UNIVERSITÉ DE STRASBOURG

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Amphi Rothé, 14h

Habilitation à diriger des recherches
Spécialité : Géophysique

Contribution à l'Hydro-Géophysique :
Développements et Applications de la Résonance Magnétique Protonique et des Méthodes Électromagnétiques

Jean-François GIRARD

Résumé

La présentation portera sur les deux principaux domaines de recherche dans lequel je me suis investi, depuis 2003, au BRGM, celui du développement de la prospection par Résonance Magnétique Protonique (RMP), et l'utilisation des méthodes Electro-Magnétique à Source Contrôlée (CSEM)

….

Jury

M. Alain TABBAGH	Professeur à l'Université Pierre et Marie Curie, Rapporteur.
M. Dominique GIBERT	Professeur à l'Institut de Physique du Globe de Paris, Rapporteur.
Mme. Laurence JOUNIAUX	Chargé de recherches à l'Institut de Physique du Globe de Strasbourg, Rapporteur.
M. Anatoly LEGTCHENKO	Directeur de recherches au Laboratoire d'études des Transferts en Hydrologie et Environnement, Examinateur.
M. Jacques HINDERER	Directeur de recherches à l'Institut de Physique du Globe de Strasbourg, Examinateur.

Géosciences pour une Terre durable
brgm

Plan

> ## Experience

- Professionnal experience
- Main projects
- Teaching experience

> ## Selection of achieved work

- MRS
- ERT
- CSEM

> ## Current and future research project

- Research project
- HDR

Work experience

2003…2010 **<u>Research Geophysicist at BRGM (Orléans) in Natural Risks Division</u>**

- In charge of the BRGM research program of **Magnetic Resonance Sounding** method applied to groundwater investigations,
- On-shore **CSEM** applied to CO2 geological storage monitoring (since 2006)
- **Electrical methods** applied to aquifers and brown field area (mining prospection arrays, induced polarization)
- **Project management**, on public and industrial funding

1999...2002 **<u>PhD at Strasbourg University</u>**

*« **Ground Penetrating Radar** modelling in dispersive media »* and applications of GPR to sedimentology (aelian sand dunes), active faults imaging, water content estimates, etc…

1996 & 1999 **<u>Engineer School at Ecole de Physique du Globe de Strasbourg</u>**

« Neural networks applied to **seismic** facies recognition» final diploma (10 months internship at **Elf Scientific centre Pau).**

1997 & 1998 **Research training** at Astronomic Observatory of Bordeaux
Celestial mechanics department (N non-ponctual bodies interactions issue)

Main research projects since 2002.

Hydro

REMAPRO (2006-2009), **coordinator** 275 k€, (500 k€), National Research Agency (ANR).
- *3D permeability mapping using PROtonic MAgnetic REsonance.*

Proton (2005 - 2007), **brgm project leader**, National Network on Innovative Technology (Riteau).
- *Improvement of accuracy and stabilty measurement in MRS.*

Waterscan (2005-2007), **brgm project leader**, Institut National des Sciences de l'Univers, (INSU).
- *Prospection et 4D hydrogeophysics modelling*

Flood1 (2005 - 2008), funded by UE via Interreg III program, **England**
- *Groundwater flooding event study,* monitoring of chalk vadoze zone

Cefipra – Inde (2003-2005), IFCPAR (Indo-French Centre for Promotion of Advanced Research), **India**
- *Geophysical characterisation of weathered granite aquifer within the Hyderabad region*

Hygeia (2001-2004), funded by UE in FP5 program, **Italy, Holland**
- *HYbrid Geophysical technology for the Evaluation of Insidious contaminated Areas* (electrical methods and field application of spectral induced polarization).

CO2

CO2FieldLab (2009-2013), **coordinator of french side** **1.5 M€ (11 M€),** EUREKA european project,
- *CO2 Field Laboratory for Monitoring & Safety Assessment.* **Norway**

EMSAP CO2 (2008 - 2010), National Research Agency (ANR),
- *Electromagnetic and active and passive seismic applied to CO2 storage monitoring*

CO2ReMoVe (2006 - 2012), funded by UE in FP6 program, **Germany, Norway**
- *CSEM applied CO2 storage monitoring,* link with CO2SINK on-shore pilot test in Ketzin.

