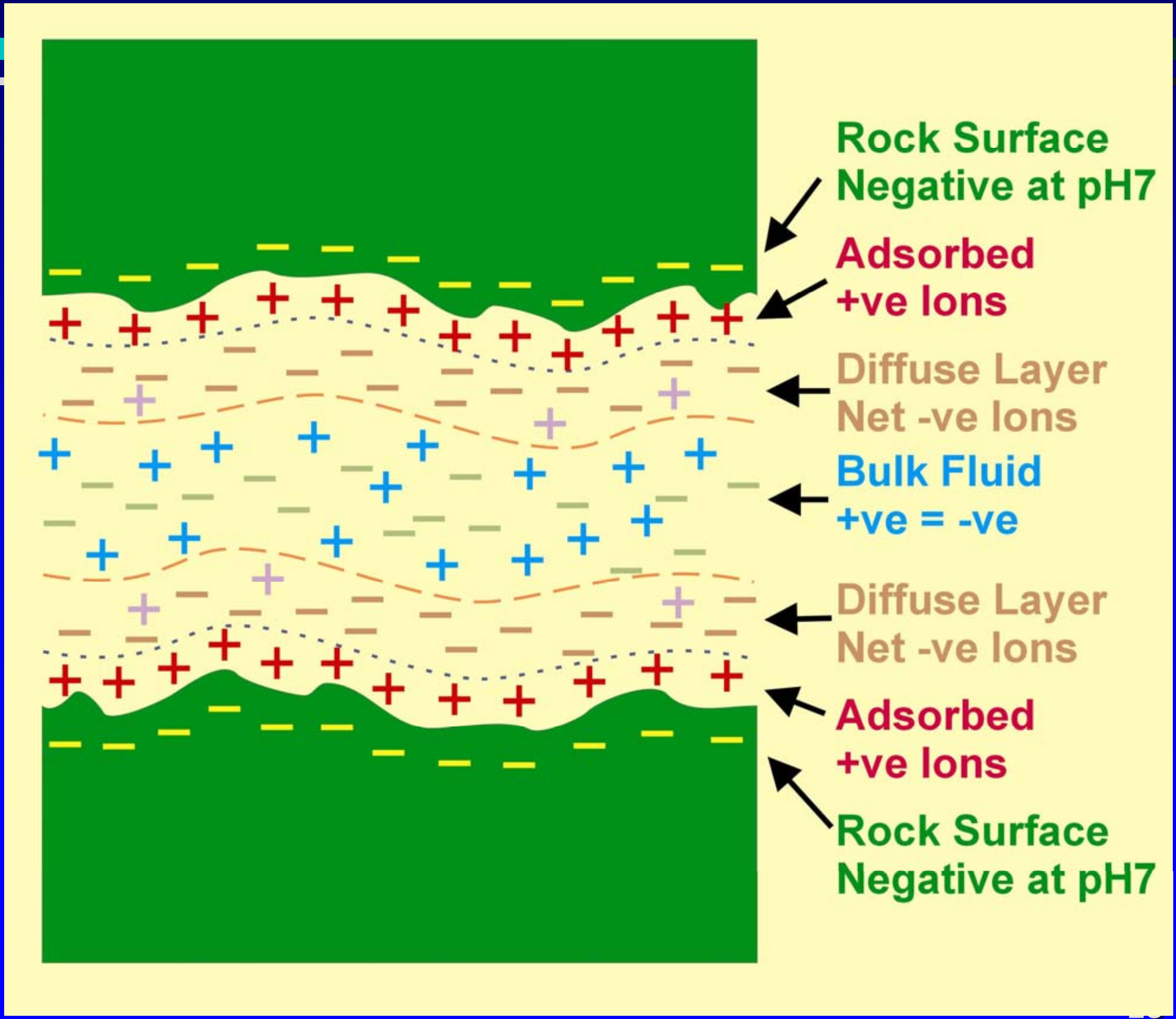
A layer of +ve adsorbed ions,

and

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

and

Net neutral bulk fluid



Electrical Conduction in Rocks

Boundary of moveable fluids is in diffuse layer

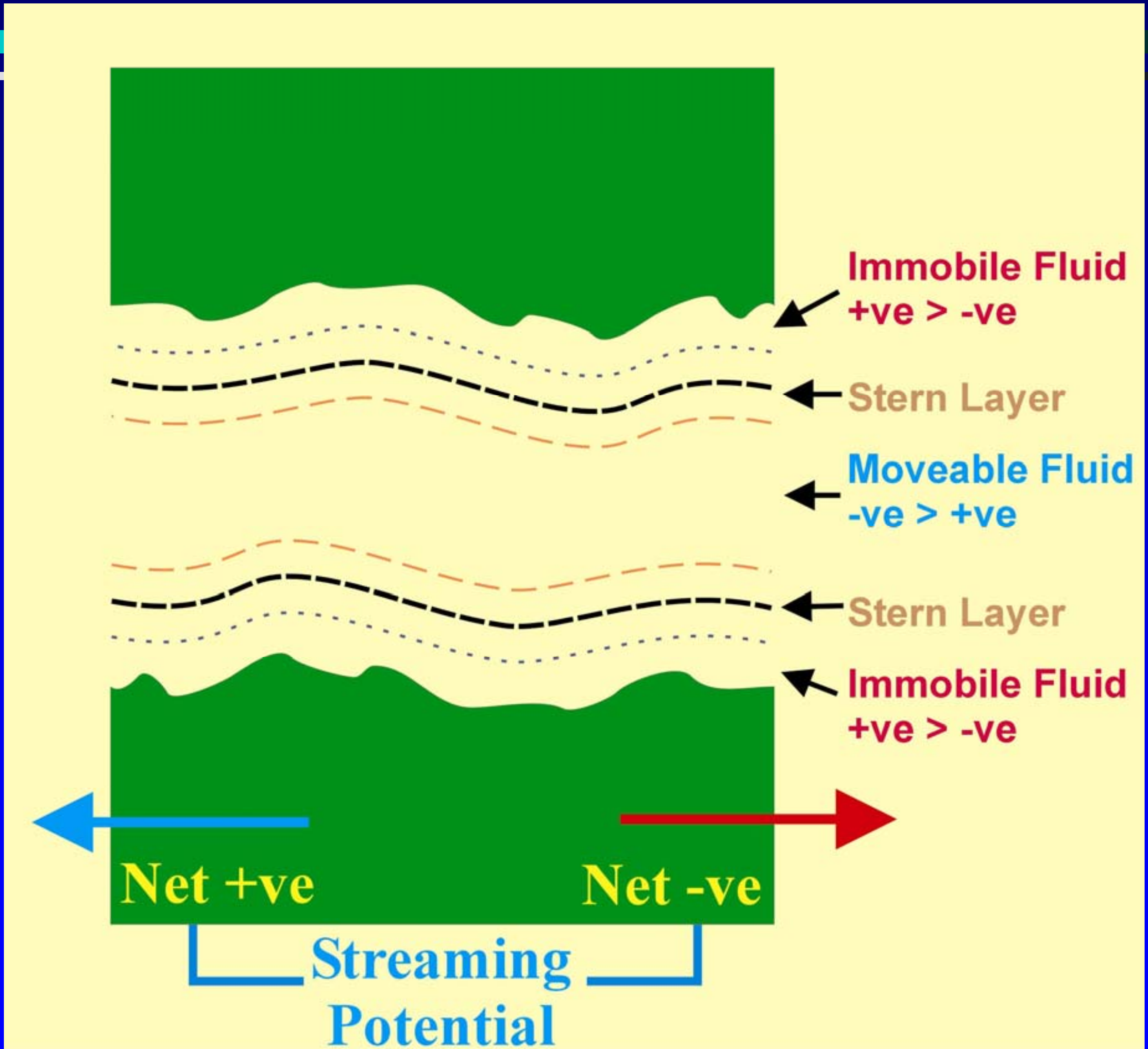
Flow separates –ve charges to the right

and

+ve charges are left behind

this

generates a potential difference called the STREAMING POTENTIAL



Challenges

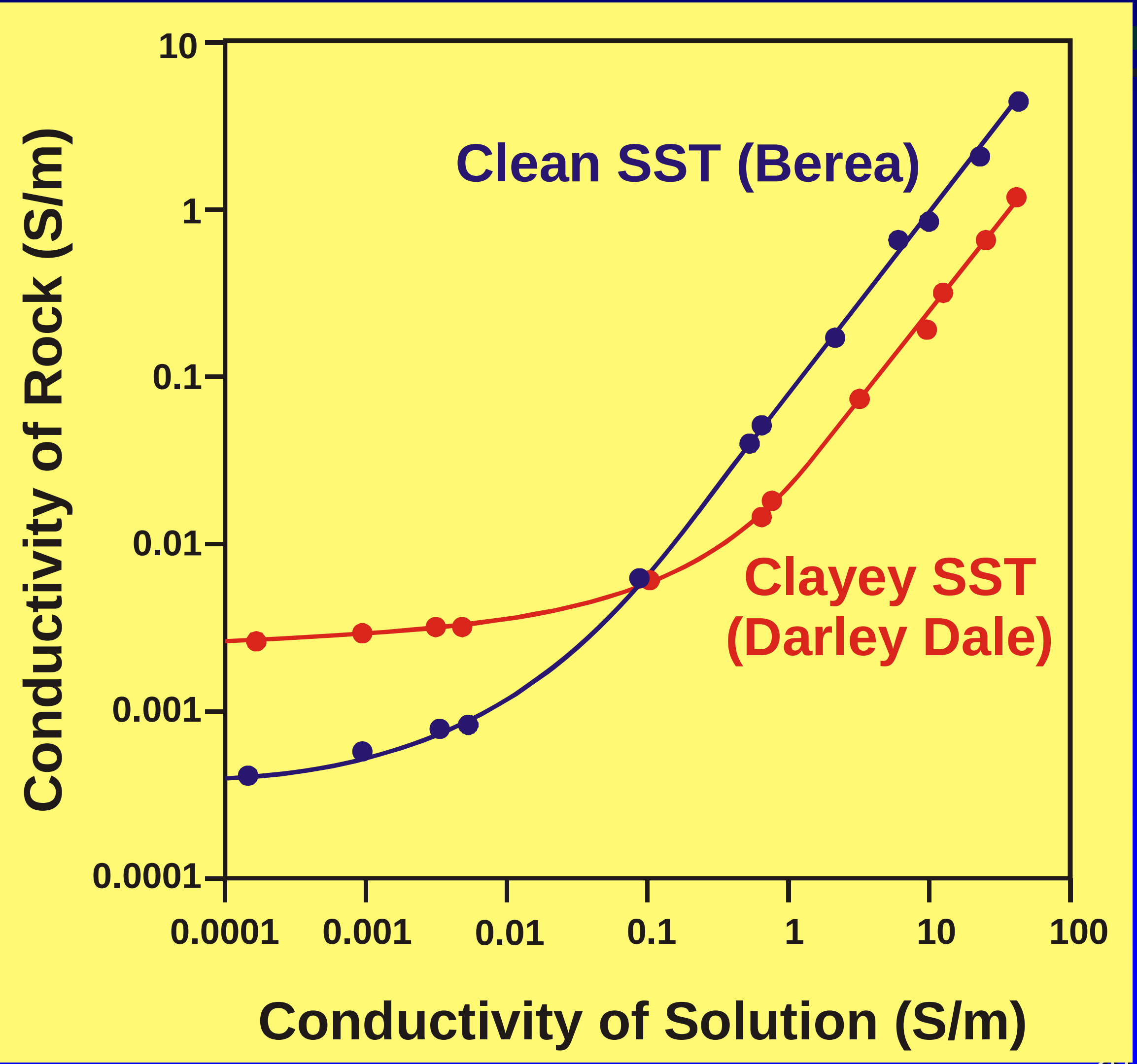
Electrical Properties in Geosciences

- Theory of bulk and surface conduction in saturated rocks
- Generalisation to multi-frequency space
- Improvement of interpretation and analysis of MT data
- Electrical precursor signals associated with earthquakes
- Electrical signals associated with volcanic activity
- Fluid flow mapping in the crust using remote electrical tomography
- Improved borehole and remote tools for the oil and water industries
- Characterisation of sites for nuclear waste storage

Some Progress

MultiSalinity Experiments (CoCw)

