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Habilitation à Diriger des Recherches

Modélisation Géophysique Multi-échelles et Hydrogéophysique : de la Théorie à la Pratique

Pascal Sailhac
Maître de Conférences

vendredi 29 septembre 2006

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HDR = Authorization to Supervise Research Activities

Multiscale Geophysics and Hydrogeophysics Modelling: from Theory to Practice

Pascal Sailhac
Associate Professor

Friday September 29, 2006

General introduction

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Main issues

- Multiscale modelling in geophysics

Using symmetries between multi-scale properties of surface data and underground images

- Hydrogeophysics

Using geophysics combined with hydrological data to constrain models of underground water flow

General introduction

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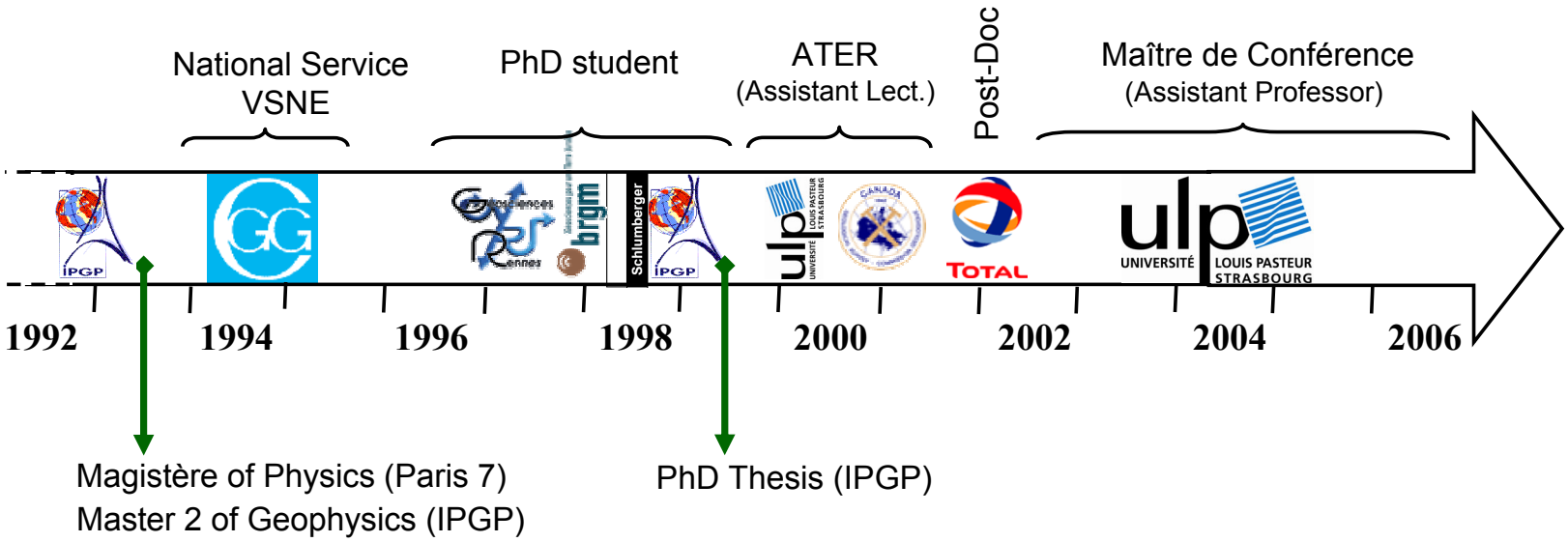
Work experience



General introduction

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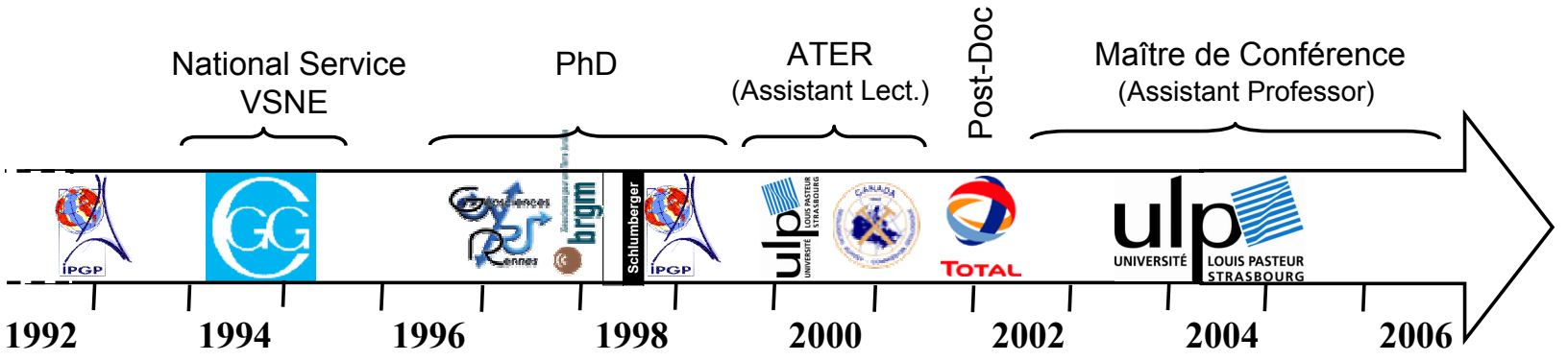
Main supervisions (PhD students)



M. Béhaegel (2003-2006)

S. Rosat (2004)

H. Boukerbout (2003-2004)

M. Darnet (2002-2004)

G. Pouliquen (2000-2001)

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Outline

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1. General introduction
2. Interpretation of geophysical data using wavelet transforms
3. Hydrogeophysics
4. Conclusions and perspectives

Wavelet transform

Multiscale approach of potential field data

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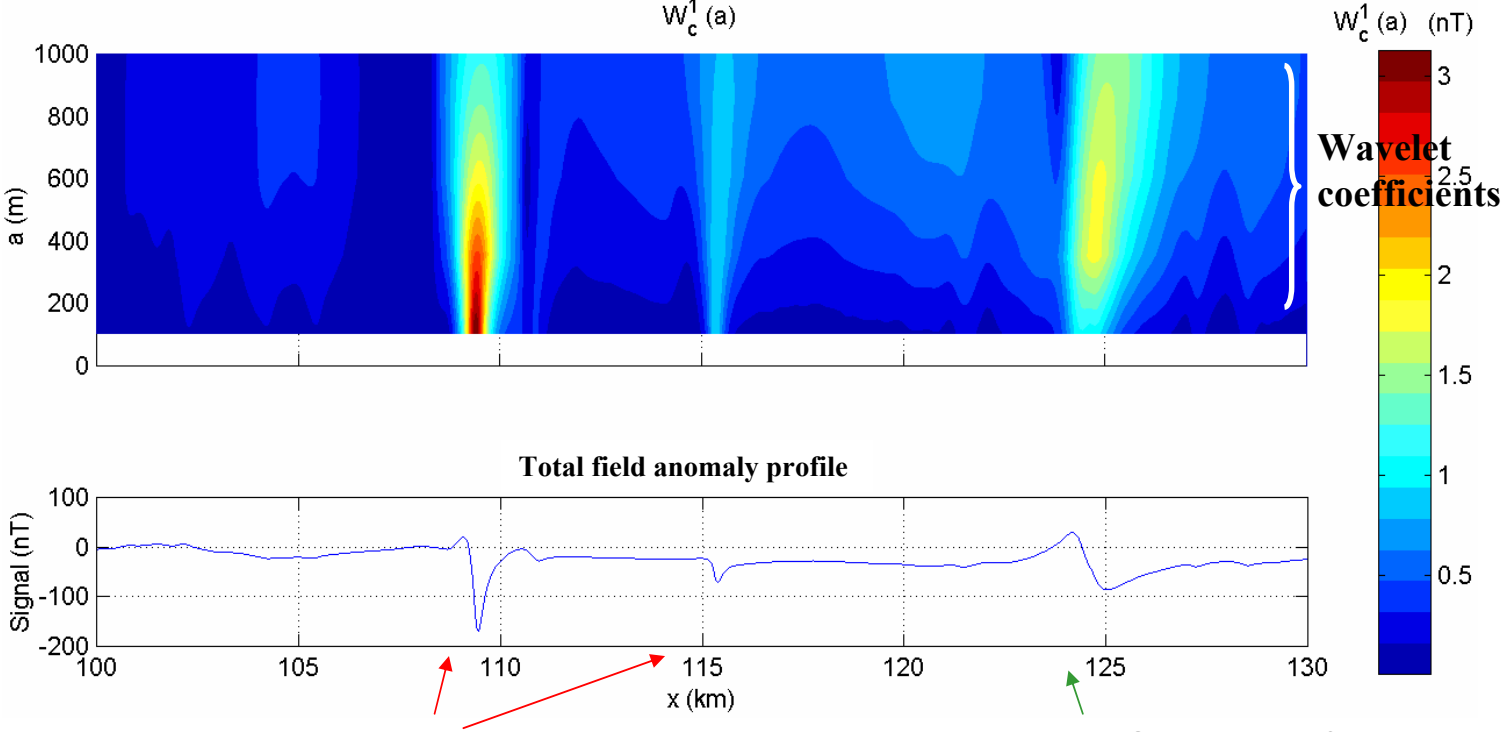

Acid plutons (~granodiorite)

Green rocks (sandstone, quartzite,…)

⇨ **Results: Geometry of Structures at Depth**

Sailhac et al. 1999

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Wavelet transform

Multiscale approach of potential field data

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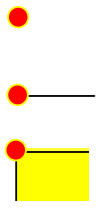
Wavelet Transform: $W(x,a) = (\phi * g_a)(x)$ **(Derivative & Upward continuation)**

Local sources: depth z_0 and structural index $\beta=\alpha-\gamma$



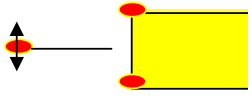
Point or short sphere: α=-3

semi-infinite pipe: α=-2

semi-infinite pipe: α=-1

$$\left|W_c^{\gamma}(a)\right| \sim a^{\gamma}(a+z_0)^{\beta}$$

Extended sources: perturbation & multipolar expansion



$$\left|W_c^{\gamma}(a)\right| \sim a^{\gamma}(a+z_0)^{\beta}\, \mathrm{f}(h,\theta,\ldots)$$