Collaborations

- **Industrial** : Schlumberger (Carbone and Water services) , CGGV, Danone, Iris-intruments
- **Academic and public organization:**
  - France : IRD, Univ. Grenoble, Strasbourg, Paris, Pau, IFP, …
  - Abroad : SINTEF, NGI, BGS, TNO, GFZ, Univ. Brighton, Roma, Berlin, …

Teaching experience

BRGM

2003…2009 **Student supervisor at BRGM**

➢**PhD**

M. Boucher, 2007, « Using MRS and other geophysical methods for aquifer hydraulic properties estimation in various geological contexts », co-dir. A. Legchenko, LTHE - Grenoble)

➢**Internships** (3 Master thesis, 3 engineer school)

2005…2009 **Annual lessons at EOST Strasbourg**

Master level, MRS in Hydrogeophysics

In-service training coordinator

« Geophysical methods awareness program» (3 days, formation.brgm.fr)

PhD

2002-2003 **Temporary attached teacher and research (ATER),** 6 months

Founder of the SUGS – French student section of the SEG

1999...2002 **Teaching during PhD (Monitorat)** at EOST

seismics in licence and master 1 level (**64 h TD / year**).

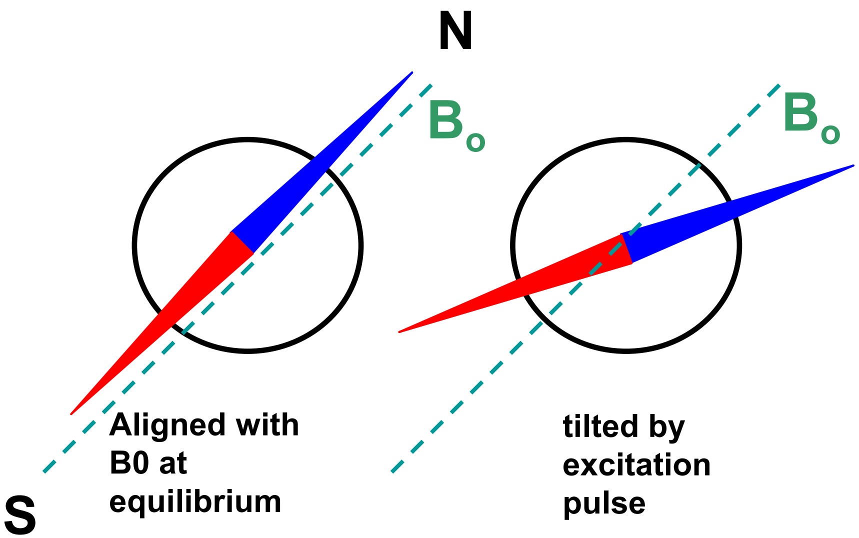
field training at EPGS.

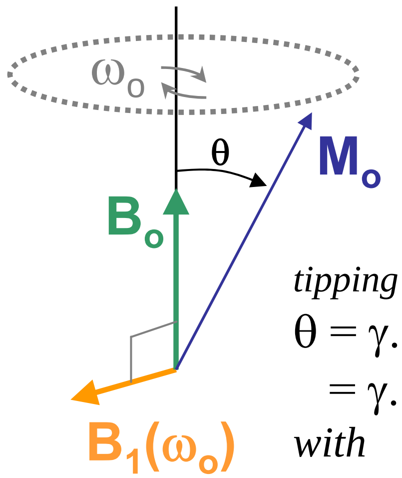
1999...2002 **Continuous training to teaching** (CIES, during 3 years, 10 days/y).

Basics of Nuclear Magnetic Resonance

Spin Magnetic Moment of the water molecules protons

Come back to equilibrium through a precession movement > generate the resonance signal





tipping angle

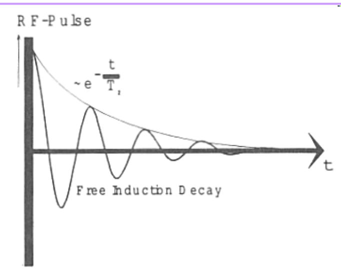
$$\theta = \gamma . \left| \mathbf{B}^{+}_{1} \right| .t$$
$$= \gamma . \left| b^{+}_{1} \right| .Q$$

with

$$Q = I.t \text{ (A.ms)}$$

Larmor Freq. → $\omega_0 = \gamma \, |B_0|$ ← Geomag. induction

($\gamma \approx 0.2675$ rad/s/nT)



Basics of Nuclear Magnetic Resonance

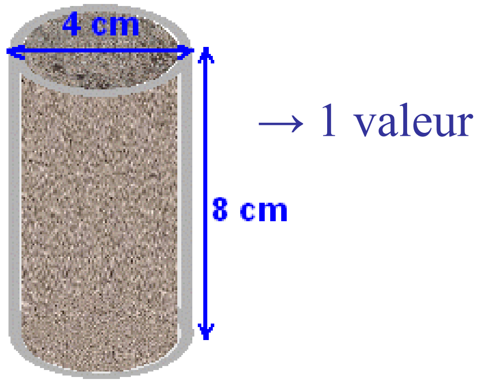
Geophysics (SNMR/MRS)

hectometric

Earth magnetic field
(47 µT)