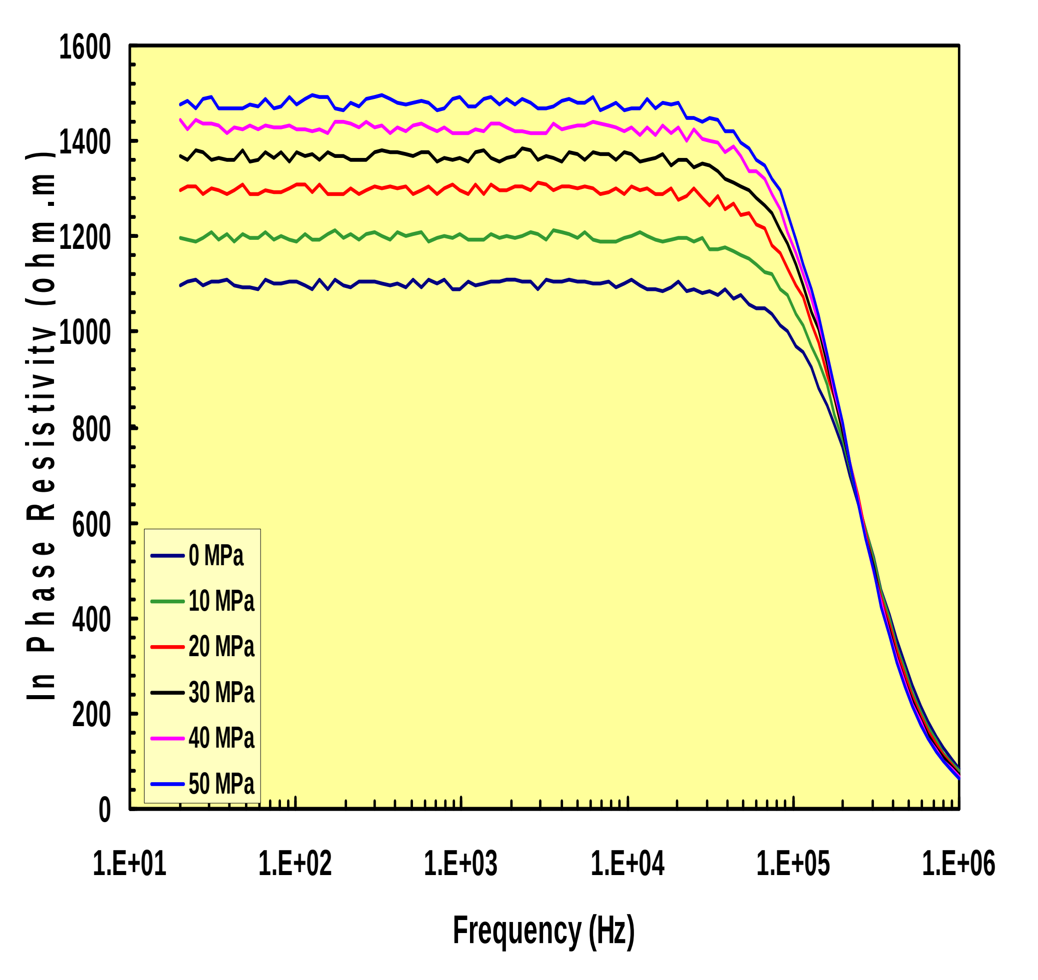
- Prepare a range of solutions of different salinities
- Measure the conductivities of each of the solutions
- Saturate the rock with solution 1
- Measure the conductivity of the rock
- Replace with solution 2
- Measure the conductivity of the rock again, and so on

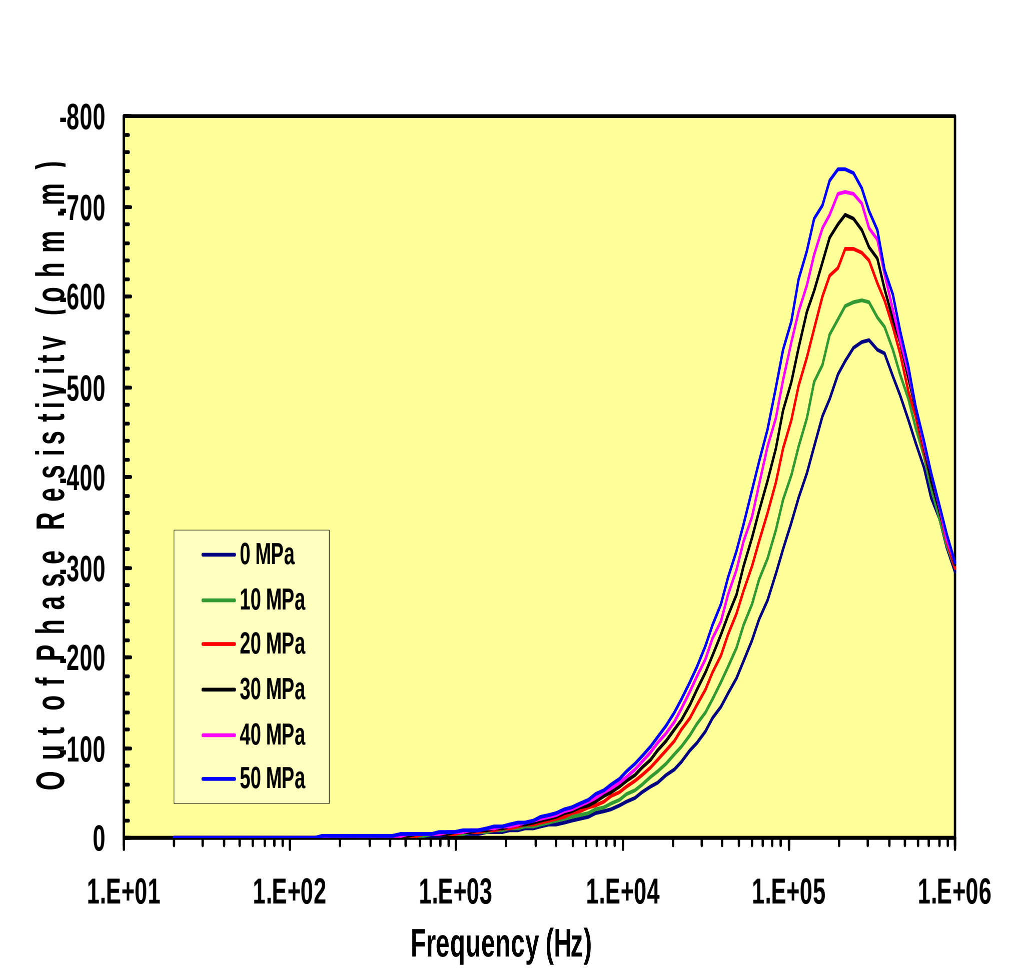


Confining Pressure

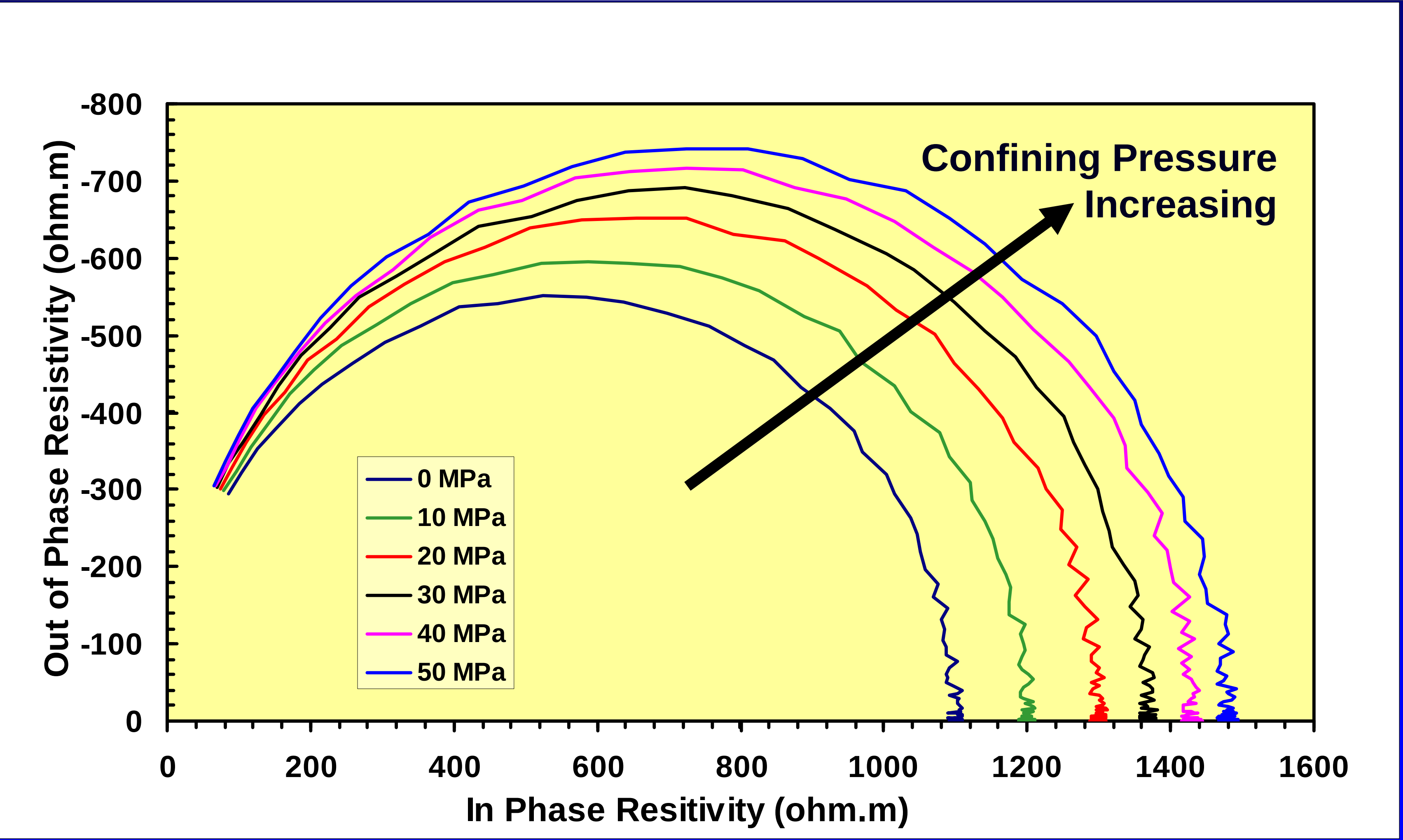
- Saturated rocks confined in a hysrostatic oil pressure vessel
- 4 electrode Pt-blacked Pt system used
- 0 to 50 and 25 to 400 MPa ranges (2 vessels)
- Frequency sweeps carried out
- Rock containing low salinity fluids
- Size of dispersion curve inflates as pore structure collapses with pressure
- Shape of dispersion curve does not change

The Bode Plots





The Argand Plot



Uniaxial Deformation

- Saturated rocks confined in a load frame
- 4 electrode Pt-blacked Pt system used
- No confining pressure, 0 to 1.5% strain at 0.0001/s
- Electrical properties measured at 1000 Hz
- Rock containing low salinity fluids
- Shape of conductivity measurements indicate that they mirror two sets of microcracks closing and opening

See 1 slide

Triaxial Deformation I

- Saturated rocks confined in a hydrostatic oil pressure vessel and load frame
- 4 electrode Pt-blacked Pt system used
- 50 MPa confining pressure, 0 to 2% strain at 0.0001/s
- Electrical properties measured at 1000 Hz and frequency sweeps
- Rock containing low salinity fluids

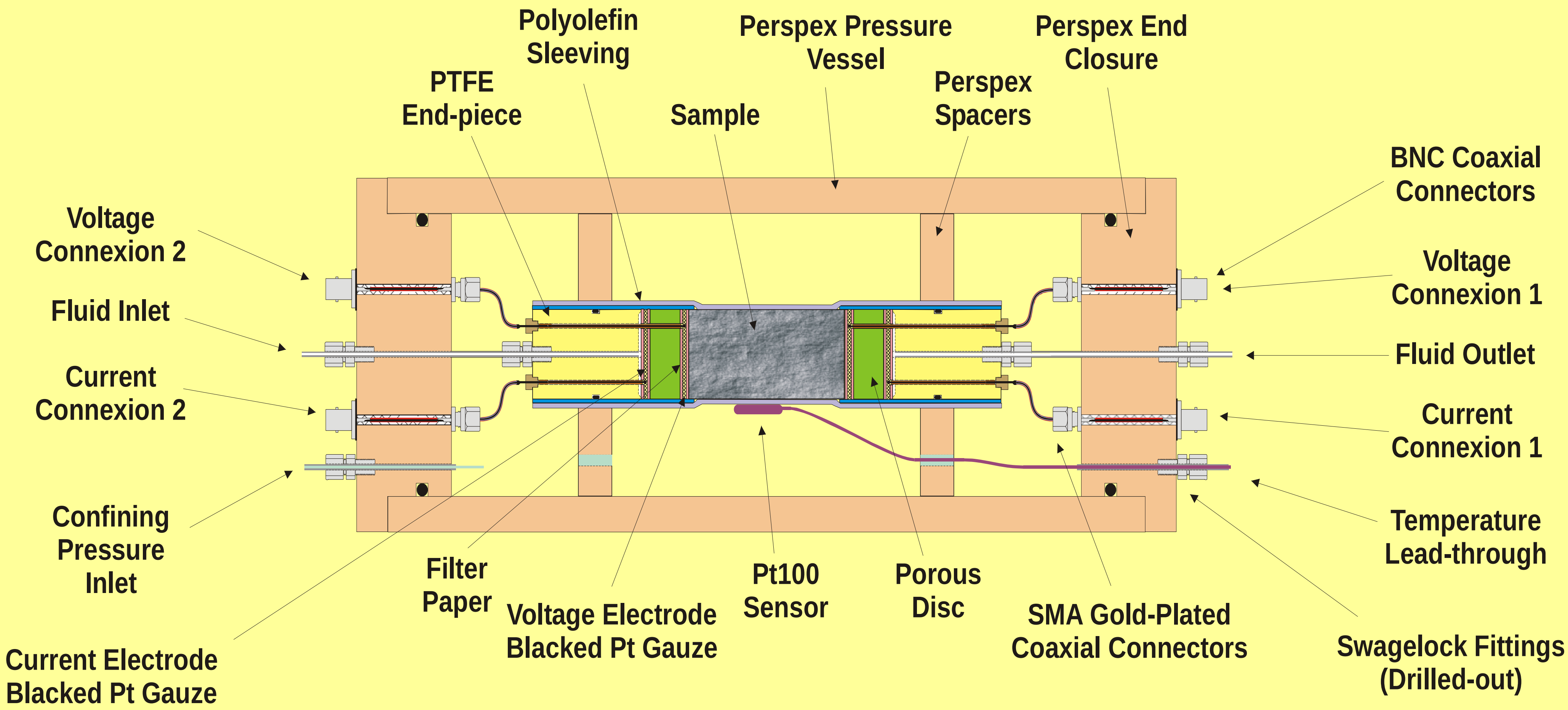
Triaxial Deformation II

- Size of dispersion curve changes with deformation
- Initially bigger as cracks close
- Then smaller as new cracks form and link
- Shape is similar indicating that the dispersion mechanism is not changing
- Single frequency measurements indicate that the conductivity is a direction sensitive crack damage parameter
- This has been used to successfully reconstruct the measured stress-strain curve