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Wavelet transform

Multiscale approach of potential field data

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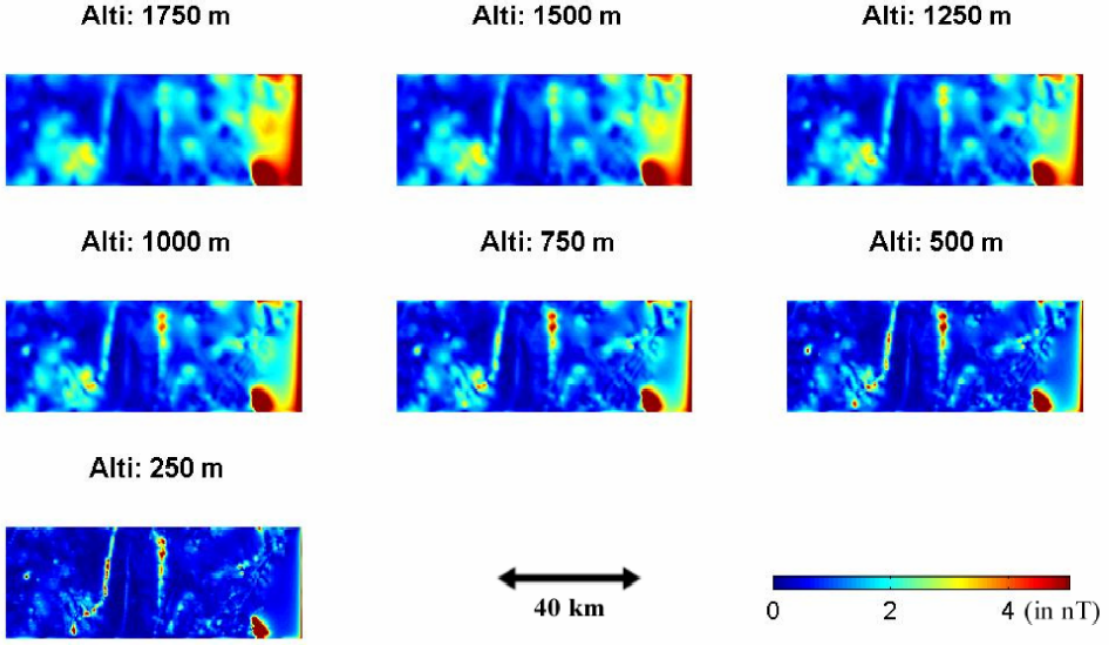

$$|\mathcal{W}_{\psi^\gamma}(a)| \approx K a^\gamma (z_0 + a)^\beta \left(B_0^0 + \frac{C_0 B_2^0 + C_2 B_2^2}{(z_0 + a)^2} \right)$$

Source strength

Depth

Structural index

Moments: related to the source density function and geometry

Wavelet coefficients from maps can be inverted by loglog fits for extended source models using multipolar expansions (harmonic): this results in estimates of the first moments B_l^m related to source geometry.

Sailhac and Gibert 2004

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Wavelet transform

Application to kimberlite detection

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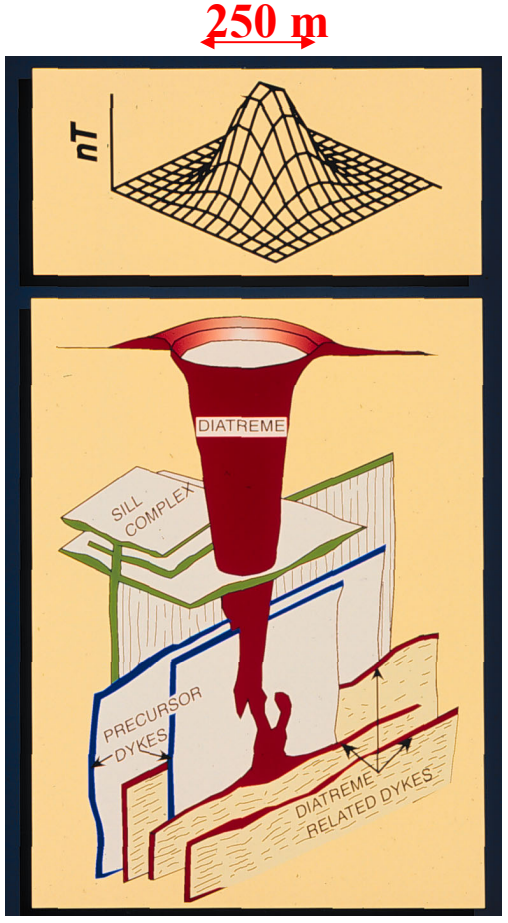
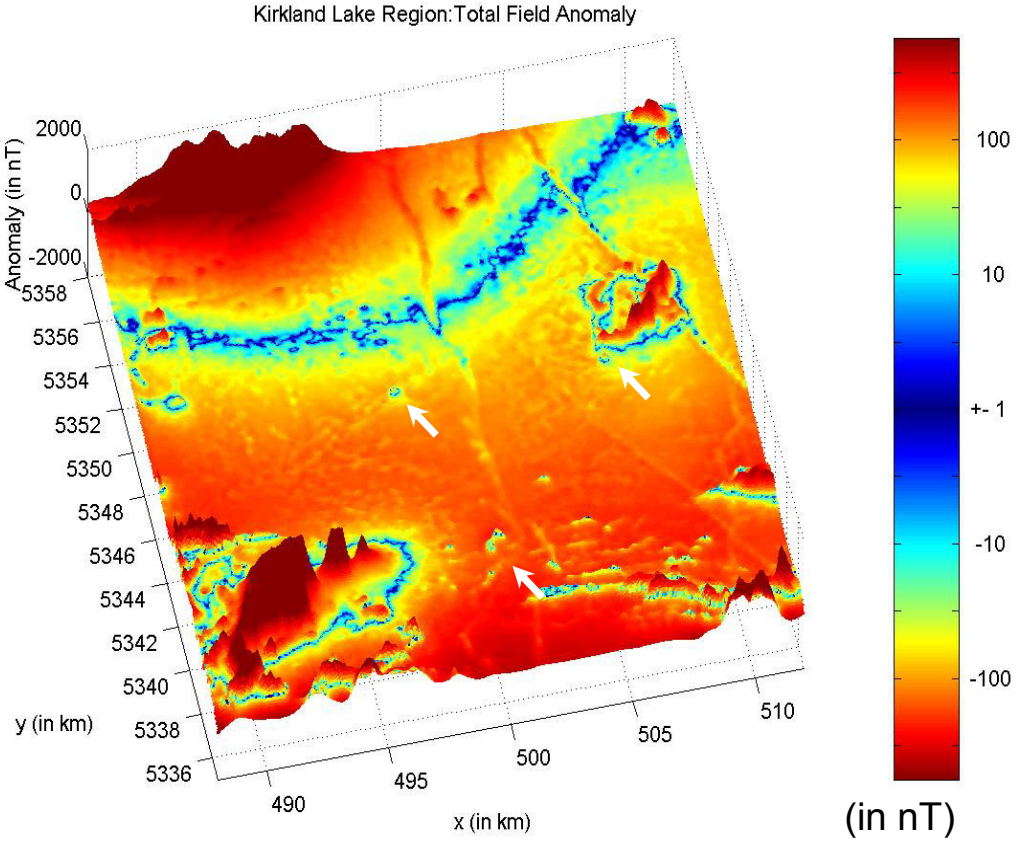
New inverse schemes to detect kimberlite chimneys





Keating and Sailhac 2004

Wavelet transform

Application to kimberlite detection

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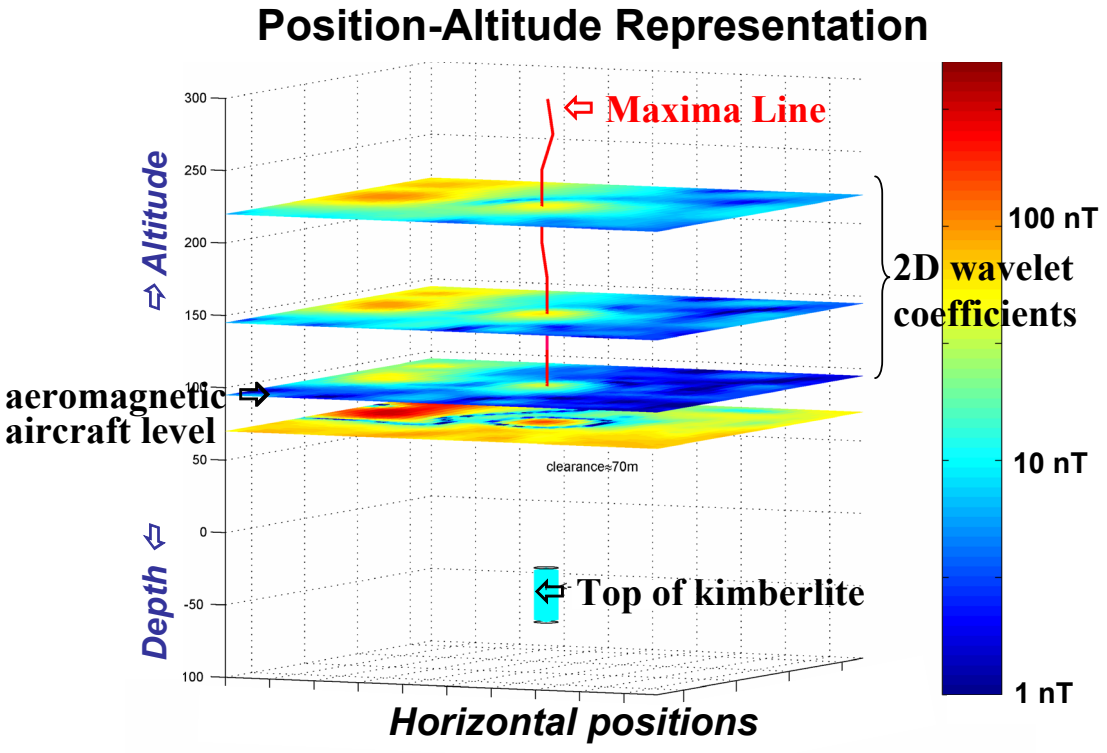
New approach is in the wavelet domain combined with statistics in shape, depth, thickness estimates



Scaling law ⇔ Shape & Depth to Sources

Wavelet transform

Application to paleomagnetism

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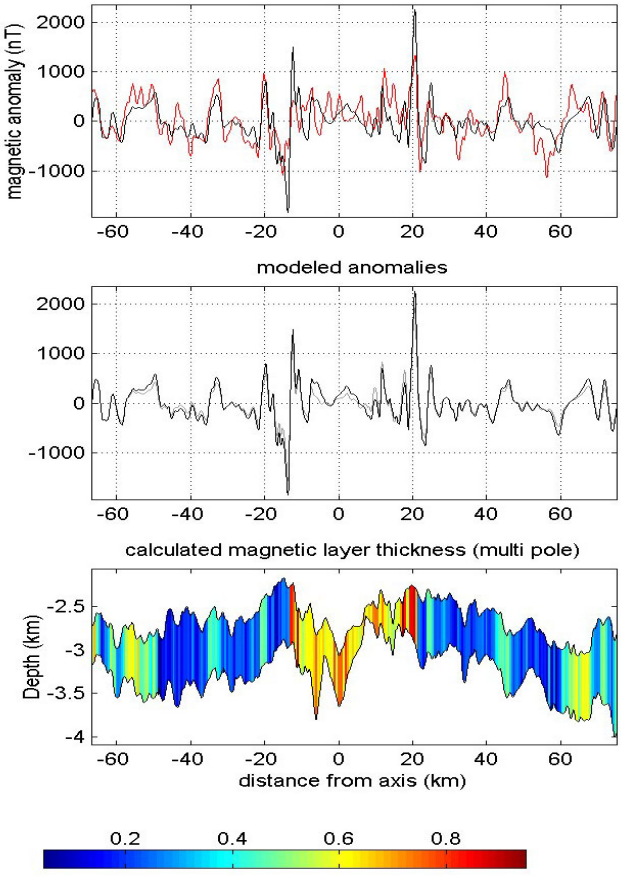
co-supervision of G. Pouliquen, PhD IPGP (2000-2001)