NMR Spectrometer

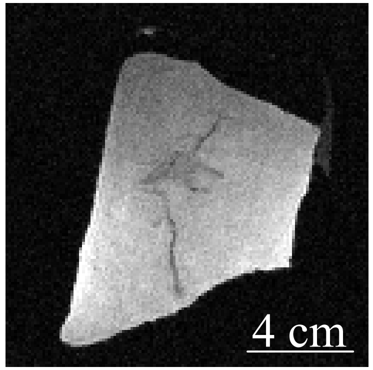
centimetric



Artificial magnetic
field (47 mT)

MRI

millimetric



Artificial magnetic
field (200 mT)

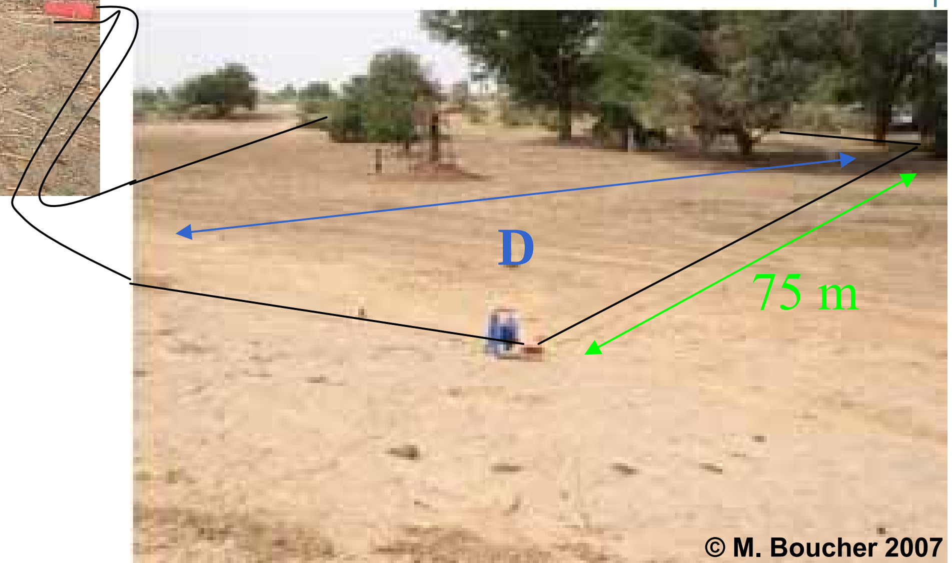
Various equipment, various scales, same physics…

But the static magnetic field B_0 is not the same !