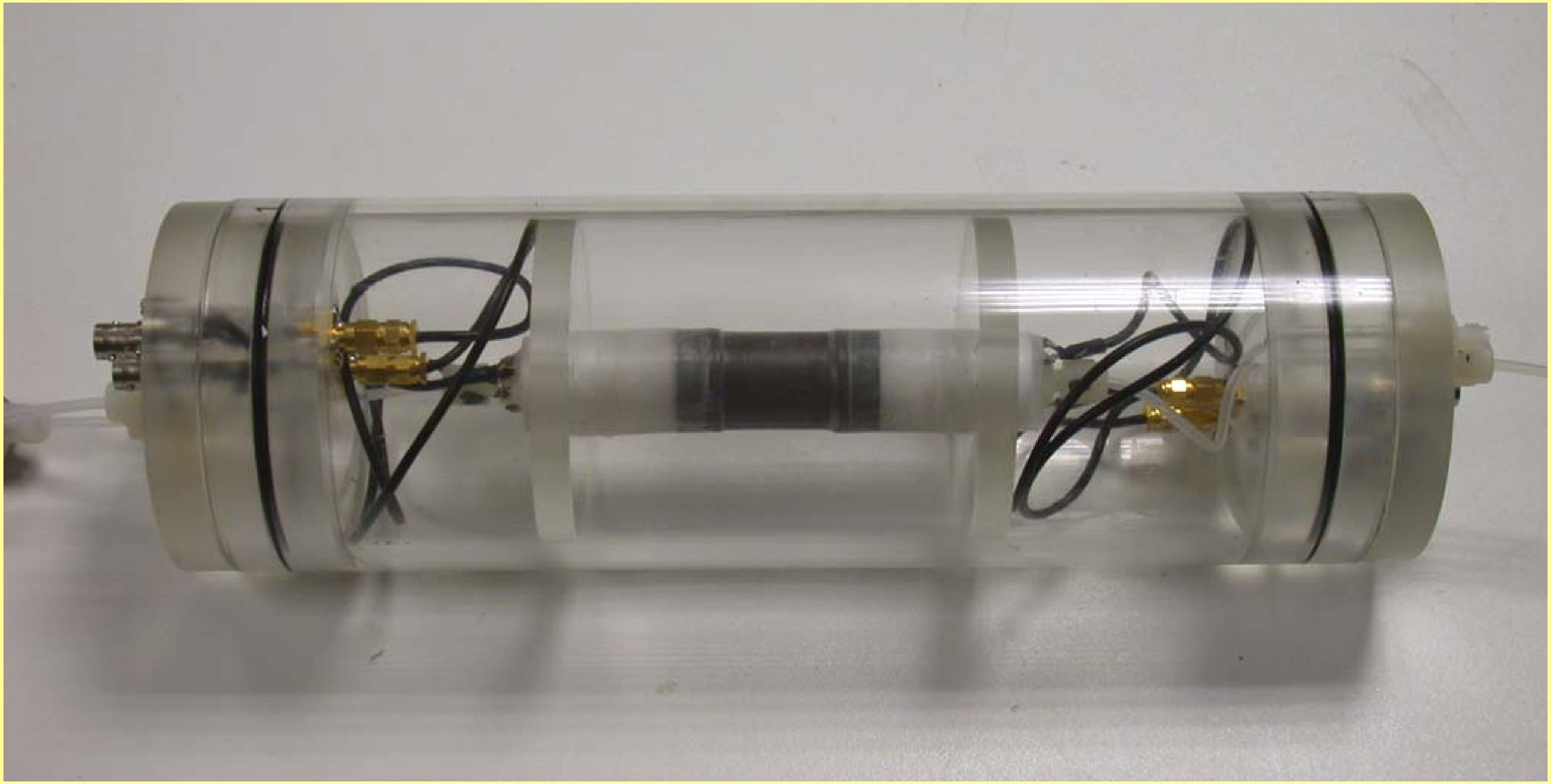
See 4 slides

Developments at the Université Montpellier II

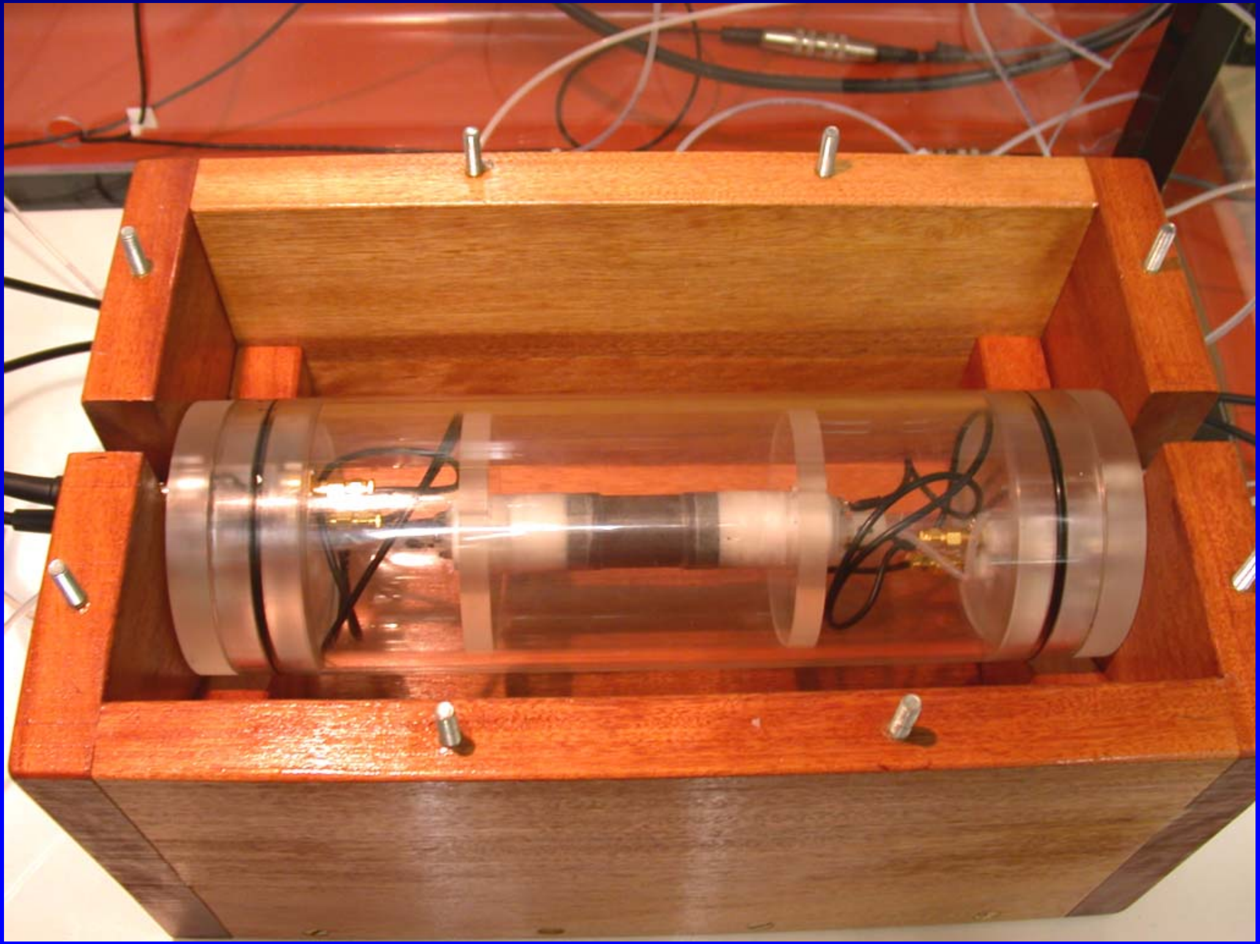
The New Measurement Cell



The Cell Fully Assembled

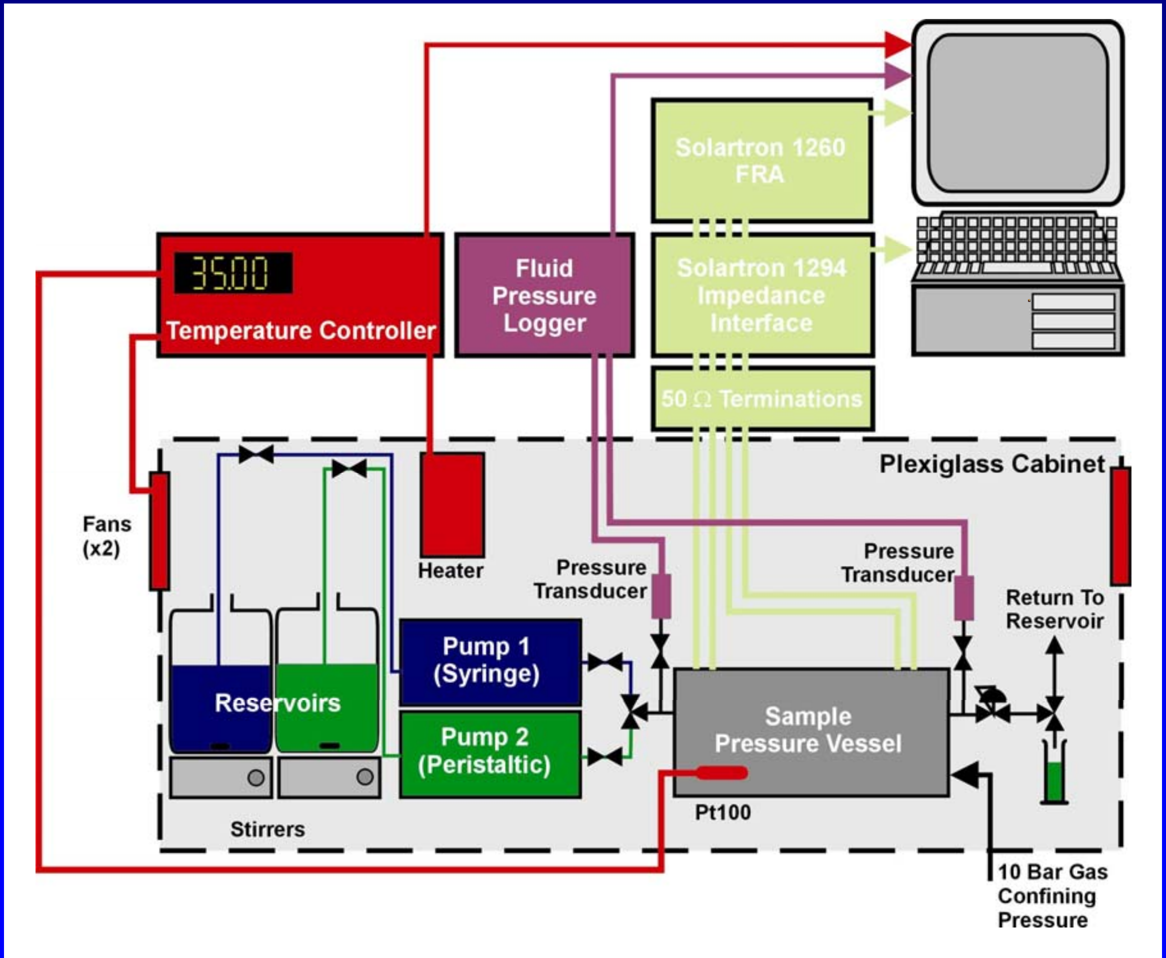


The Cell in its Retaining Box



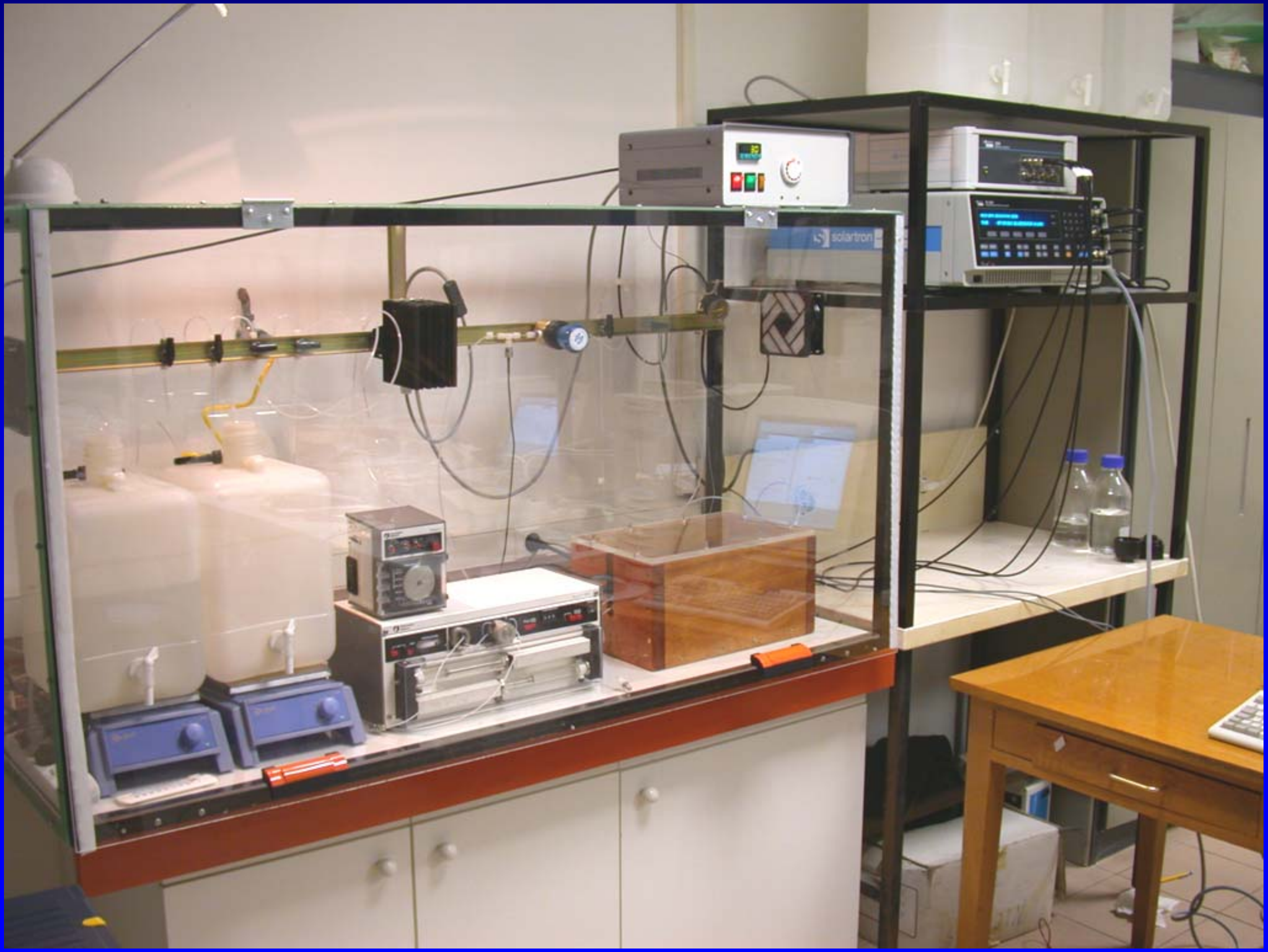
- Non-conducting materials
- 4 or 2 electrodes
- Pt-blacked Pt Gauze
- Heat-shrink sleeving with silicone
- 50 Ω miniature coaxial leads with SMC connectors

Schematic Diagram of the Rig



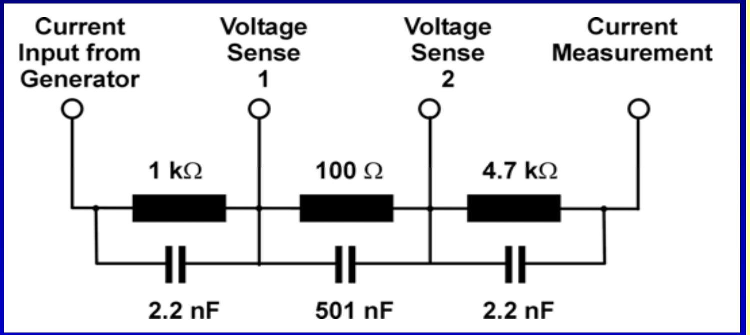