Modelling crustal magnetization and thickness variations from deep-tow magnetic data

Deep-tow magnetics



Observed magnetic anomalies

Modelled using variable thickness

Pouliquen and Sailhac 2004

Wavelet transform

Application to near-surface imaging

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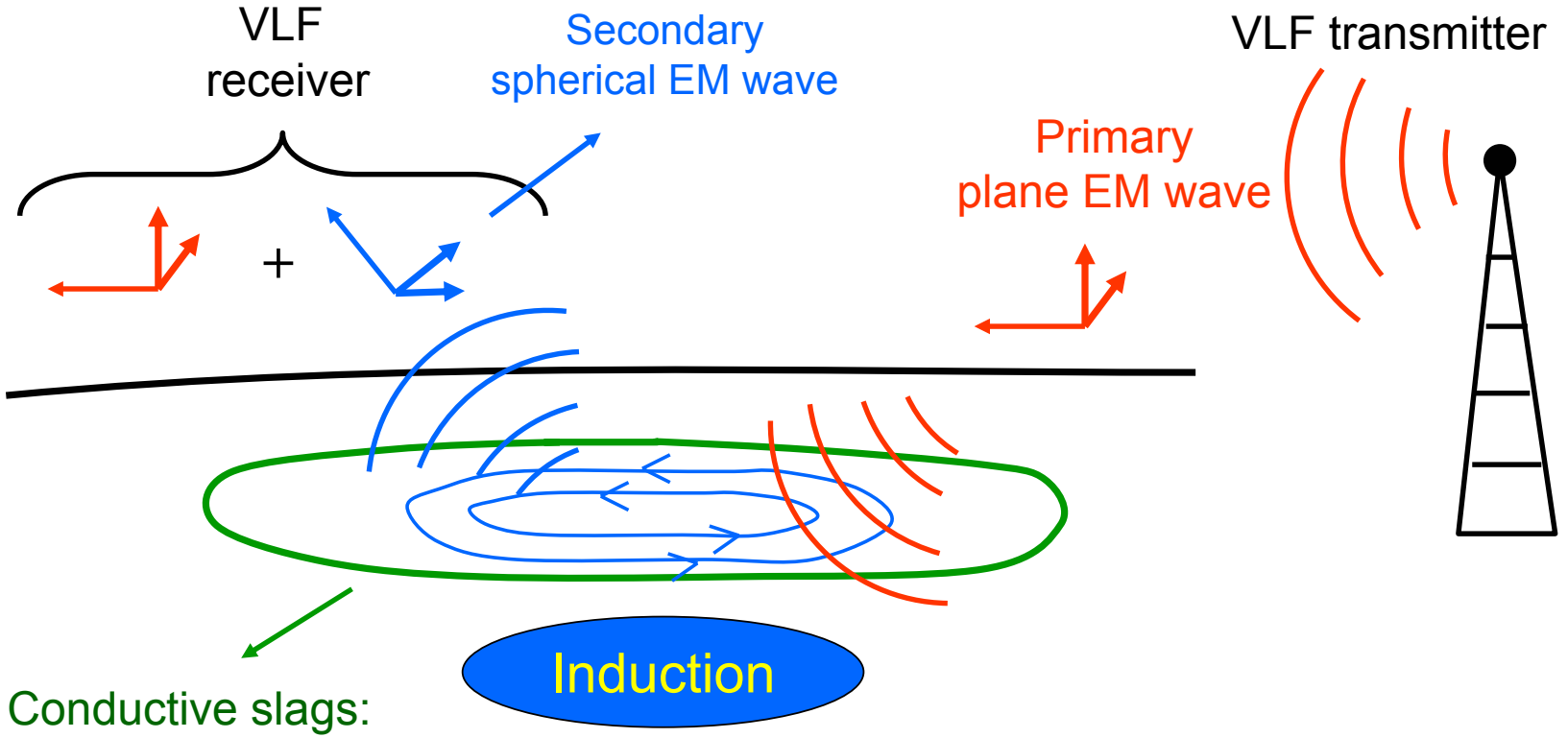
co-supervision of M. Darnet, PhD IPGS (2002-2004)
& H. Boukerbout, PhD Geosciences Rennes (2003-2004)



Wavelet transform

Application to near surface imaging

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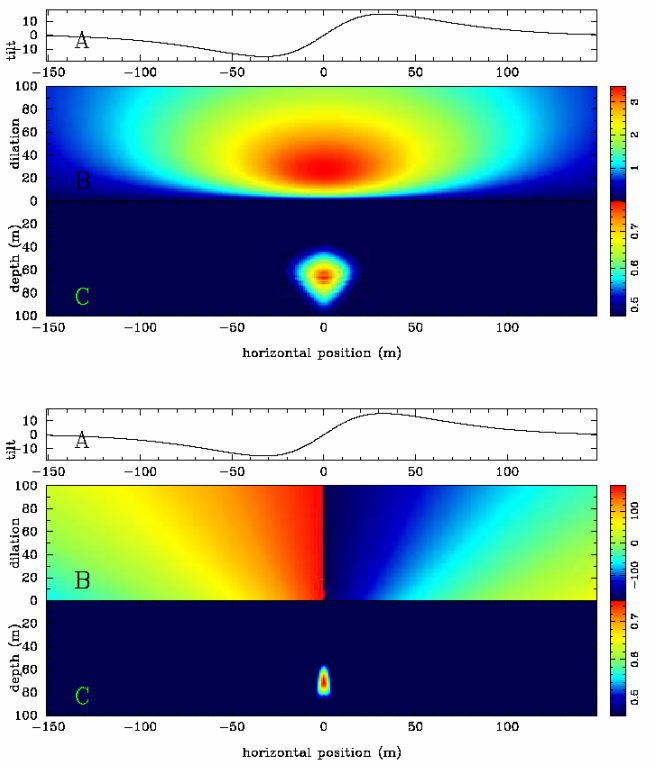
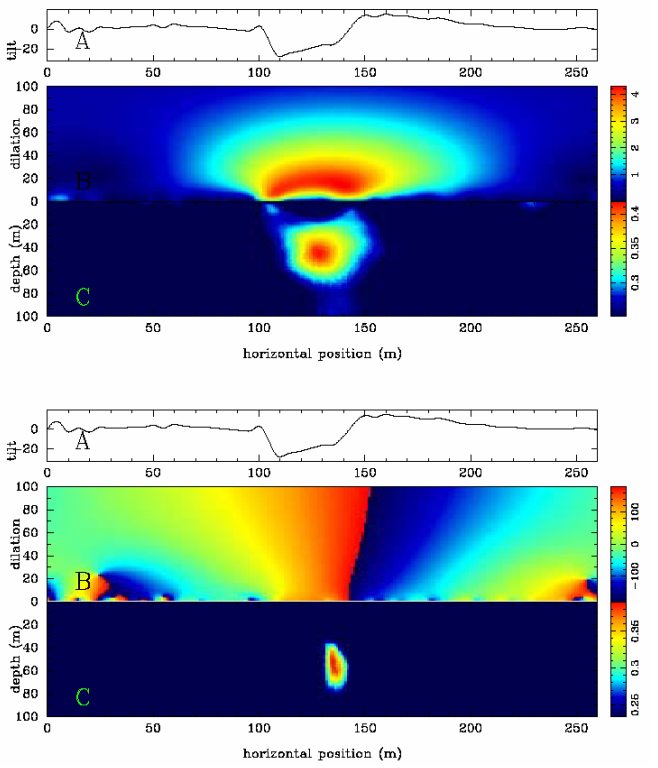
co-supervision of H. Boukerbout, PhD Geosciences Rennes (2003-2004)

Synthetic dike (top at 60 m depth)



Mineralized diorite dike of Pont-Péan (Brittany)



Tilt: $\bar{\Phi}(f,x,y) = H_z^s/H_x \propto H_z^s(f,x,y)$ (we assume $H_x^s \ll H_x^p$)

Boukerbout et al. 2003

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Wavelet transform

A new wavelet for damped transient signals

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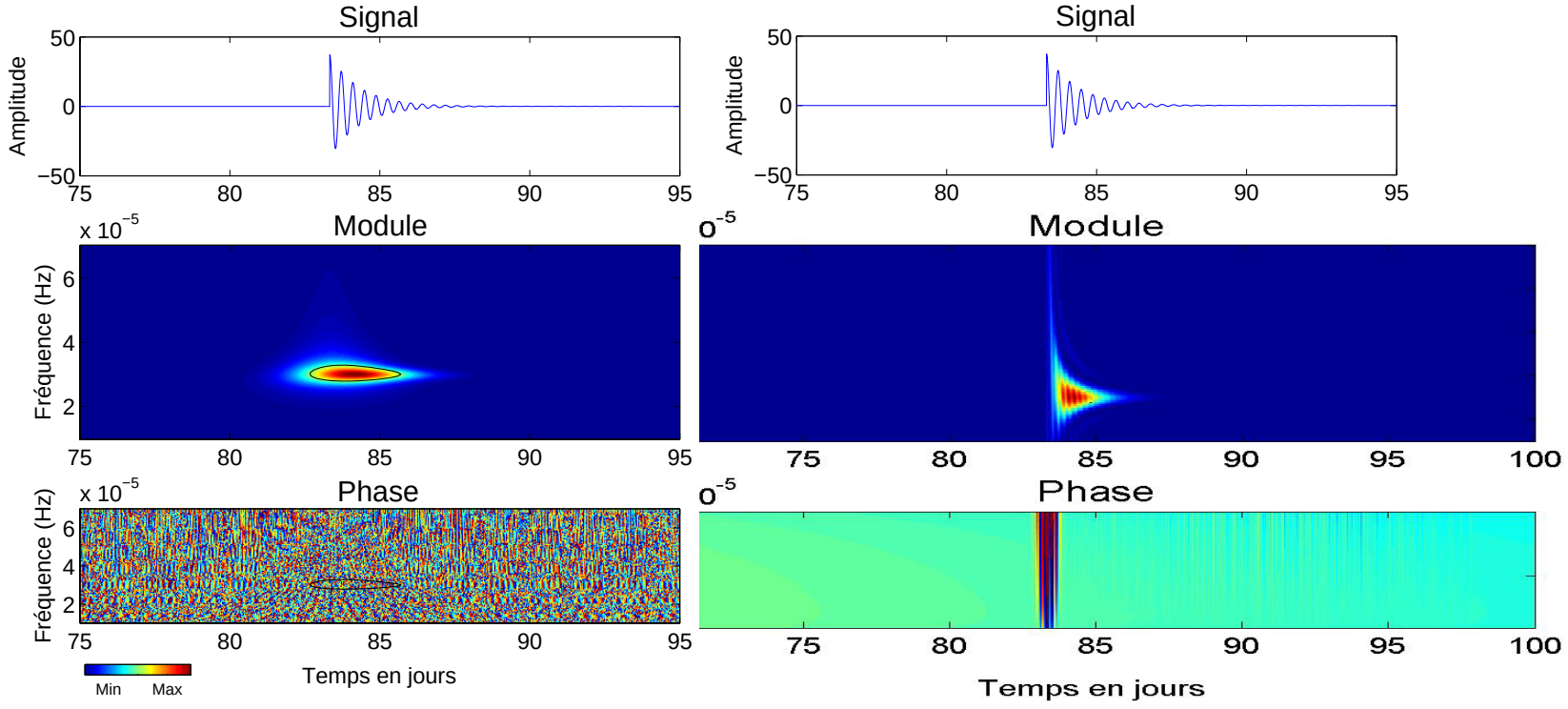
co-supervision of S. Rosat, PhD IPGS (2004)