Magnetic Resonance - field set-up

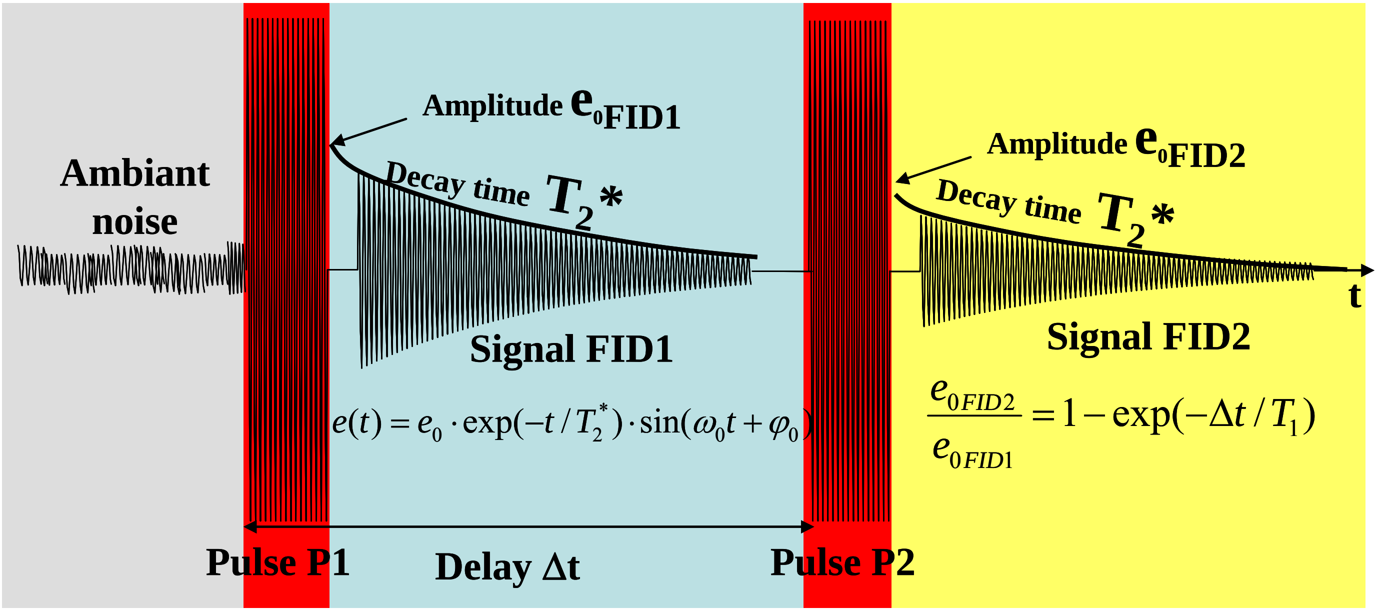
Investigation depth ≈ D

Maximum investigation ≈ 100-150 m



- **Powered by car batteries**
- **Laptop controlled**
- **Wire loop (20 to 150 m side)**
- **Coincident Loop or separated TX-RX loops**

Magnetic Resonance - standard sequence and signal



Amplitude e_0 → Water content

Decay time T2* → Pore size + magnetic heterogeneities

Ratio e1/e2 → Longitudinal relaxation / T1 → Pore size

Pulse intensity Q(A.ms) → Investigation depth

Magnetic Resonance « Sounding » - coincident loop

1D Kernel

water content at depth z

$$e_0(q) = \int_0^{Z\,max} K(q,z)w(z)dz$$

$$K(q,z) = \omega_0 M_0 \int_{x,y} h_{1\perp} \sin\left(\frac{1}{2}\gamma . h_{1\perp} . q\right) dx.dy$$

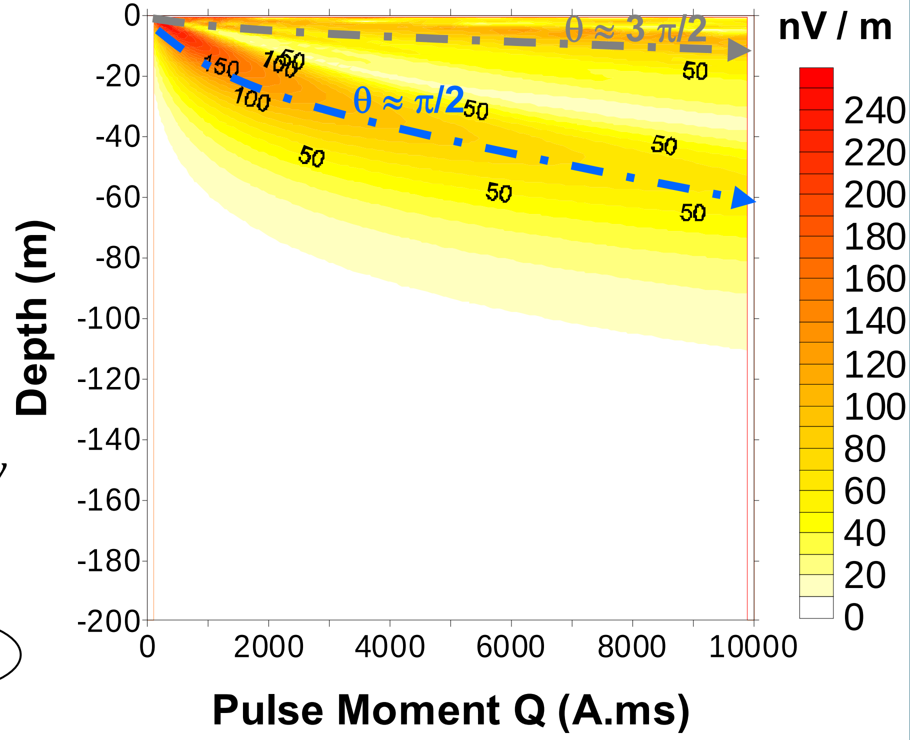
Larmor Freq.