- Rig in temperatures controlled enclosure
- Heater, fans and special control box
- Measurements made from 10 μHz to 32 MHz
- Solartron 1260 FRA
- Logging of fluid pressures, with back pressure

The Assembled Rig

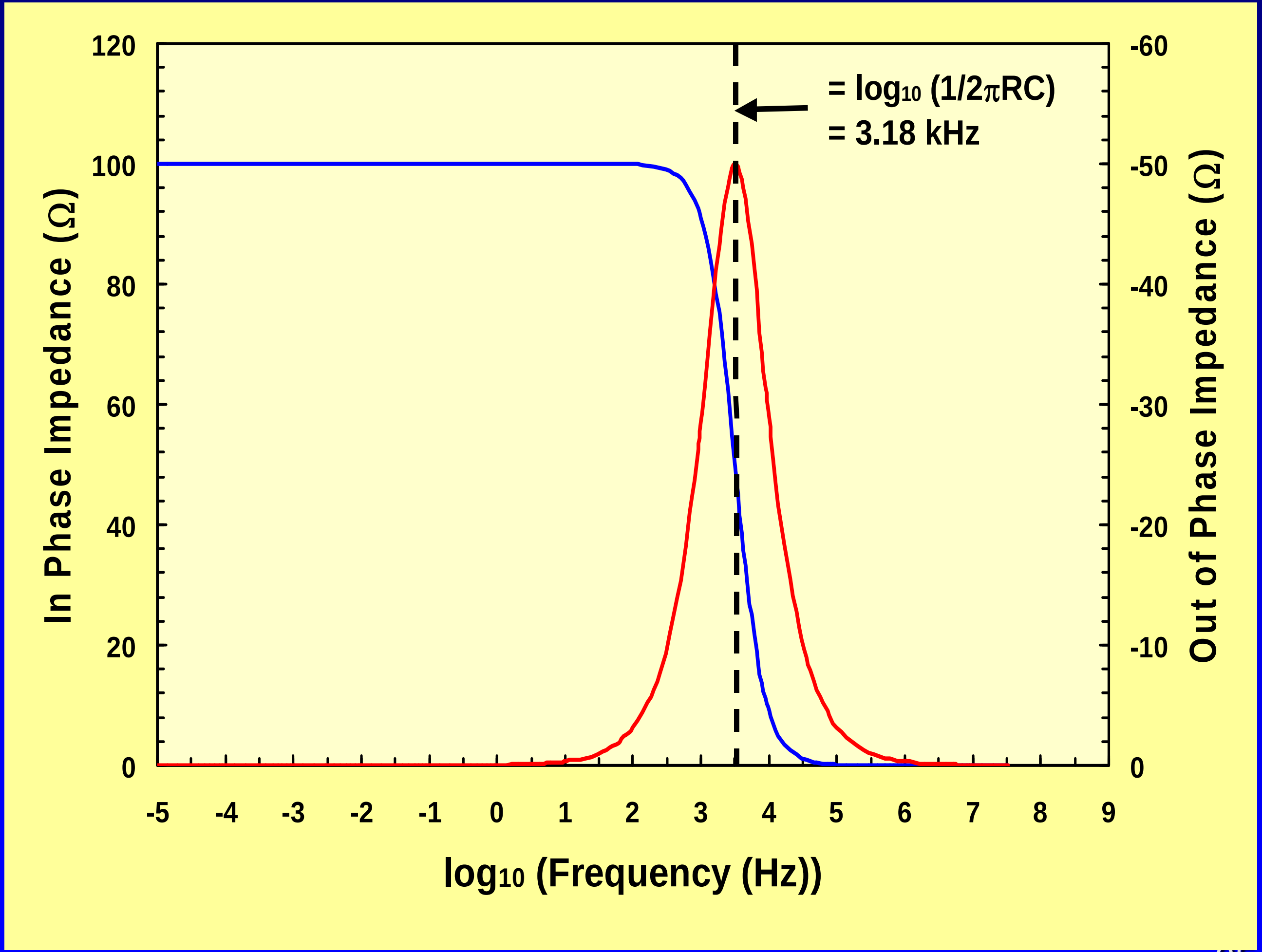


- Entire fluid process in temperature controlled environment
- All measurements logged to PC
- Shielded, low electrical noise apparatus

Dummy Test Measurements



- 10 μHz to 32 MHz
- Noise-free measurements
- Single dispersion curve for 501 nF element