Using Morlet wavelets

Using causal damped sinusoid wavelets

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Hydrogeophysics

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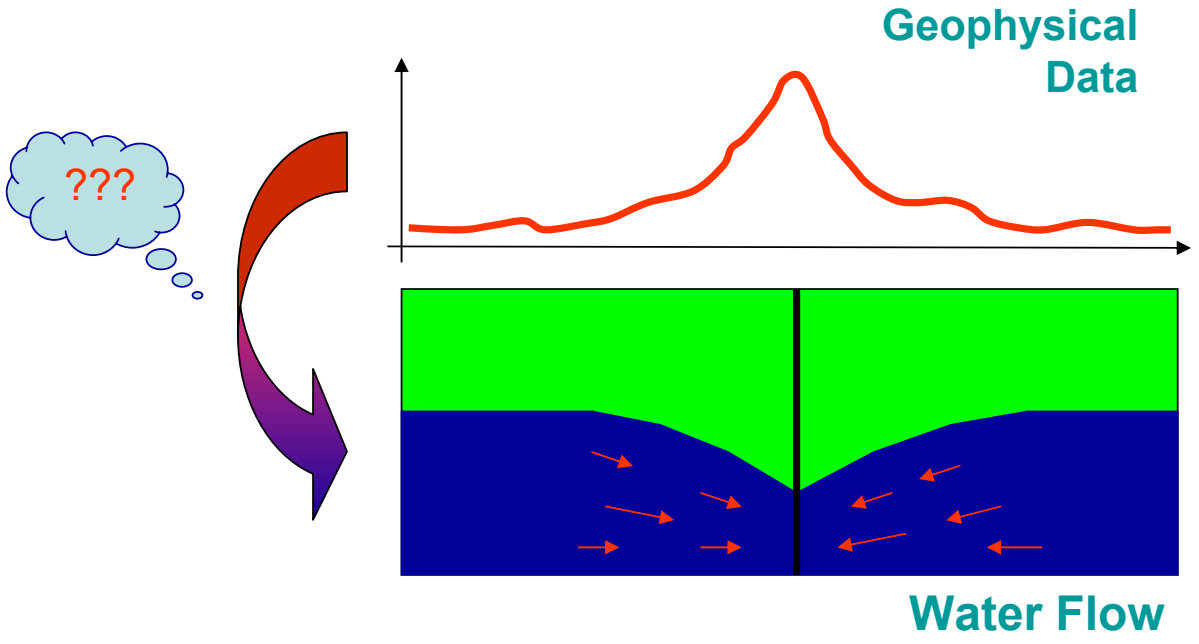
Objectives: Constrain fluid flow models based upon interpretation of both geophysical and hydrological data



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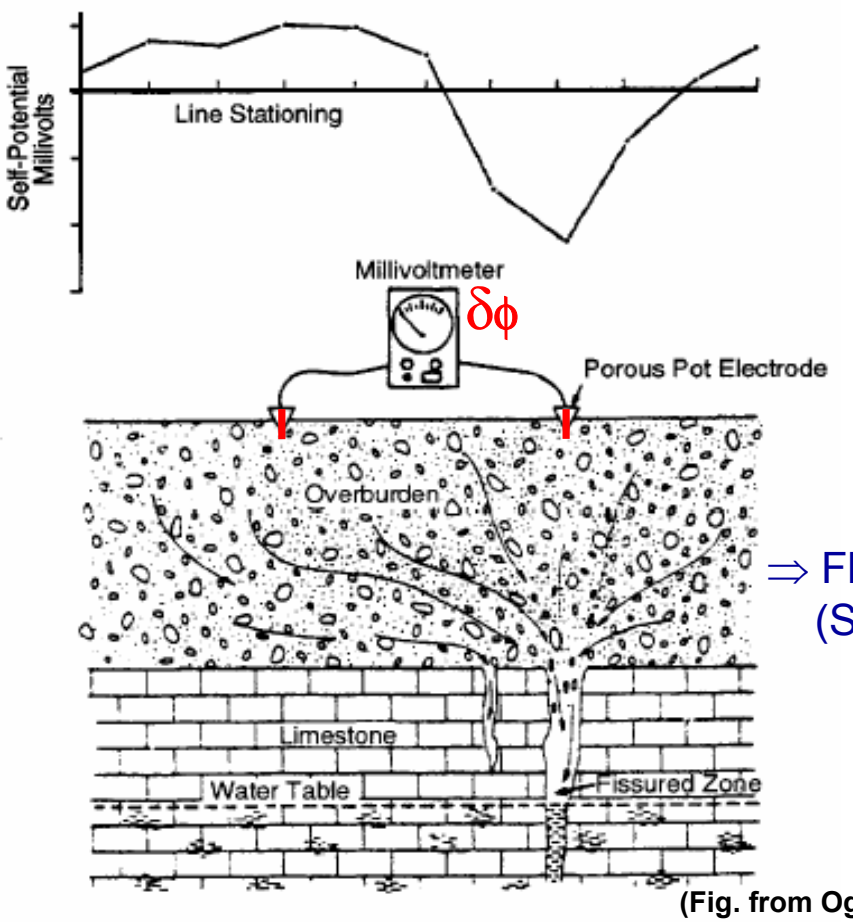
Surface SP data



⇒ Fluid circulations in depth (SP sources)

(Fig. from Ogilvy and Bogoslovsky, 1979)

Hydrogeophysics

Principles of elektrokinetics

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At the macroscopic scale: Electric and hydaulic currents

Physical principles: Ohm law - Darcy law

	Hydr. modelling	Elec. modelling
Flux	$\vec{q} = -K\vec{\nabla}\varphi$	$\vec{j} = -\sigma\vec{\nabla}V$
Conservation law	$\vec{\nabla}.\vec{q} = -S_h$	$\vec{\nabla}.\vec{j} = -S_e$

Total electric current:

$$j_T = -\sigma(CK\vec{\nabla}\varphi + \vec{\nabla}V)$$

$$\nabla . j_T = 0$$

Electrofiltration coupling for electric ϕ et hydraulic φ potentials:

$$\vec{\nabla}.(\sigma\vec{\nabla}\phi) = -\vec{\nabla}.(C\sigma\vec{\nabla}\varphi)$$

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Hydrogeophysics

SP: example on a numerical flow

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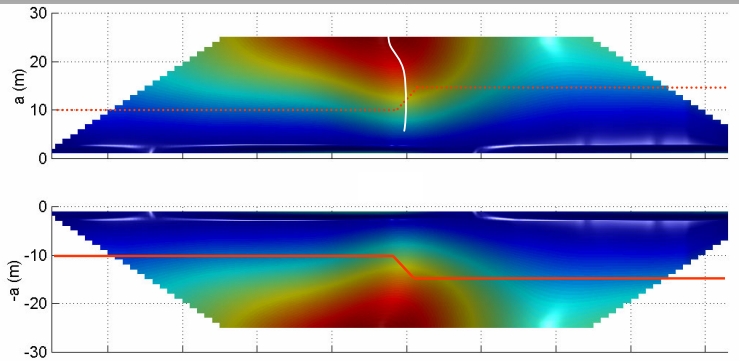
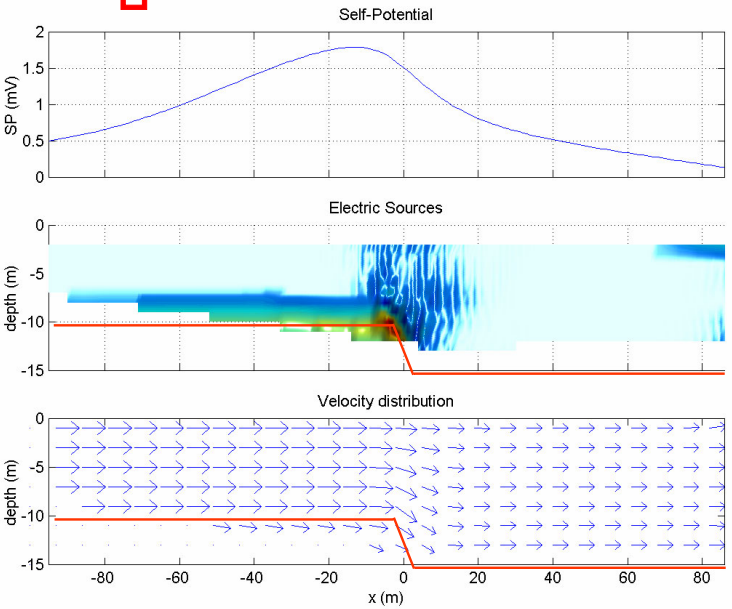


Wavelet transform

Patella's probability tomography

⇧ Computing Correlation Coefficients of SP with Green's Functions



SP anomaly at ground surface

Equivalent electric charges

Flow Model

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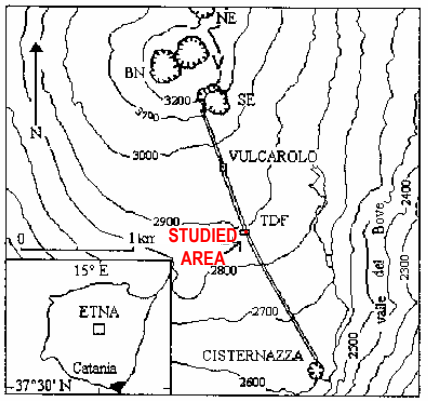
Hydrogeophysics

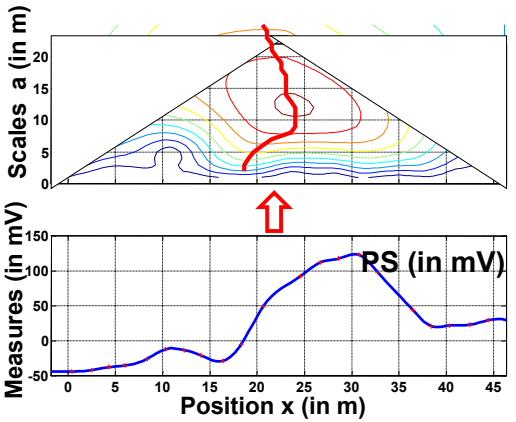
SP: example on hydrothermal site

Application : Hydrothermal circulation at Etna volcano

Fissure Vulcarolo (Etna)