Nuclear Magnetization

Exciting field

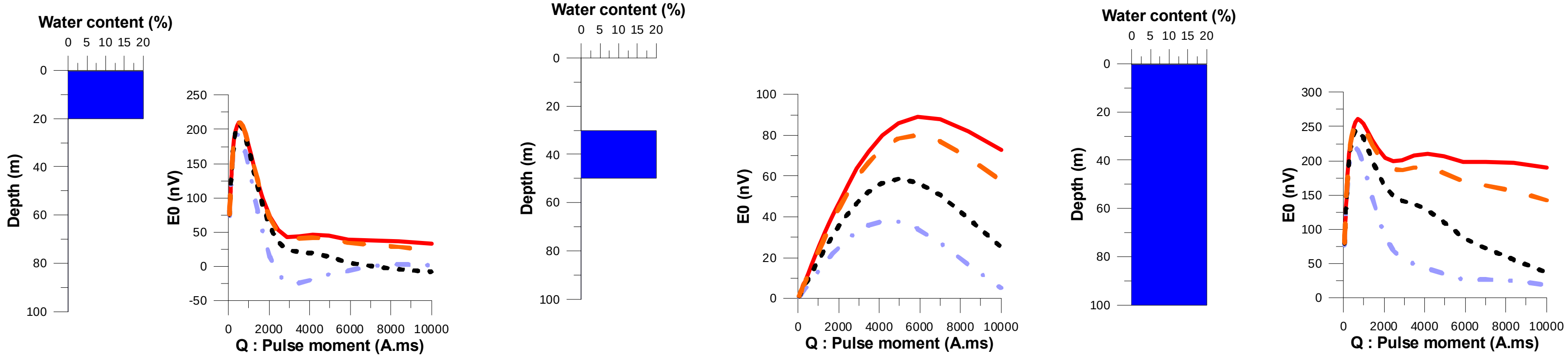
Tilt angle θ

Larmor frequency F_L=2kHz,
Geomagnetic Inclination = 60°
Square loop 75 m

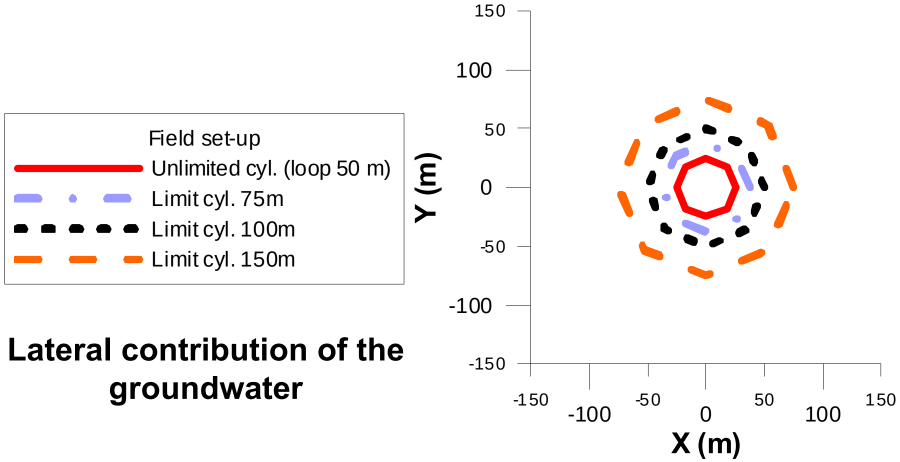


Intrinsic sounding behaviour of MRS based on B_1 gradient… (MRI based on B_0 gradient)

Magnetic Resonance « Sounding » - coincident loop



Samples of MRS amplitude response for a circular 50 m diameter loop, for a shallow, medium and thick aquifer