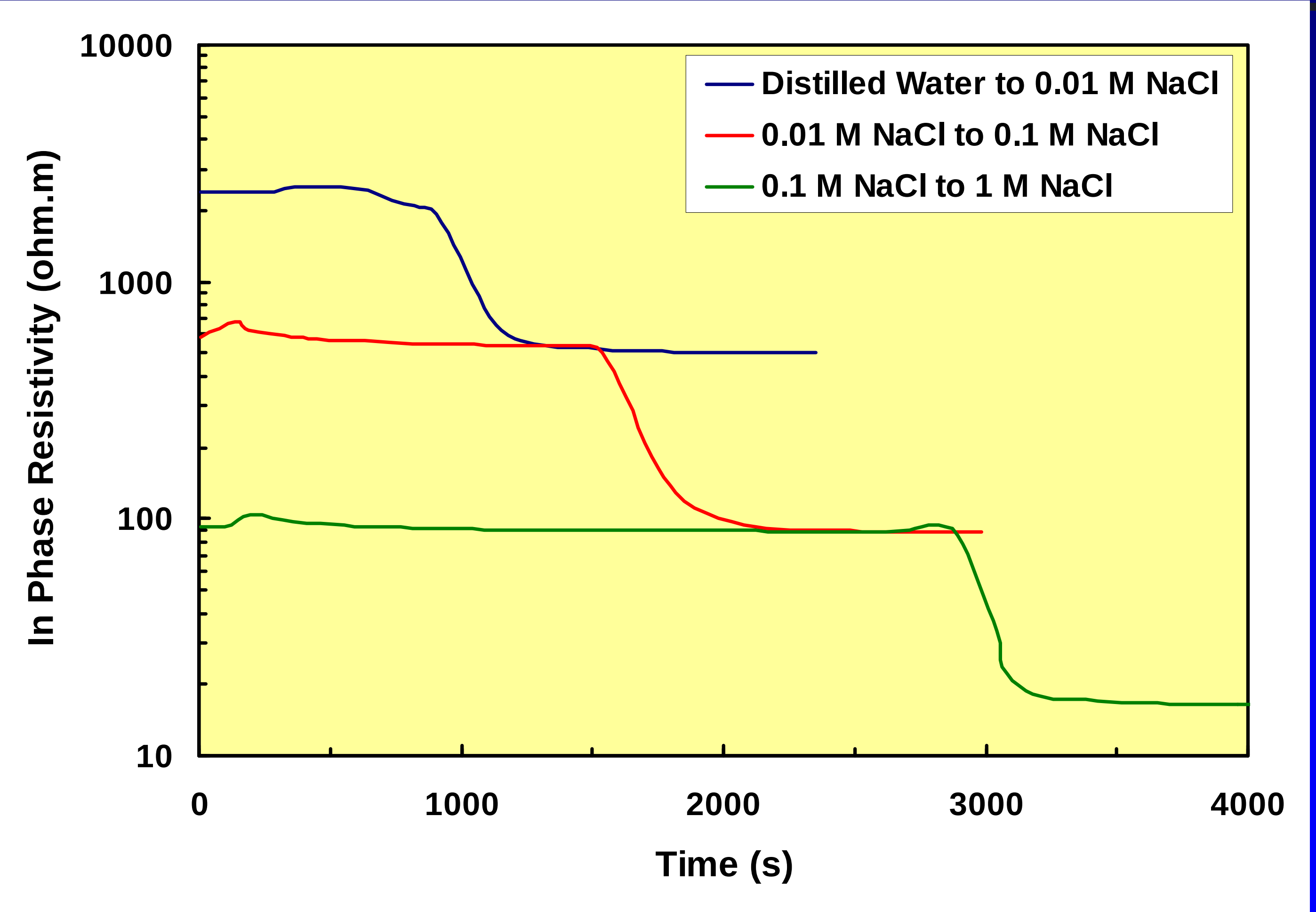


New Fluid Change Experiments

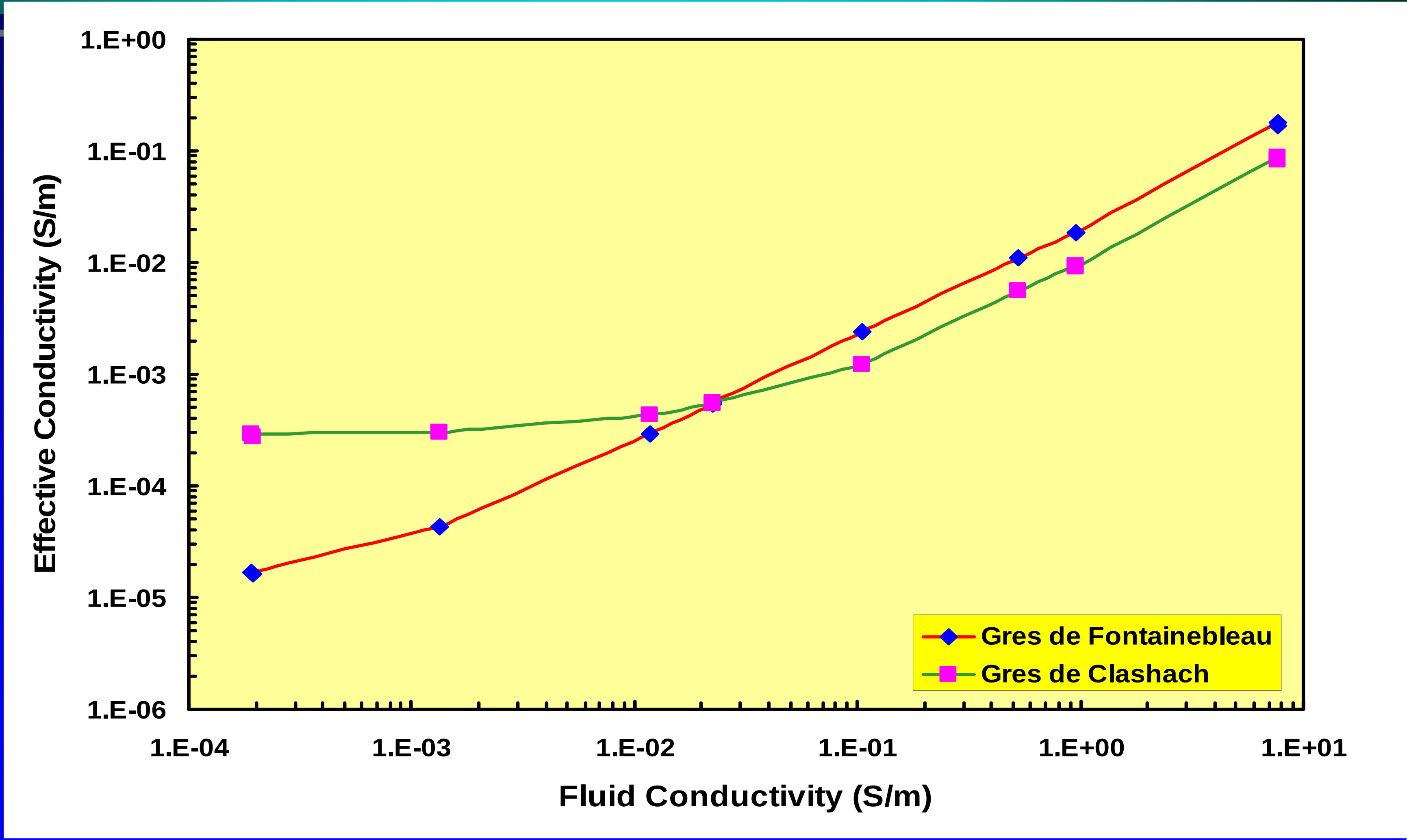
- Single Frequency
- 200 Hz
- Changing Fluids from Distilled Water to 1 M NaCl

Porosity = 0.12

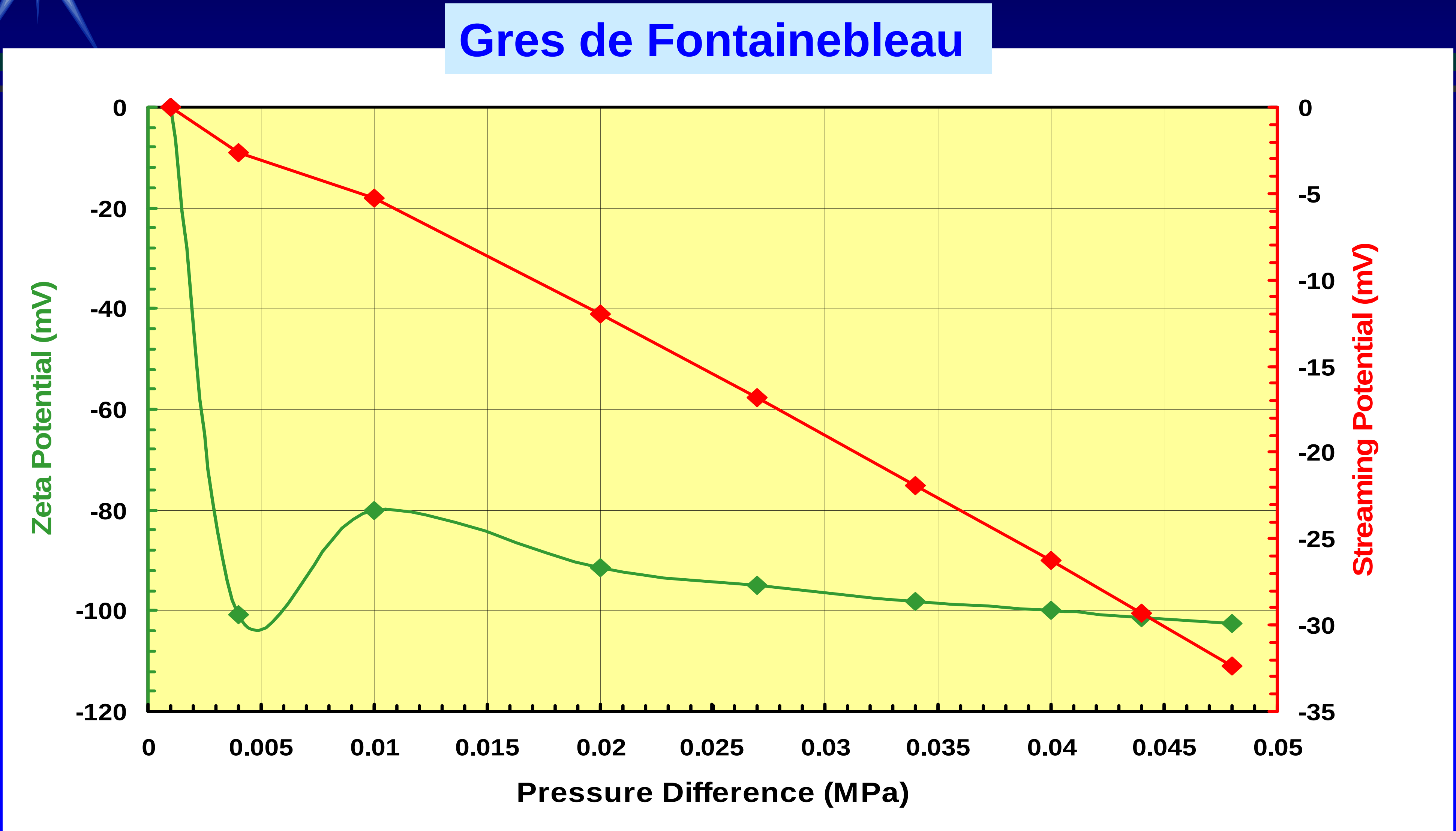
NaCl (M)	m
0.001	1.76
Distilled	1.96
0.01	1.85
0.1	2.07
1	2.27