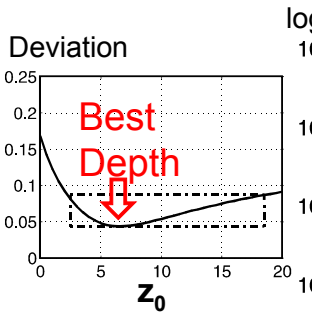


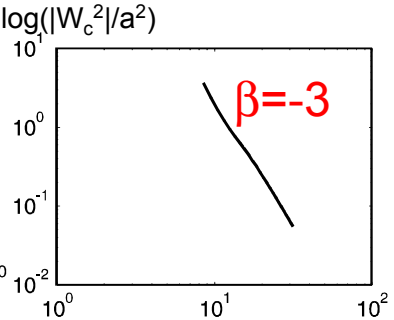
SP wavelet transform



Inversion by adjusting a power law
(linear least-squares in log-log)

$$\left|W_c^2\right| \sim \frac{mC}{K} a^2 (a + z_0)^{\beta}$$





depth = 3 to 18 m
⇨ **intensity = 2400 mV/m**
flux ~ 0.1 m³/h

Sailhac and Marquis 2001

Hydrogeophysics

SP: example on aquifer pumping

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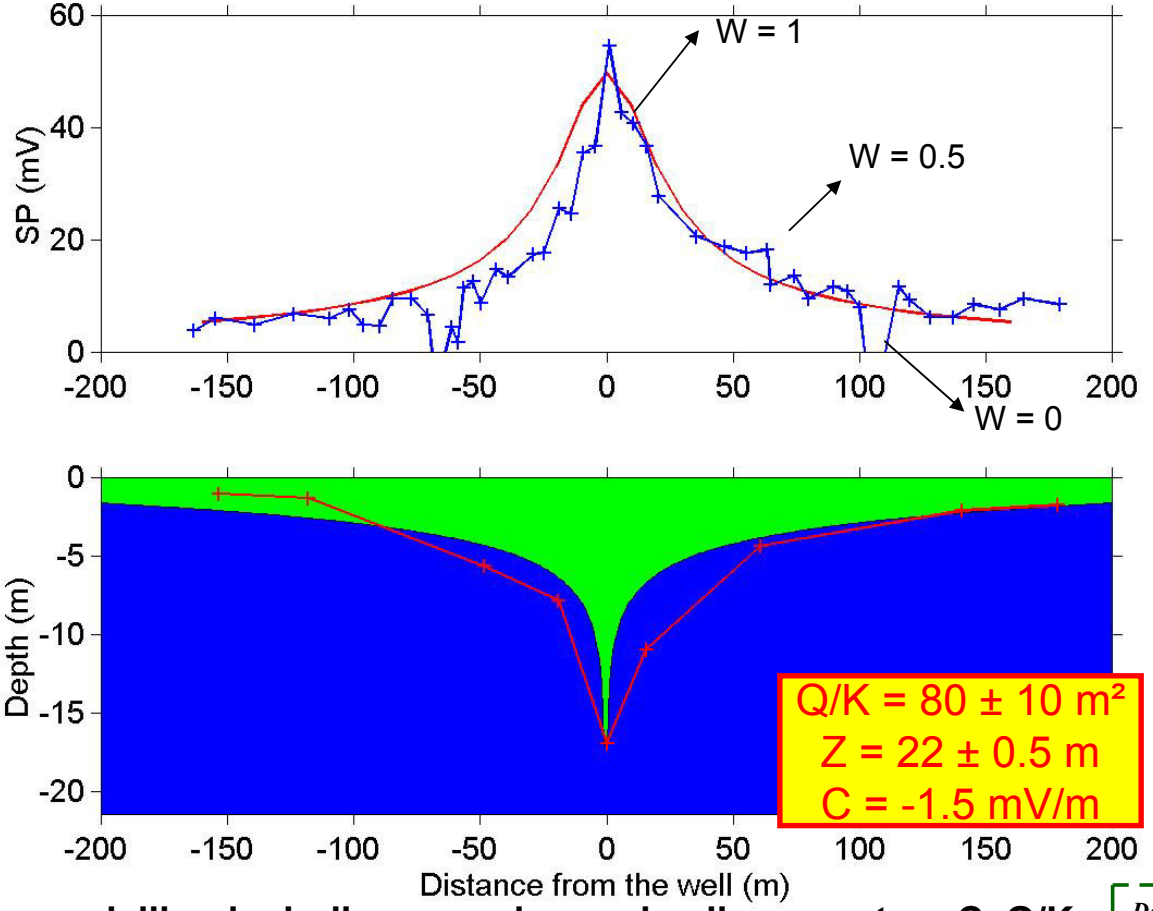
co-supervision of M. Darnet, PhD IPGS (2002-2004)

Genetic algorithm and pumping test application



Use full inverse modelling including pumping and soil parameters C, Q/K,…

Darnet et al. 2003

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Hydrogeophysics

SP: problems in the vadose zone

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Target Processes: Infiltration, Aquifer recharge, capillary fingering, etc.

Infiltration = Diffusion of water θ (Richard's Equation):

$$\frac{d\theta}{dt} = \nabla.(D\nabla\theta) - \frac{\partial K}{\partial z} = \nabla.(K\nabla h) - \frac{\partial K}{\partial z}$$

Target parameters:

Corey-Brooks

$$K = K_s \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{3+2/\lambda_b}$$

Van Genuchten

$$S_e = \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right) = \left[1 - \left(\frac{h}{h_b} \right)^c \right]^{-\lambda_v / c}$$

Gardner

$$K = K_S \, \mathrm{e}^{\alpha h}$$

Russo

$$S_e = \left\{ \mathrm{e}^{\frac{1}{2}\alpha h} \left(1 - \tfrac{1}{2}\alpha h \right) \right\}^{2/2+m}$$

Hydrogeophysics

SP: 2D infiltration in the vadose zone

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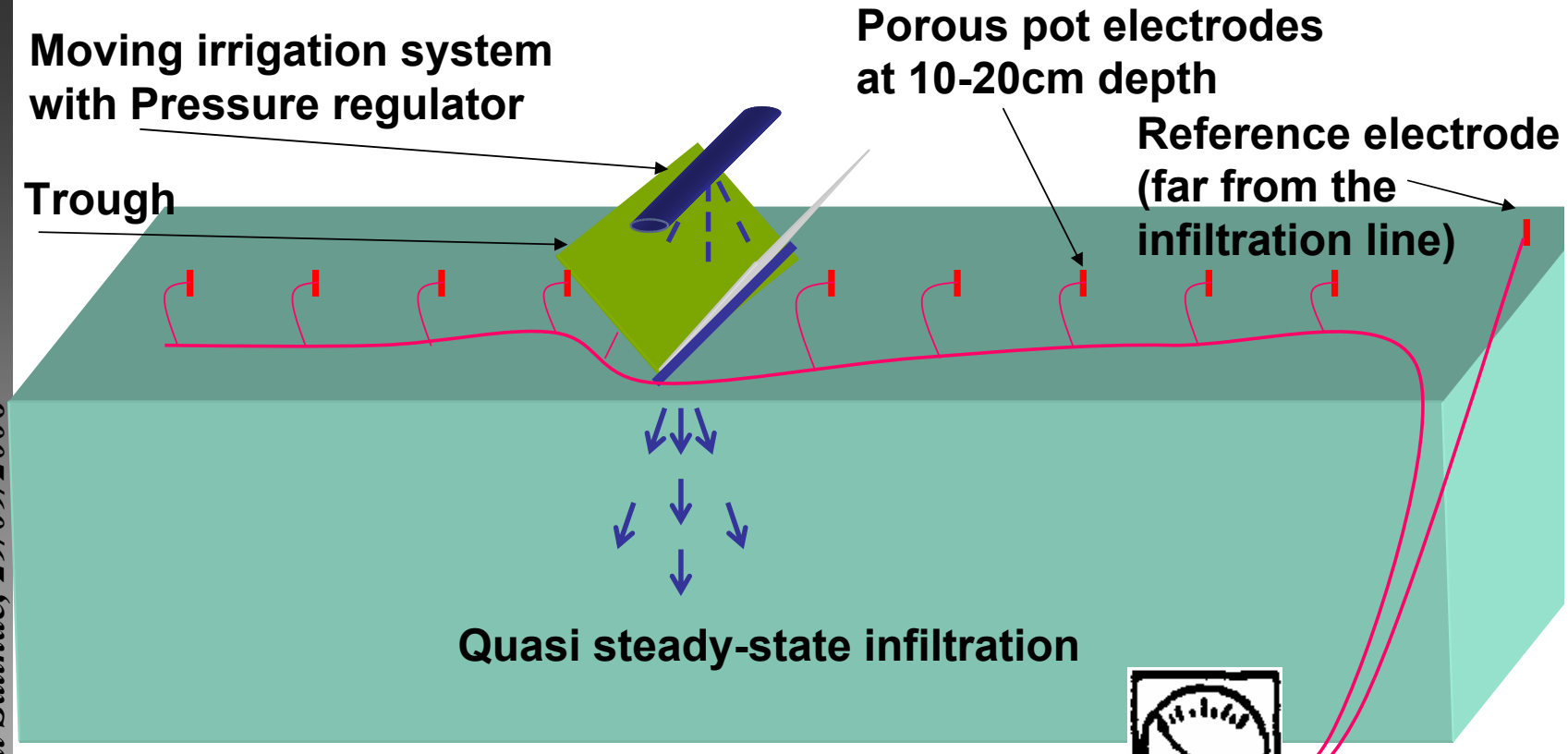