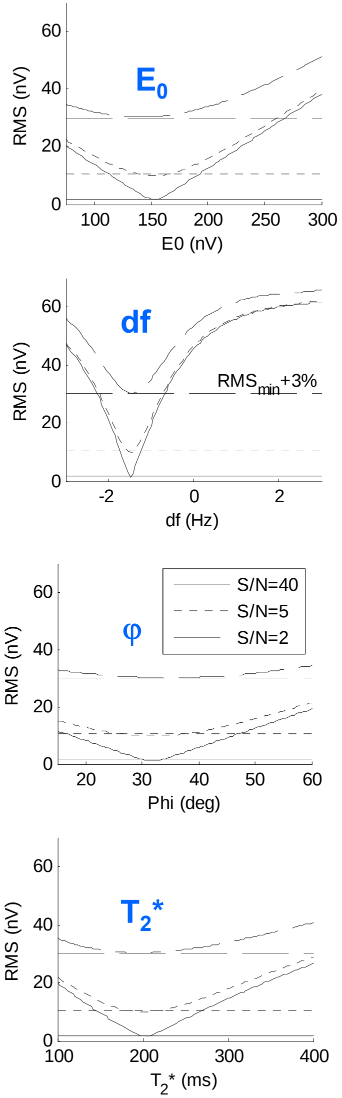
Lateral contribution of the groundwater

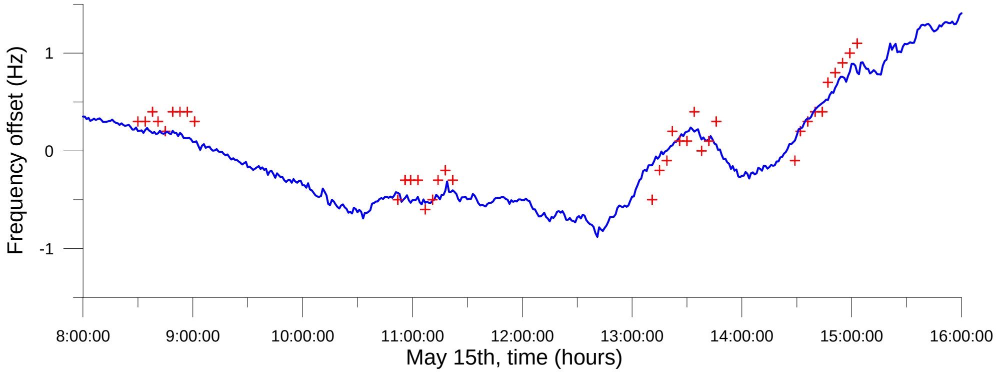
Investigated volume… generally approximated by a cube 1.5 D x 1.5 D x 1.5 D

… But looks more like a cone !

Magnetic Resonance – accuracy & signal stability

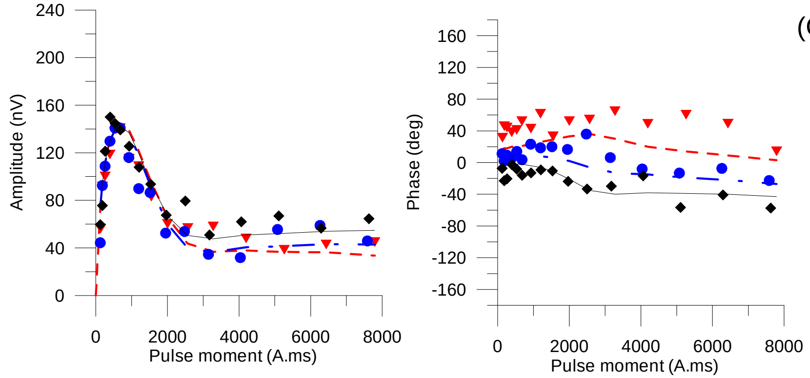
$$E(t) = E_0 \cdot \exp\left(-\frac{t}{T_2^*}\right) \cdot \cos(2\pi f \cdot t + \varphi)$$





Diurn variation of Larmor frequency calculated from magnetic measurement (Chambon-la-foret observatory) and from MRS data (crosses).

(Girard et al., 2005)



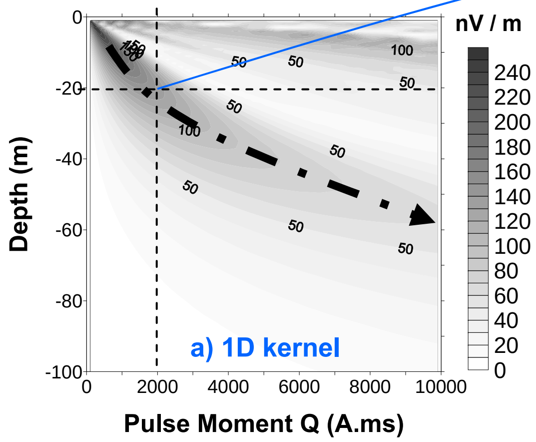
(-1.7 Hz triangles, -0.7 Hz circles, +0.7 Hz squares)

MRS signal measured the same day (Orleans)

> Amplitude of the shallow aquifer response almost unchanged

> Phase is strongly affected by the frequency shift

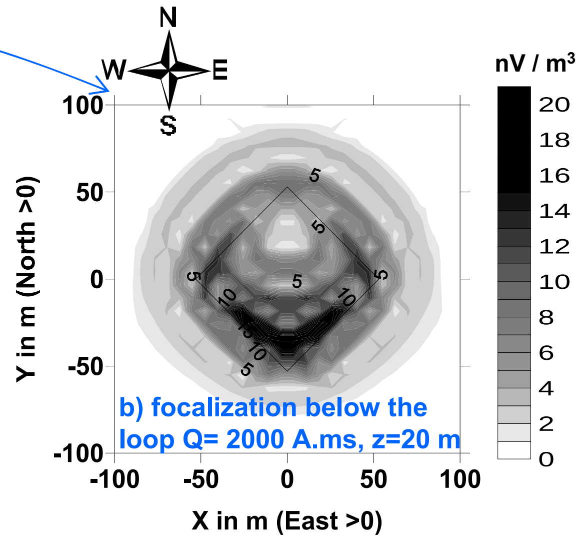
Magnetic Resonance - focalization and topography