New CoCw Measurements

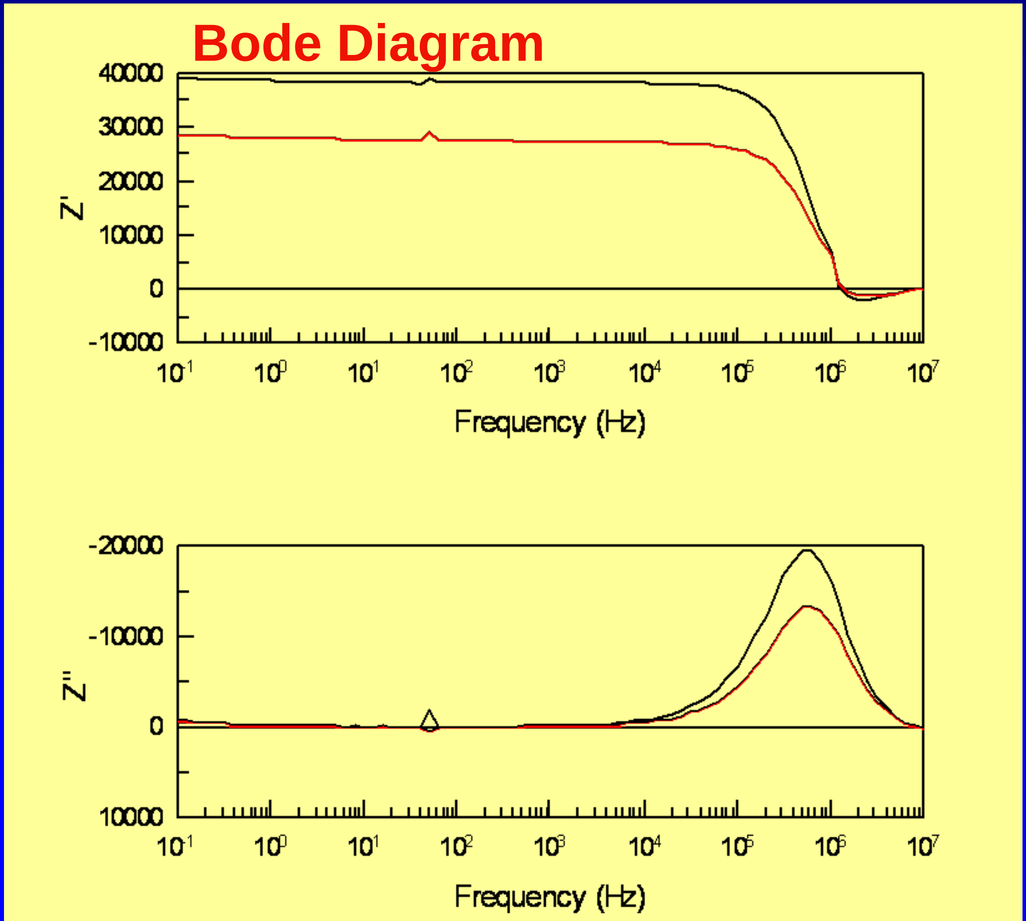


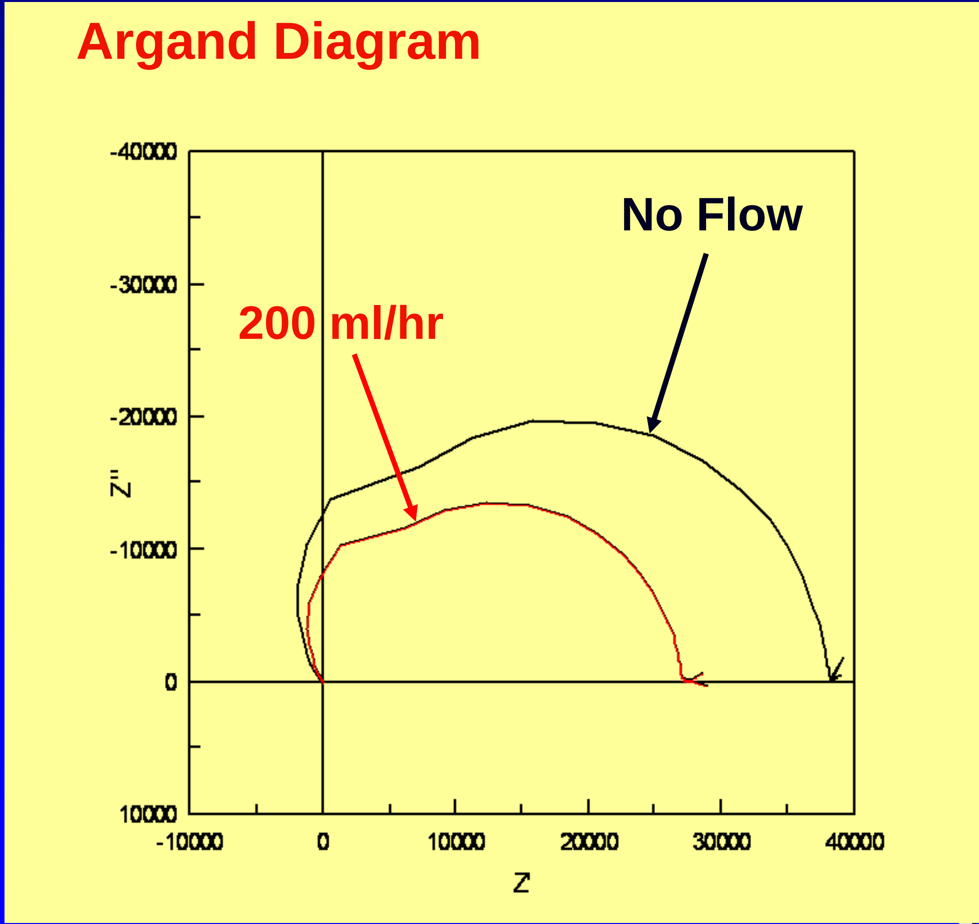
New Electro-Kinetic Measurements



New Impedance Measurements

Gres de Fontainebleau

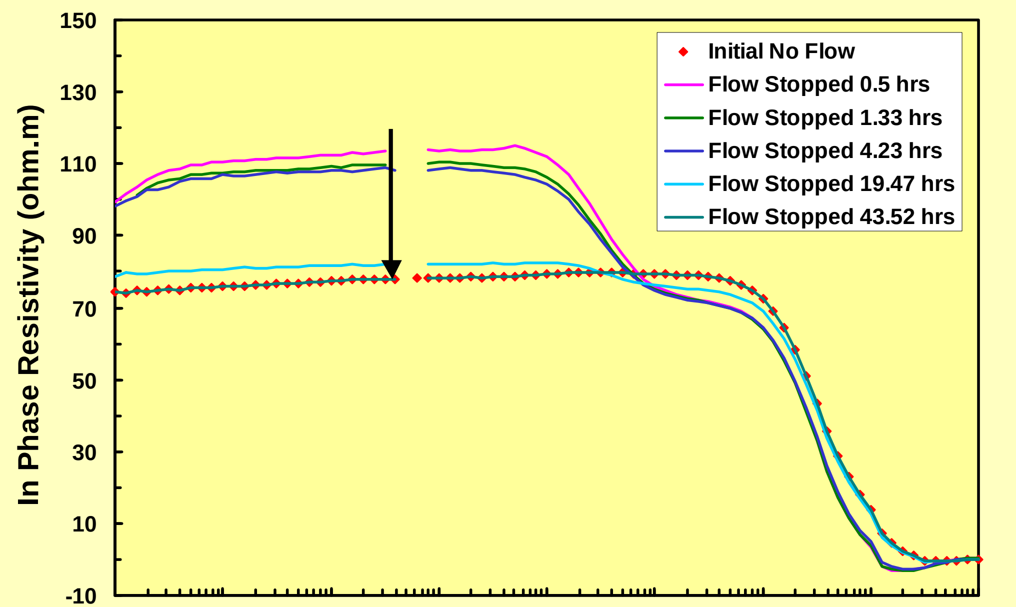


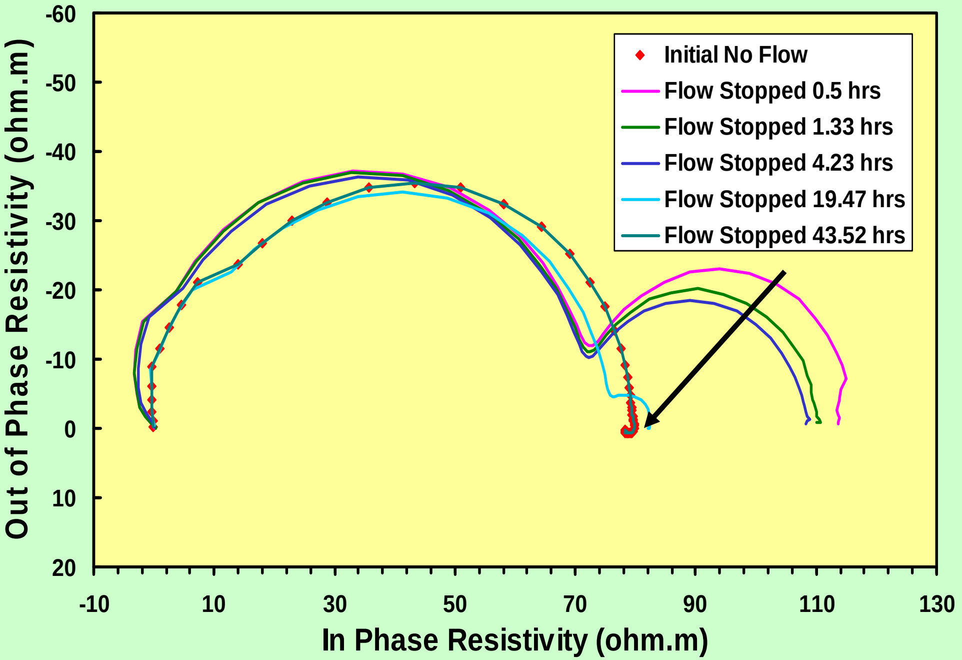


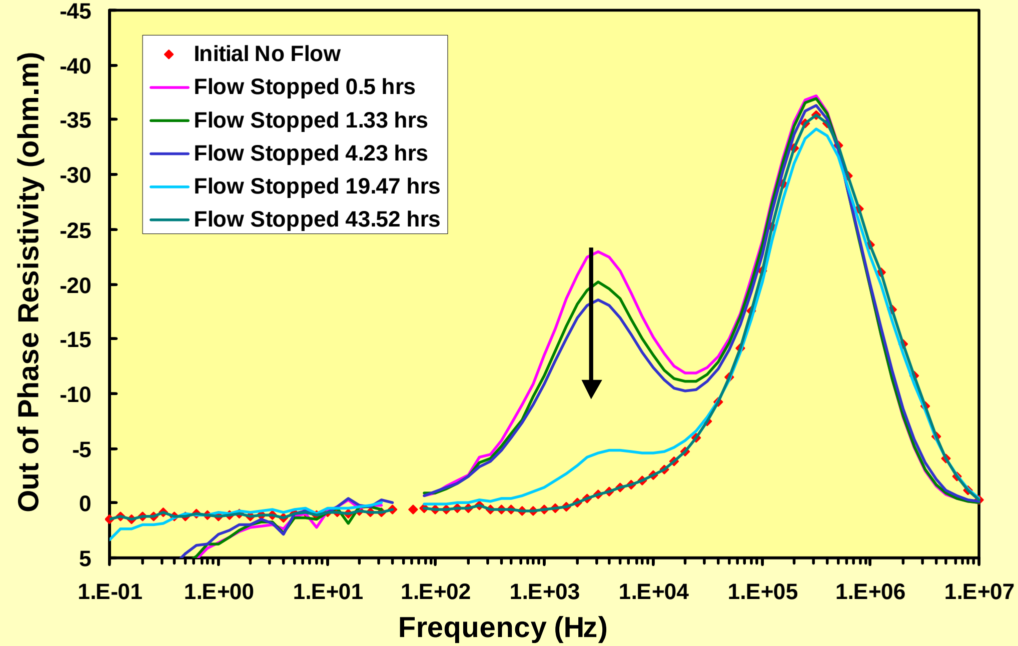
Spectroscopy of Carrara Marble

Flow causes charge separation that takes 2 days to relax

Now known to be ARTIFACT

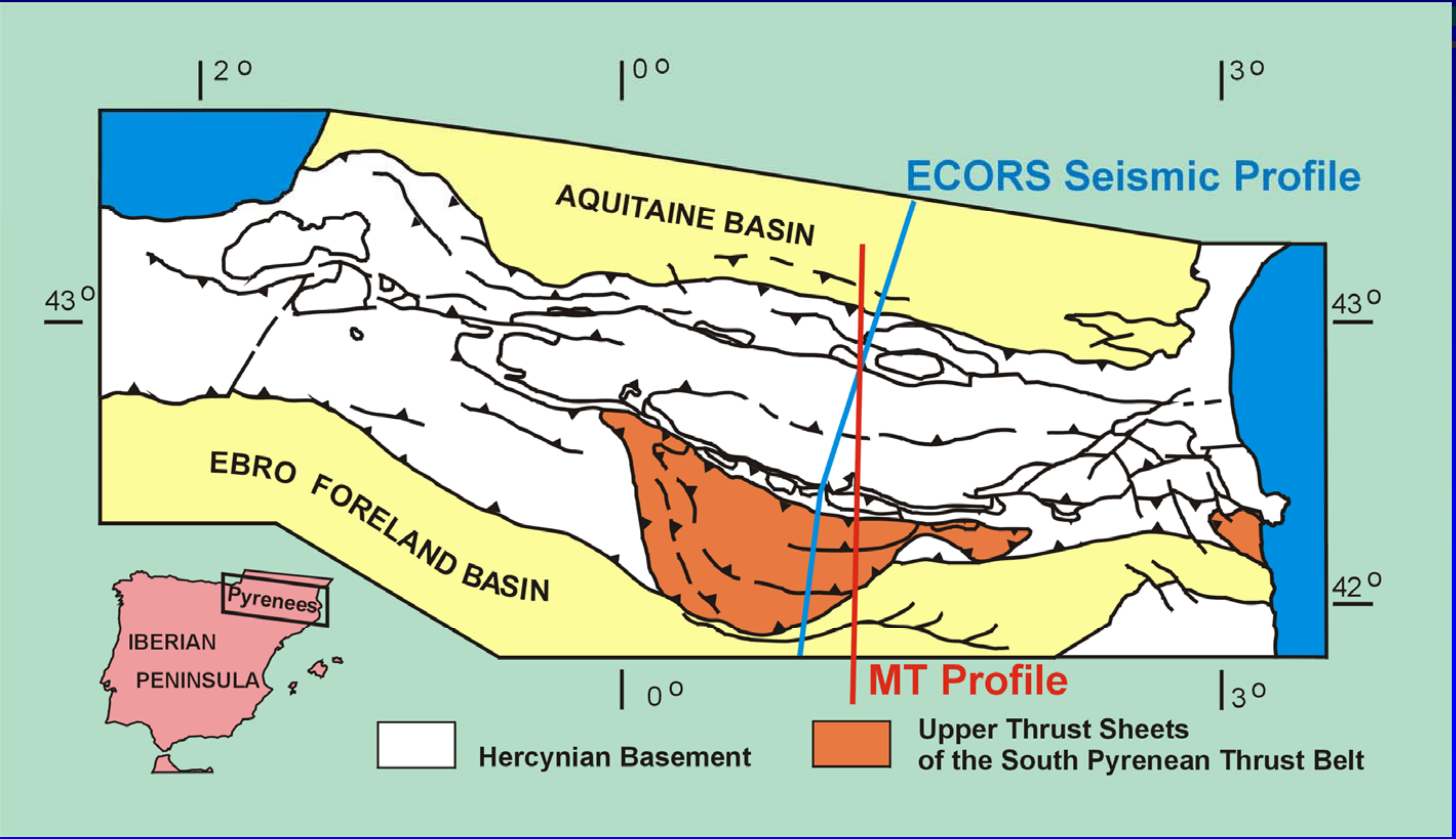






Crustal Conductivity Modelling

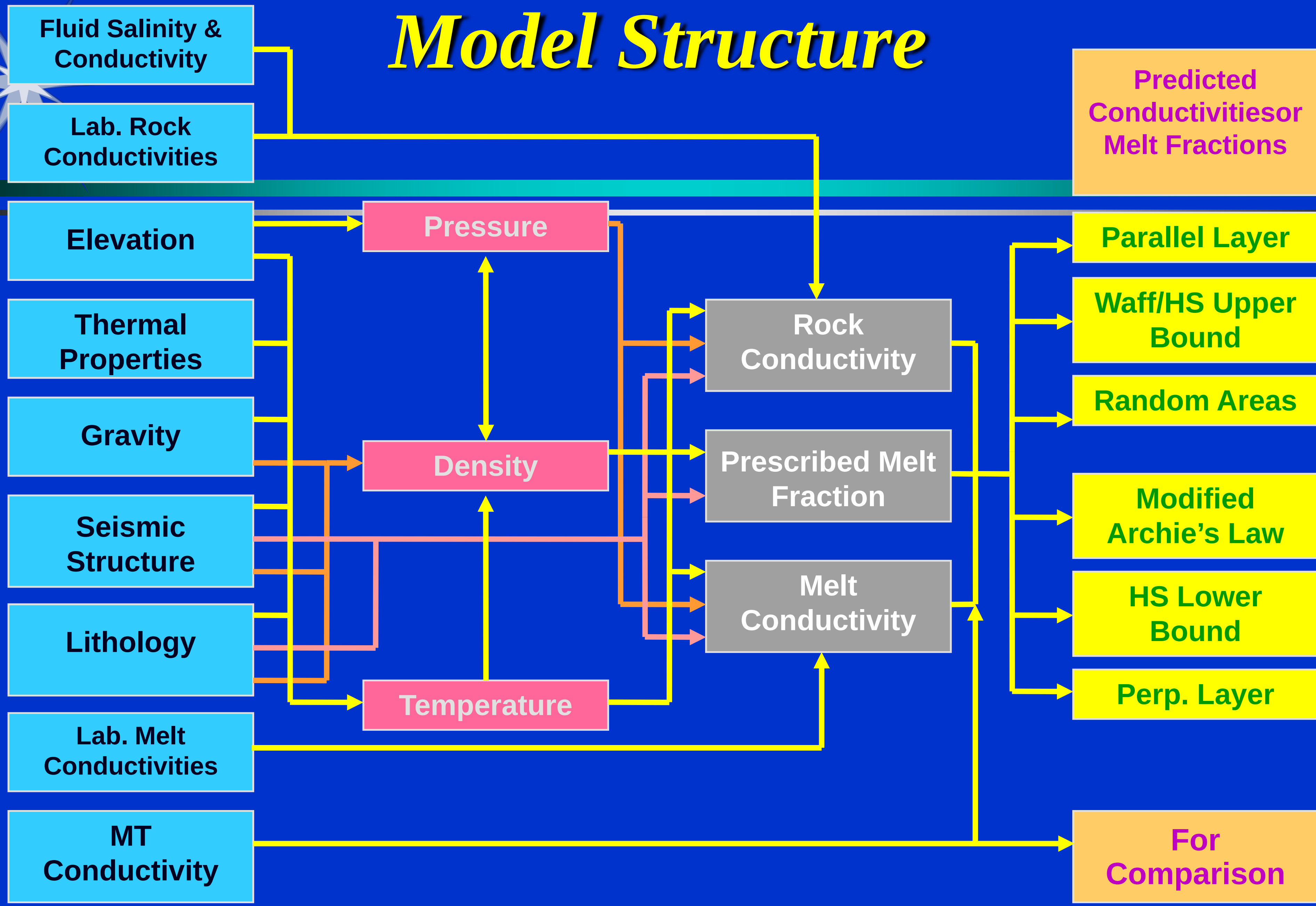
Location of the Study



Questions

- **What are the mechanisms of the conductivities in the crust and mantle?**
- **What is the mechanism of the high conductivities in the slab?**
- **If the slab high conductivities are caused by partial melting, what is the partial melt fraction and what is the melt connectivity?**
- **Why is there no surface volcanism in the Pyrenees?**