Sailhac et al. 2004

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Hydrogeophysics

SP: Analogic modelling

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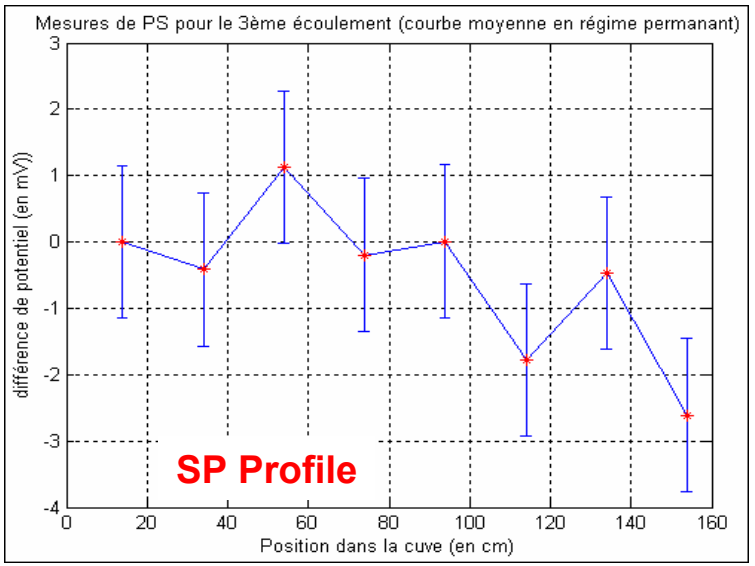
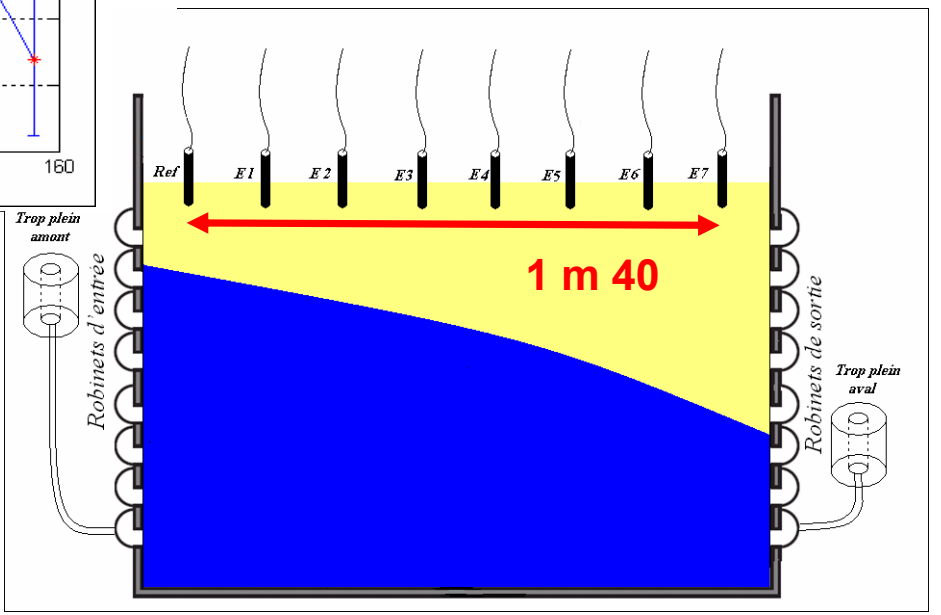
co-supervision of M. Essalhi, MSc IPGS-IMFS (2005)





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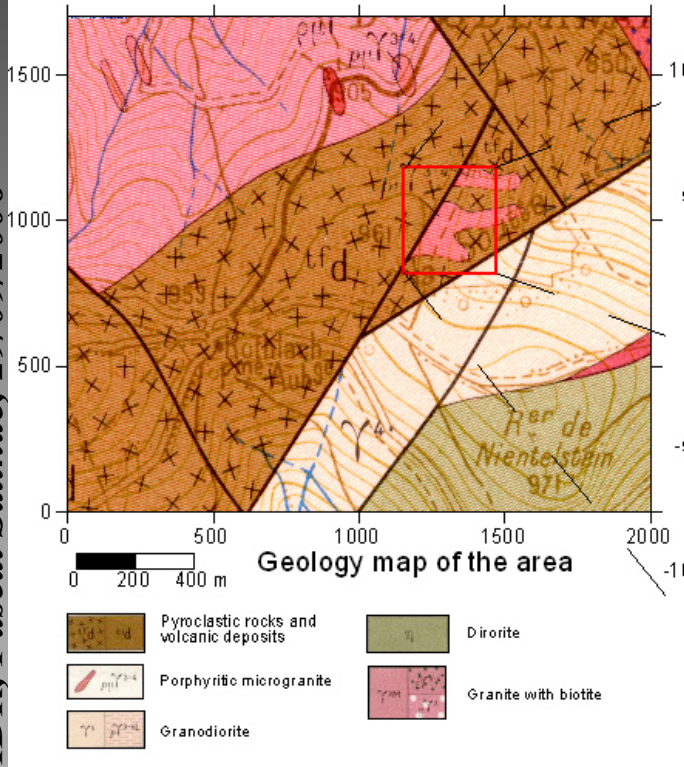
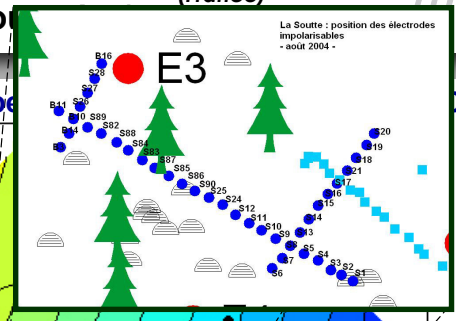
Hydrogeophysics

Experimental site of La Soutte (Les Vosges Mo

co-supe …004-2006)

"La Soutte", Vosges, France





Hydrogeophysics

Electric Resistivity Tomography at La Soutte

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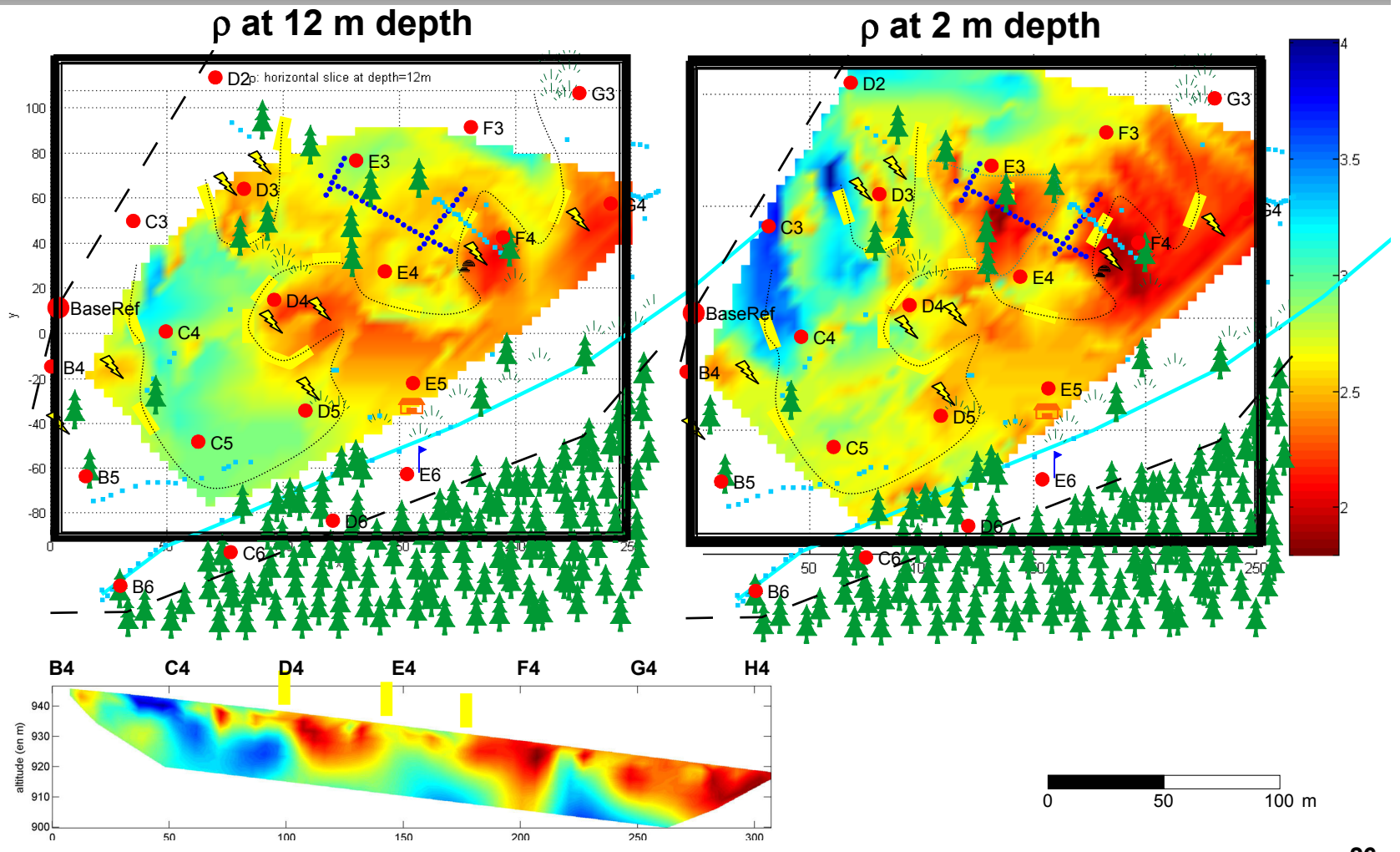

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Hydrogeophysics

ERT and SP profile at La Soutte

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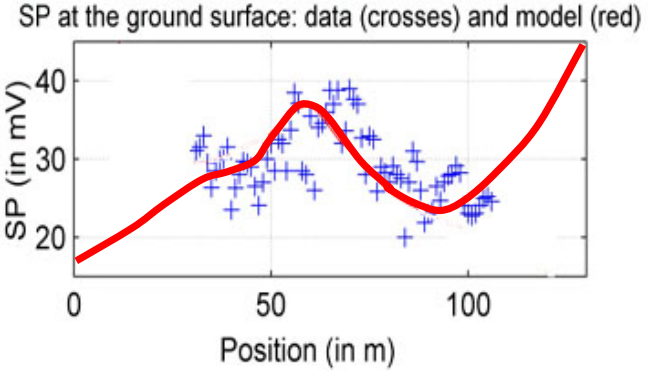
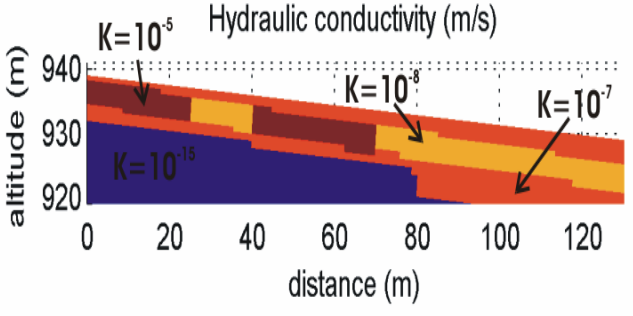
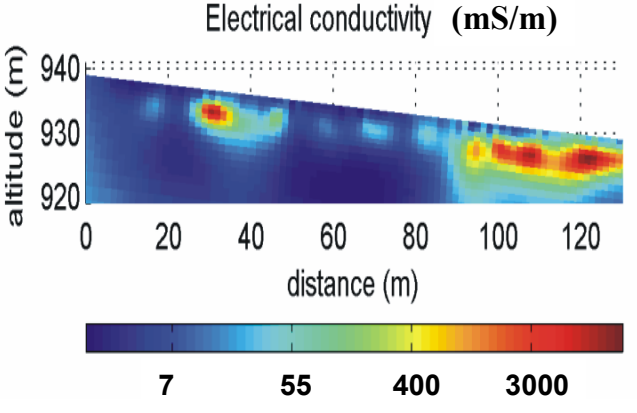
co-supervision of M. Béhaegel, IPGS (2004-2006)