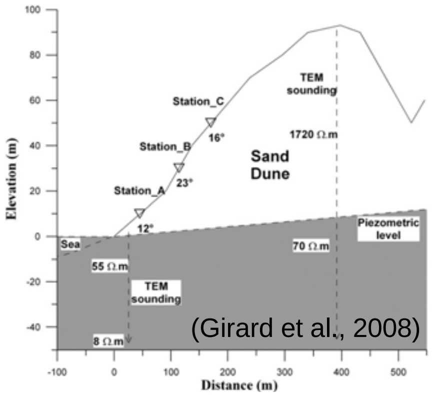
(Girard et al., 2007)

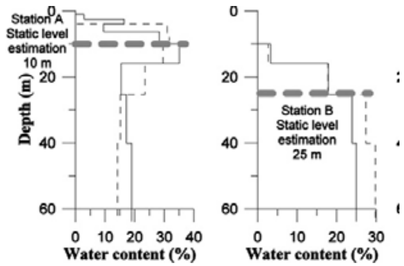
Square loop 75m
60° geomagnetic inclination

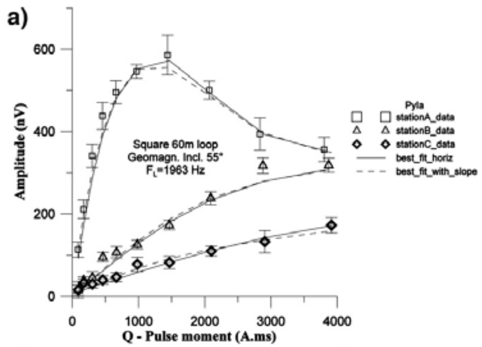
MRS is sensitive to local geomagnetic intensity but also to inclination (complex pattern below the loop)



Impact of topography on MRS coincident loop (99% of MRS field data), Pyla sand dune case

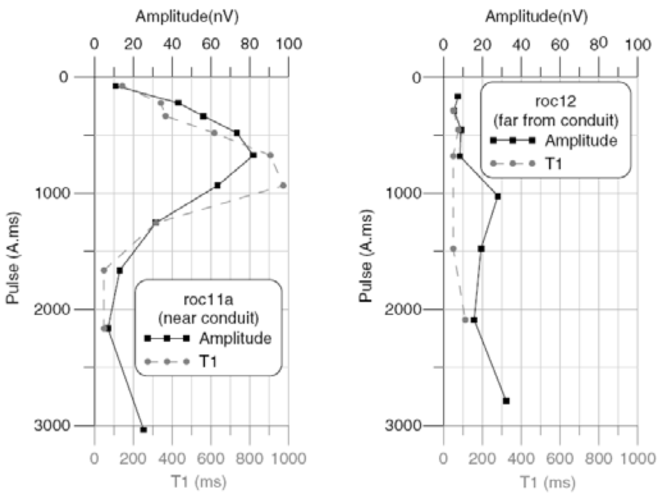




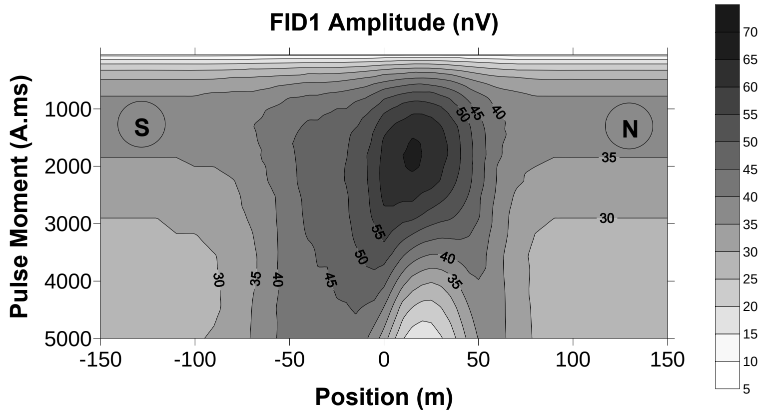


1D MRS is very robust (until 30° slope, undetectable impact on 1D inversion)
Separate loop meas. are affected through a goemetric coupling coefficient