Model Structure



Mixing Models

6 mixing Models have been used:

- Parallel model (arithmetic mean)
- Hashin-Shtrikman upper bound
- Waff's model

Well Connected Melt

- Random model (geometric mean)
- Modified Archie's law

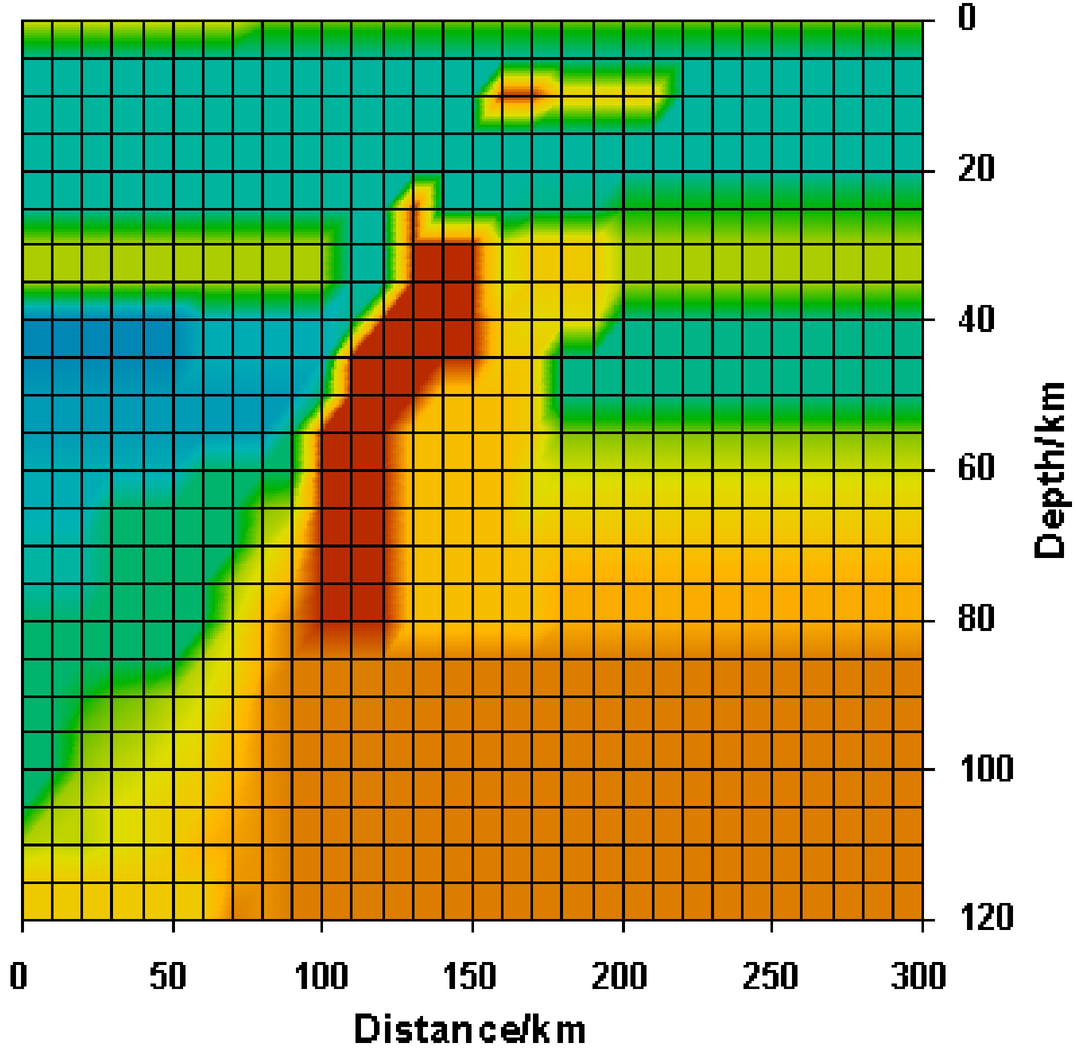
Moderately Connected Melt

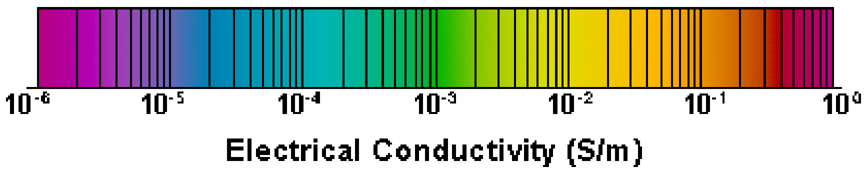
- Hashin-Shtrikman lower bound
- Perpendicular model (harmonic mean)

Badly Connected Melt

Effective Conductivity

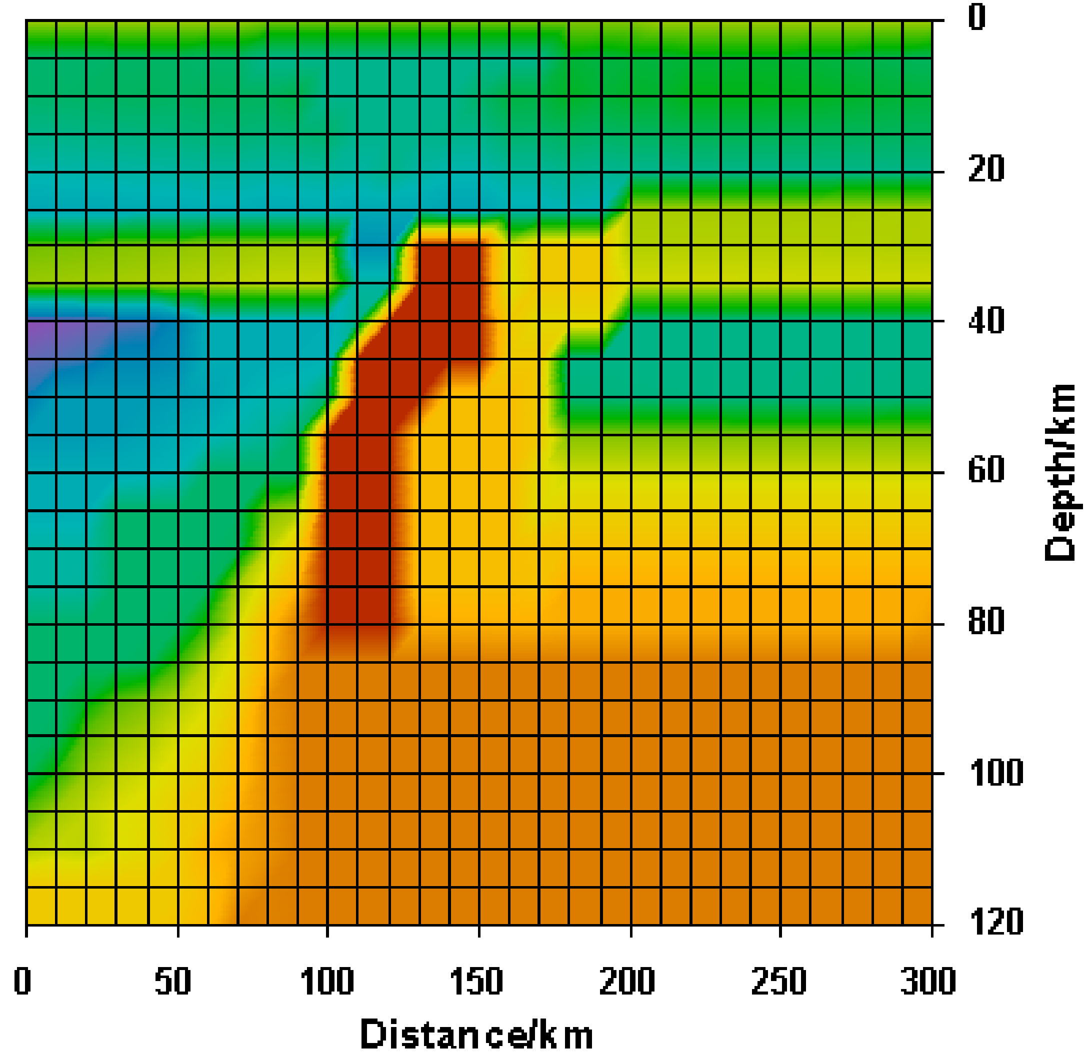
MT Observed Conductivities

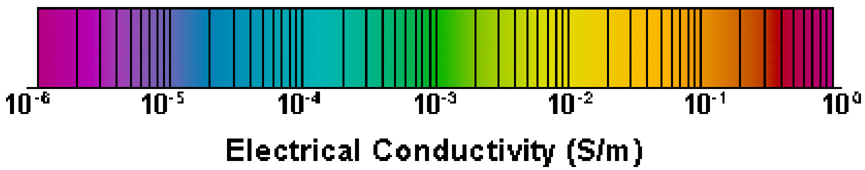




Effective Conductivity

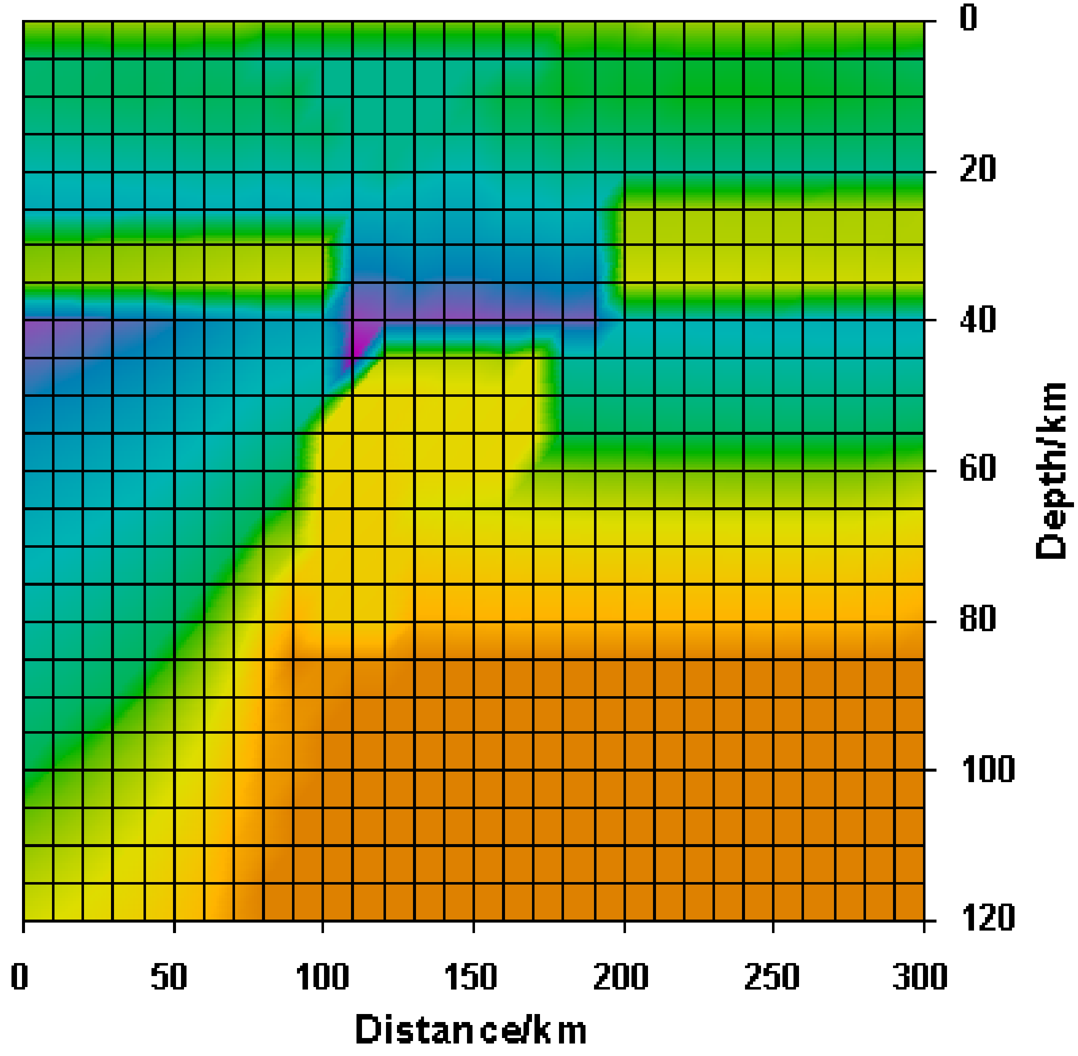
Hashin-Shtrikman Upper Bound/Waff's Model