Self-Potential and ERT along a profile: Our first flow model







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Hydrogeophysics

SP Map at La Soutte

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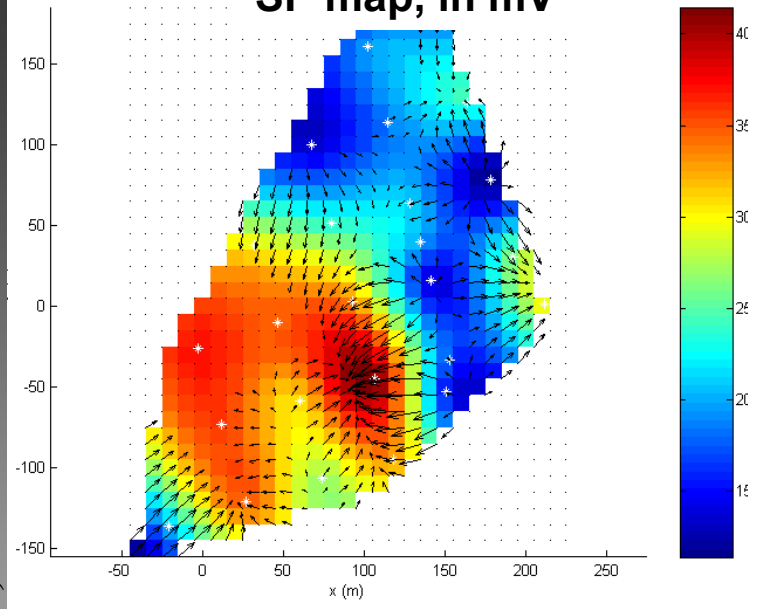
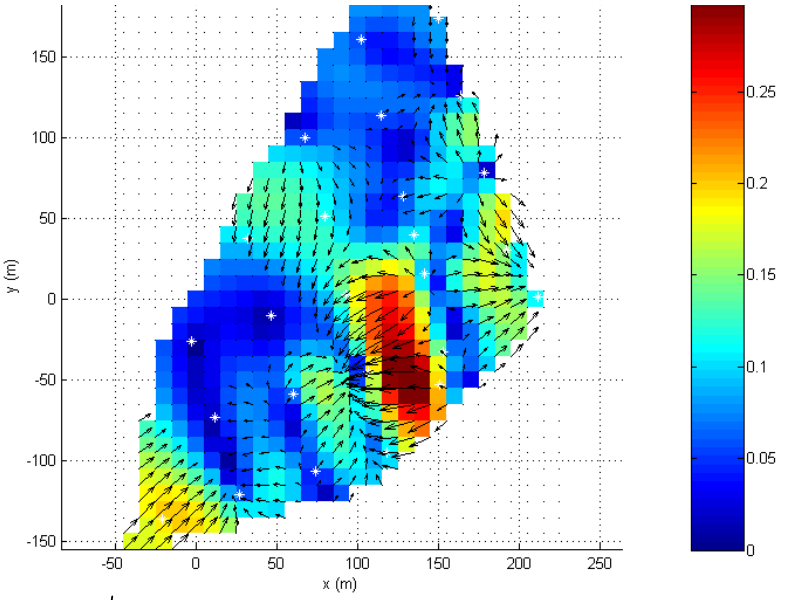
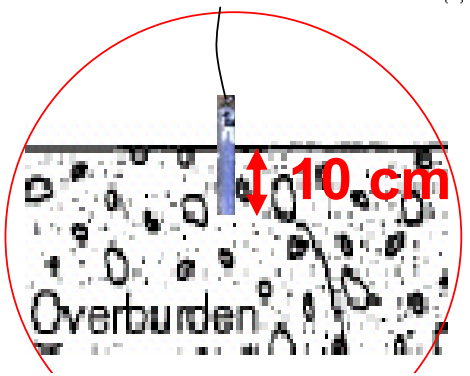
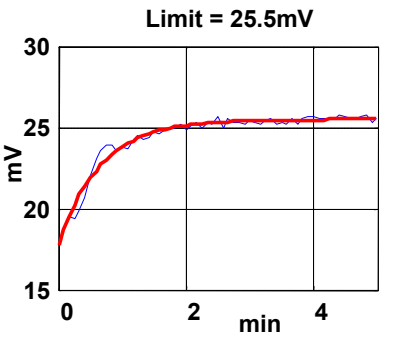
SP map, in mV



SP gradient, in mV/m (∝Darcy velocity)







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Hydrogeophysics

Continuous Measurement at La Soutte

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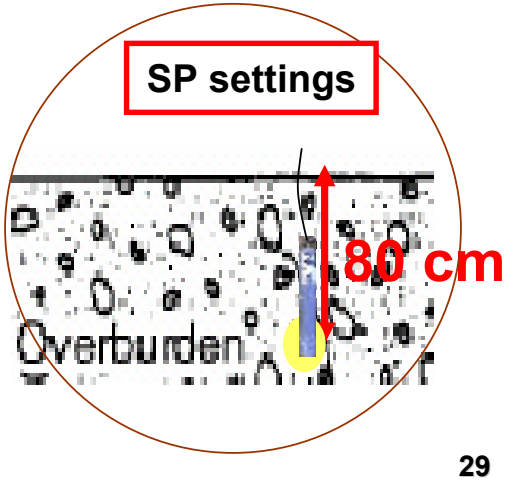

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Self-Potential

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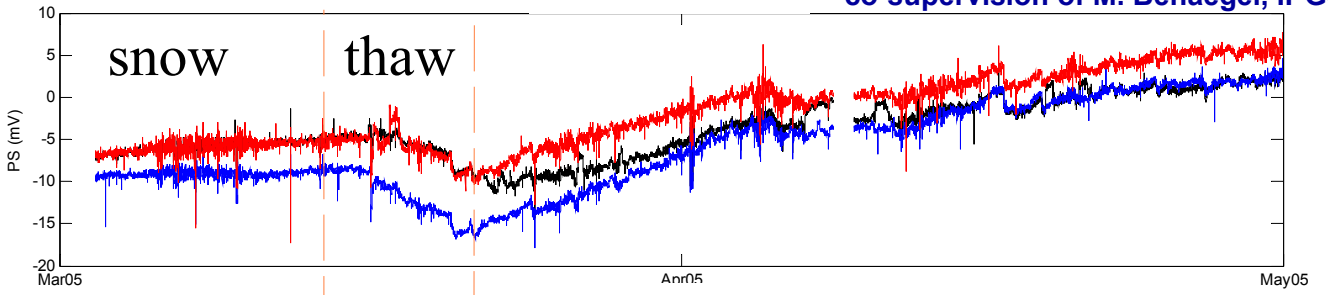
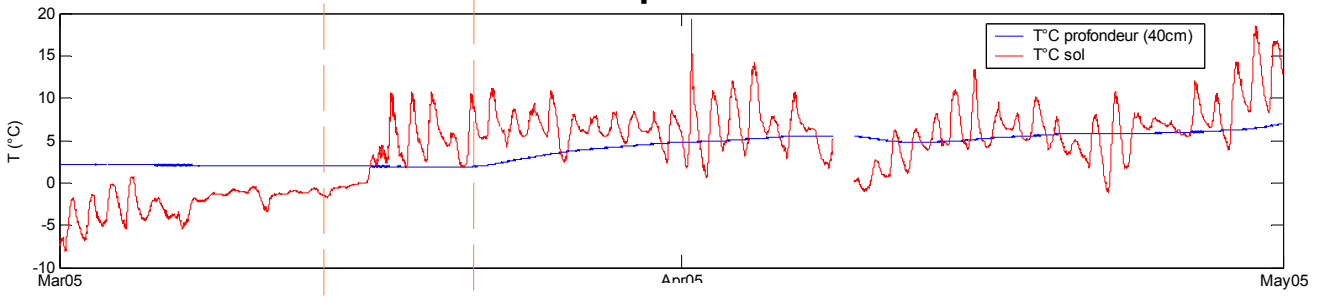
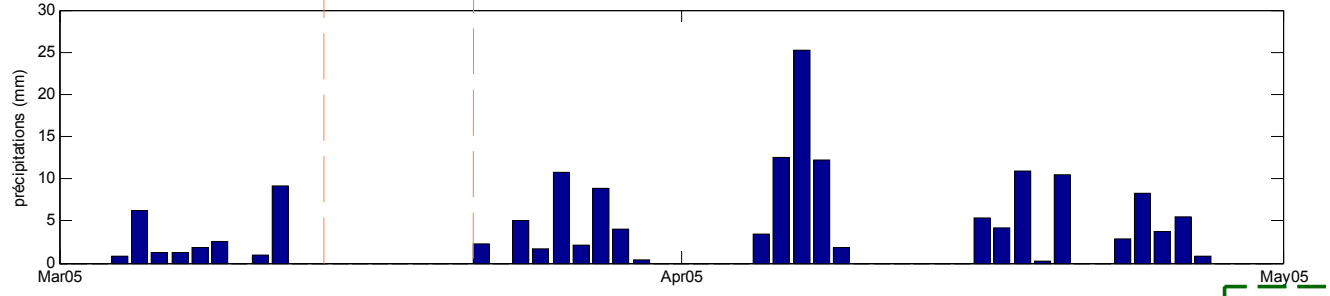


Temperature



Rainfall



Béhaegel et al. 2005

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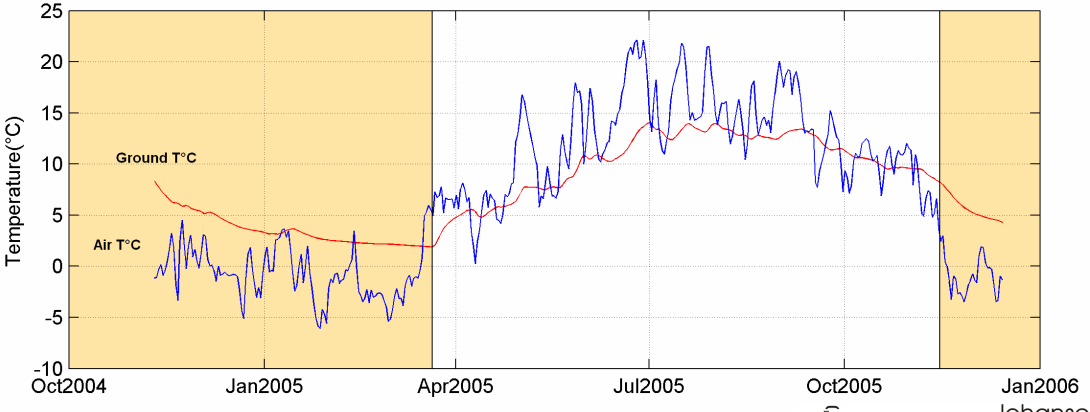
Ground Temperature: thermal diffusivity and water content variations