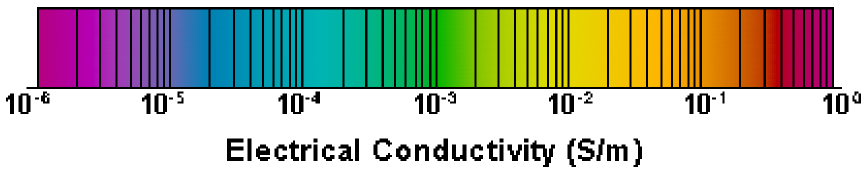




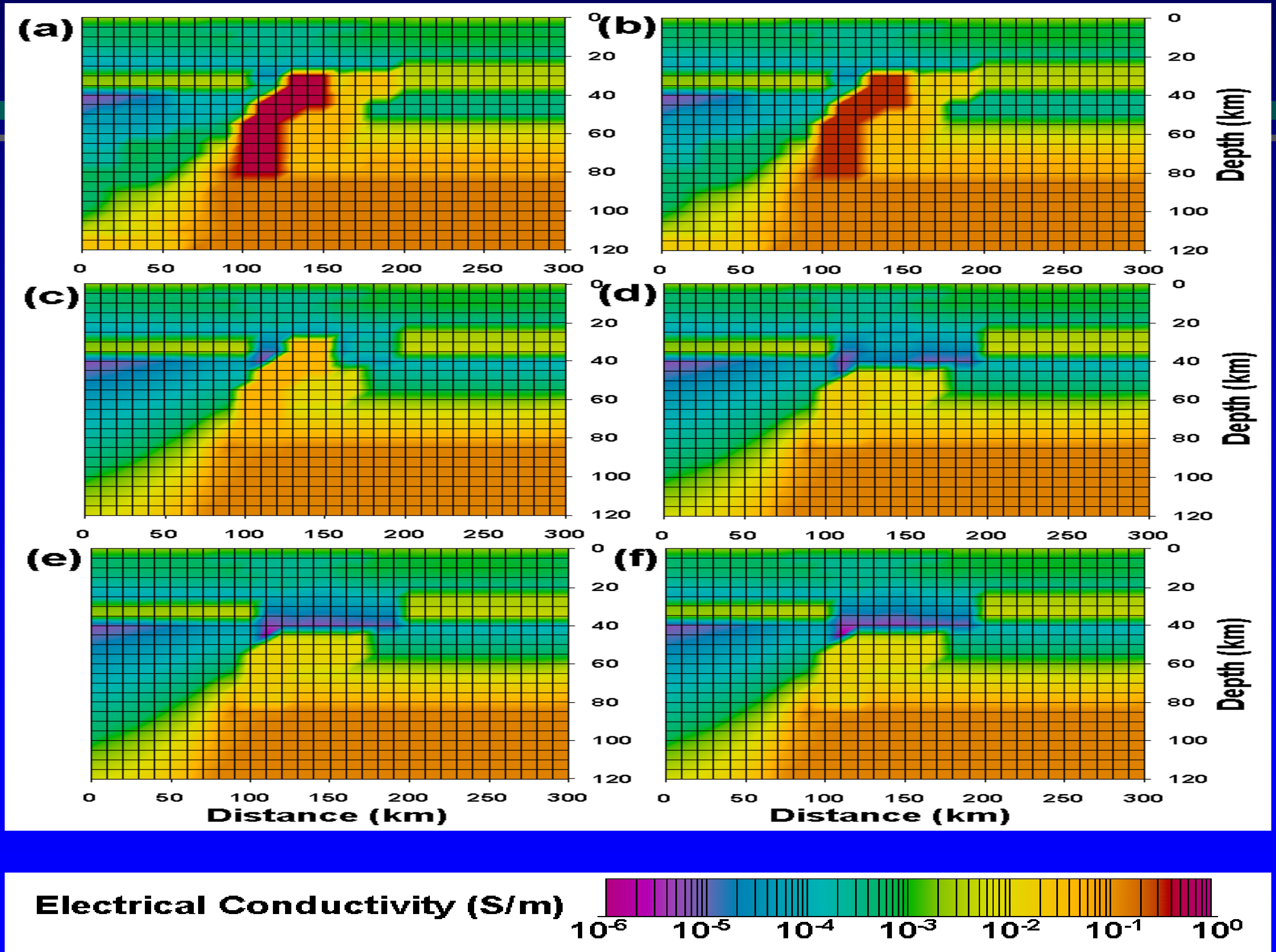
Effective Conductivity

Hashin-Shtrikman Lower Bound



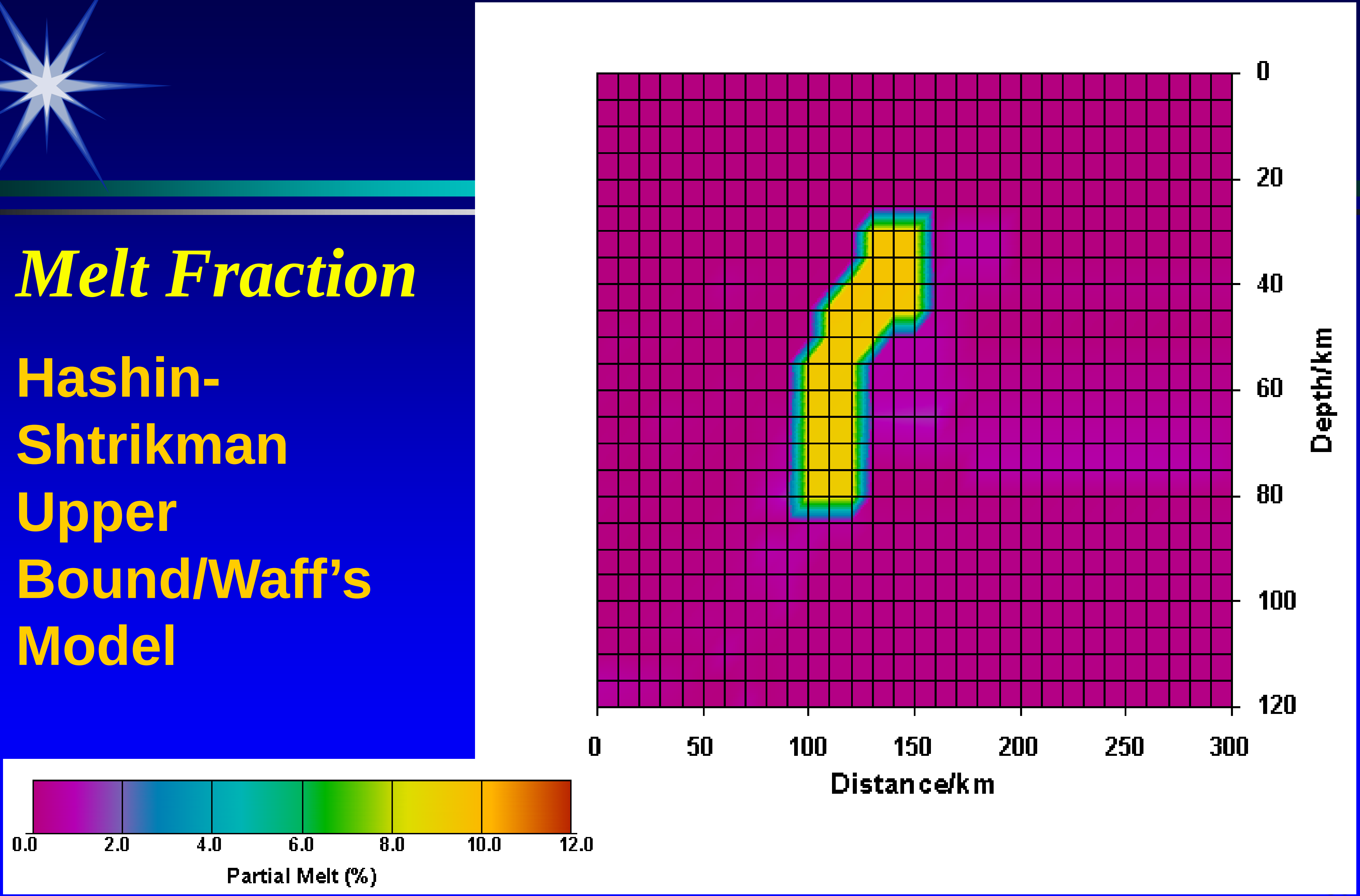


All Effective Conductivity Models



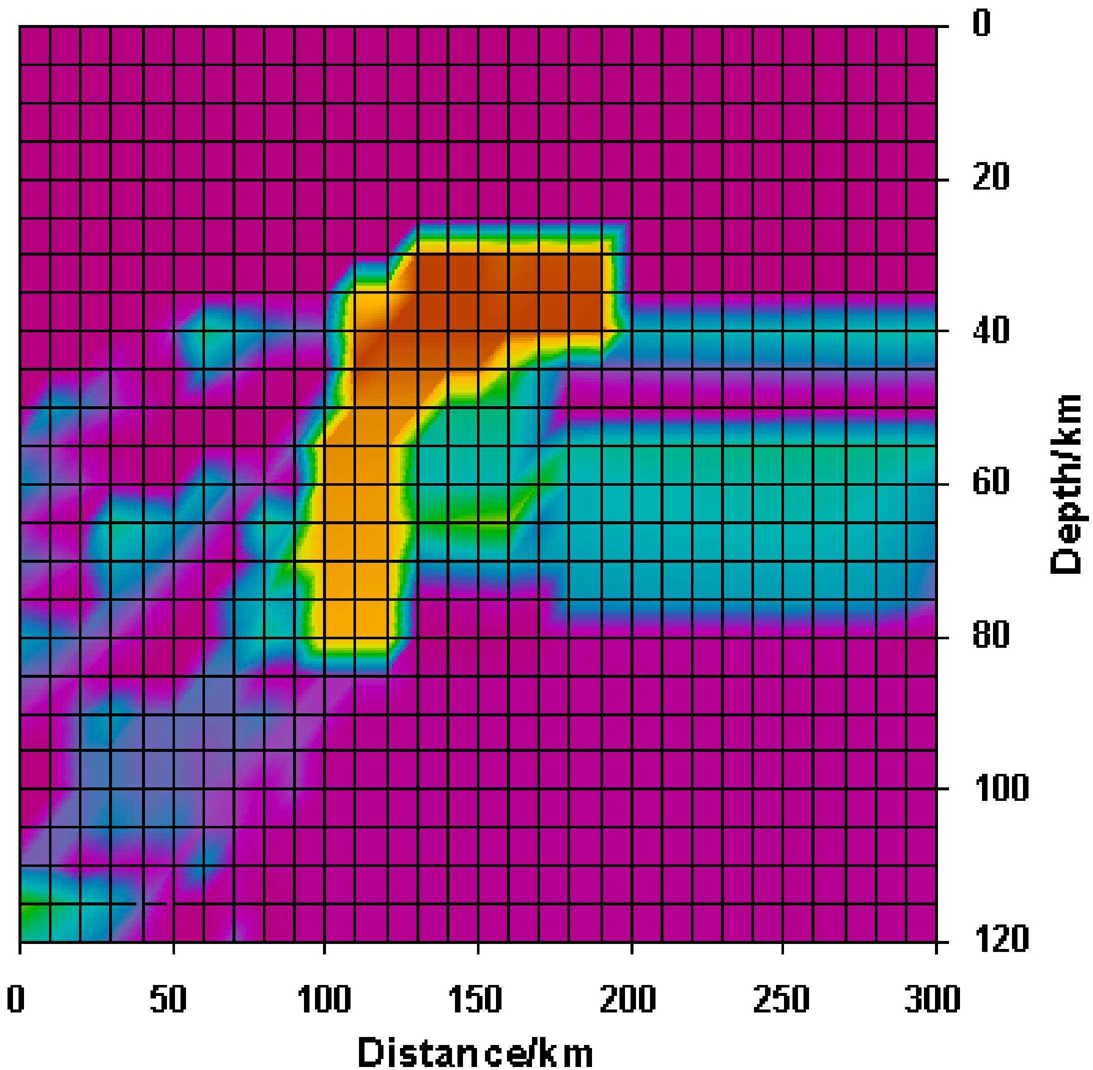
Melt Fraction

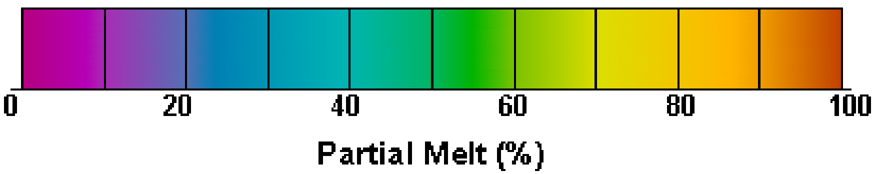
Hashin-Shtrikman Upper Bound/Waff's Model



Melt Fraction

Hashin-Shtrikman Lower Bound





Summary I

- A two-dimensional conductivity model for the Pyrenees has been constructed
- A good match to the conductivities observed by MT is possible
- Aqueous fluids alone can explain the conductivity in most of the profile
- Aqueous fluids cannot explain the conductivity of the subducting slab

Summary II

- Partial melting is likely to be the cause of the very high slab conductivities
- A partial melt fraction of at least 4.7% is necessary
- This is consistent with geochemical melting models
- The melt must be well connected
- The absence of surface volcanism is partly due to its compressive tectonic regime, and volcanism is likely in the Pyrenees if the area becomes extensive