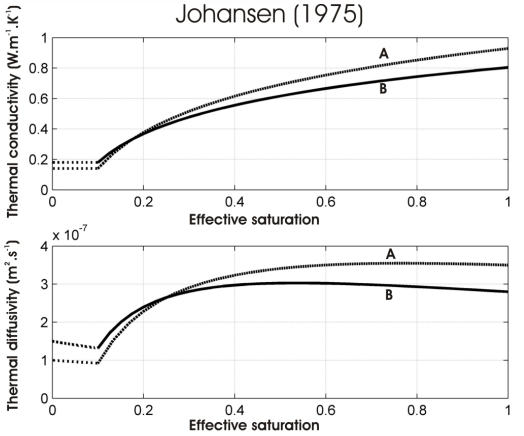


Diffusivity: $\kappa = \lambda / C$

Capacity: $C = (1-n).C_{solid} + \theta.C_w$

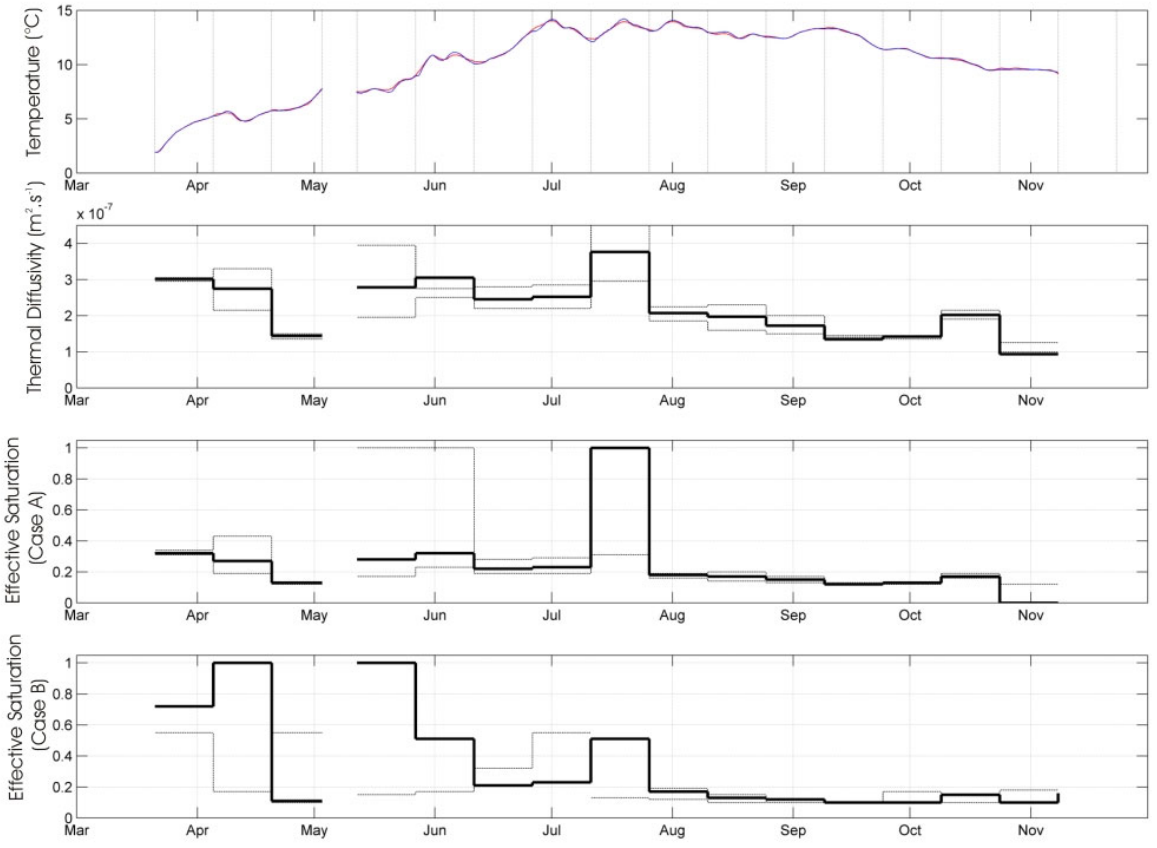
Conductivity: $\lambda = Ke(\lambda_s - \lambda_d) + \lambda_s$

Kerten Number: $Ke = log_{10} S_r + 1$ for $S_r > 0.1$



co-supervision of M. Béhaegel, IPGS (2004-2006)

Ground Temperature: thermal diffusivity and water content variations



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Perspectives

Reservoir Monitoring using MT & Multi-scale Impedance

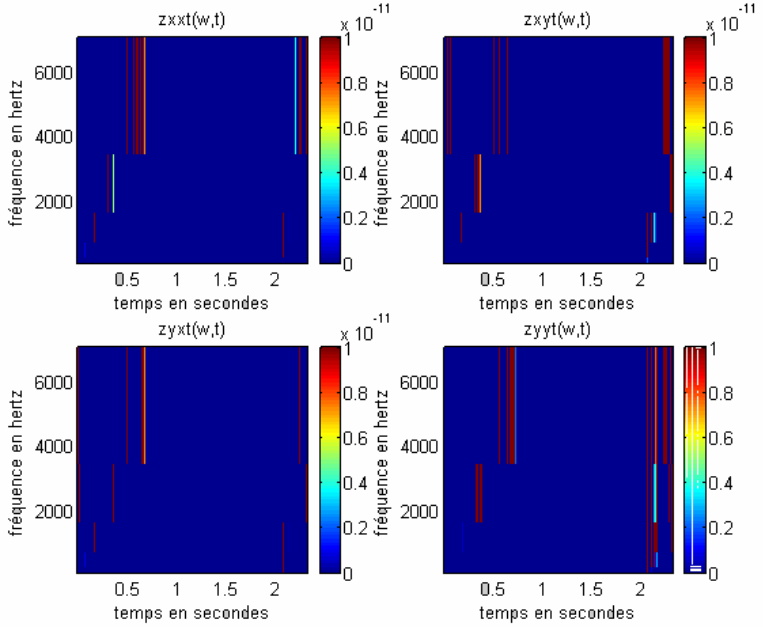
co-supervision of J. Klinger, MSc IPGS (2005)

MT Induction

$$\begin{vmatrix} E_x \\ E_y \end{vmatrix} = \begin{vmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{vmatrix} * \begin{vmatrix} H_x \\ H_y \end{vmatrix}$$

Fourier Spectrum of the Impedance $Z_{ij}(\omega)$ ⇨ **Conductivity Model in Depth**

Time-frequency decomposition $W[Z_{ij}](t,\omega)$ ⇨ **Conductivity in Depth & Time**



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Perspectives

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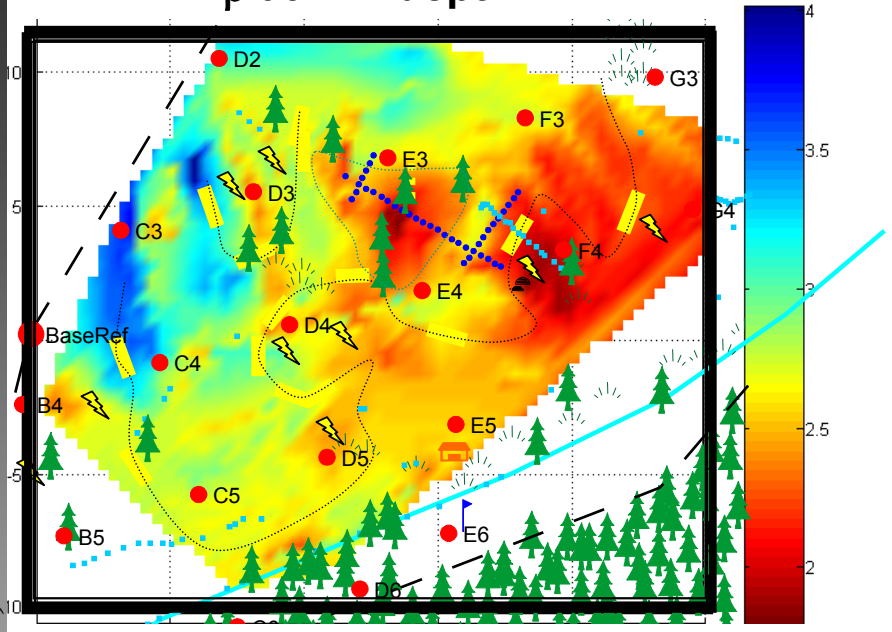
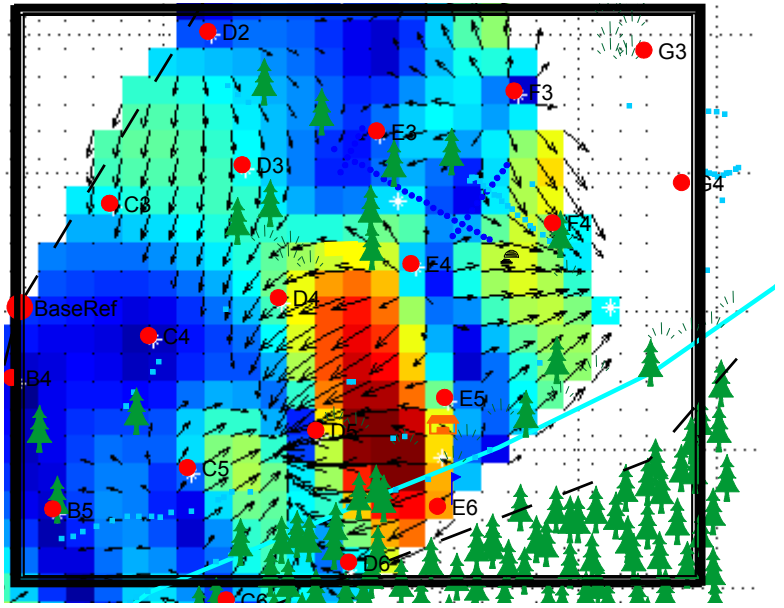
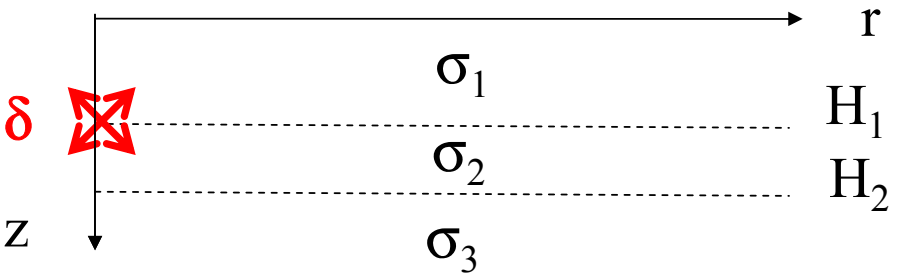
SP Modelling using Heterogeneous Green's functions

ρ at 2 m depth



SP gradient at 8 cm depth





Perspectives

And also…

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Inversion of magnetic data using multidimensional wavelet transforms

- **Invariants of tensor wavelet transform**
- **Curvelet transform**

SP monitoring:

- **Data reduction for MT induction**
- **Electric field induced by cloud activity**

…

Acknowledgements

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Merci à tous pour votre attention