Magnetic Resonance - over a 2D conduit

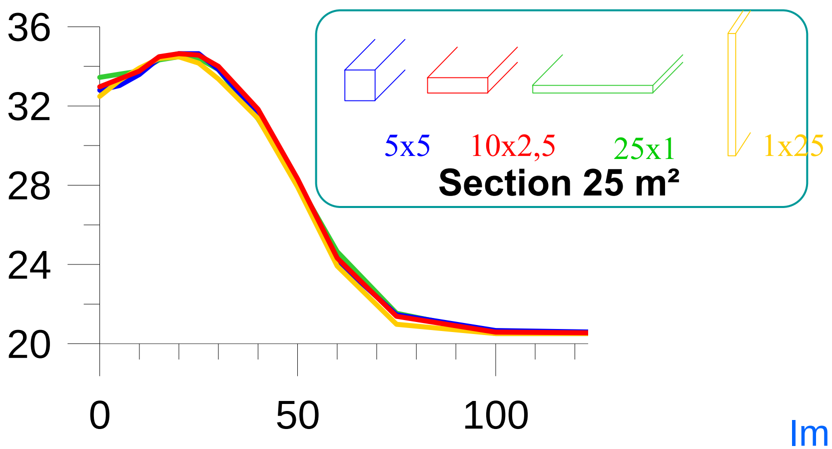


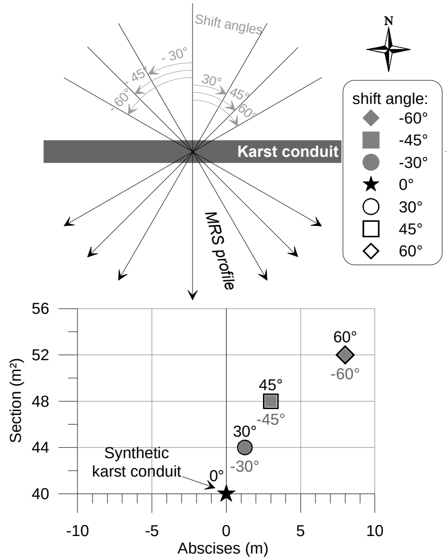
MRS signature of a water filled cavity (left) and limestone (right).



South to North profile (75m square loop) above a 2.5 x 10 m at 27.5 m depth

(Girard, Boucher et al., 2007, J. of Applied Geophysics).

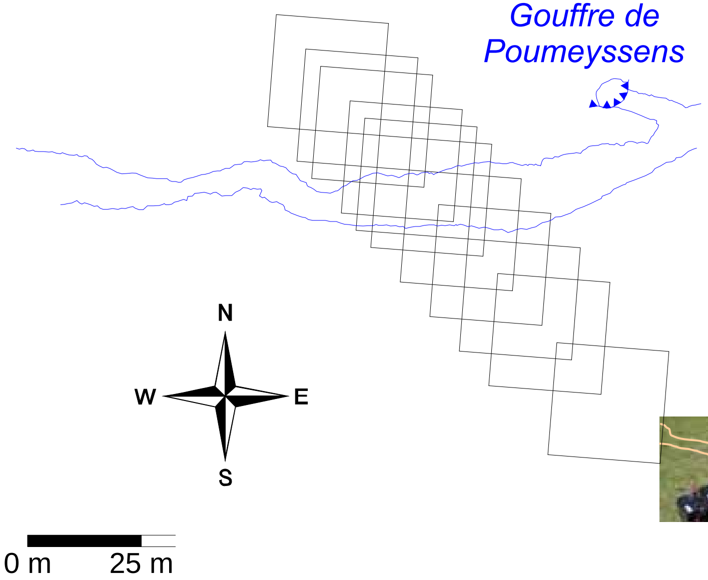


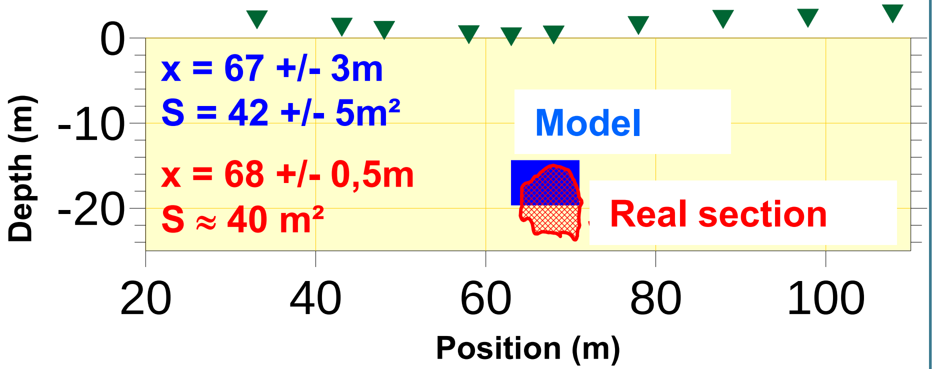


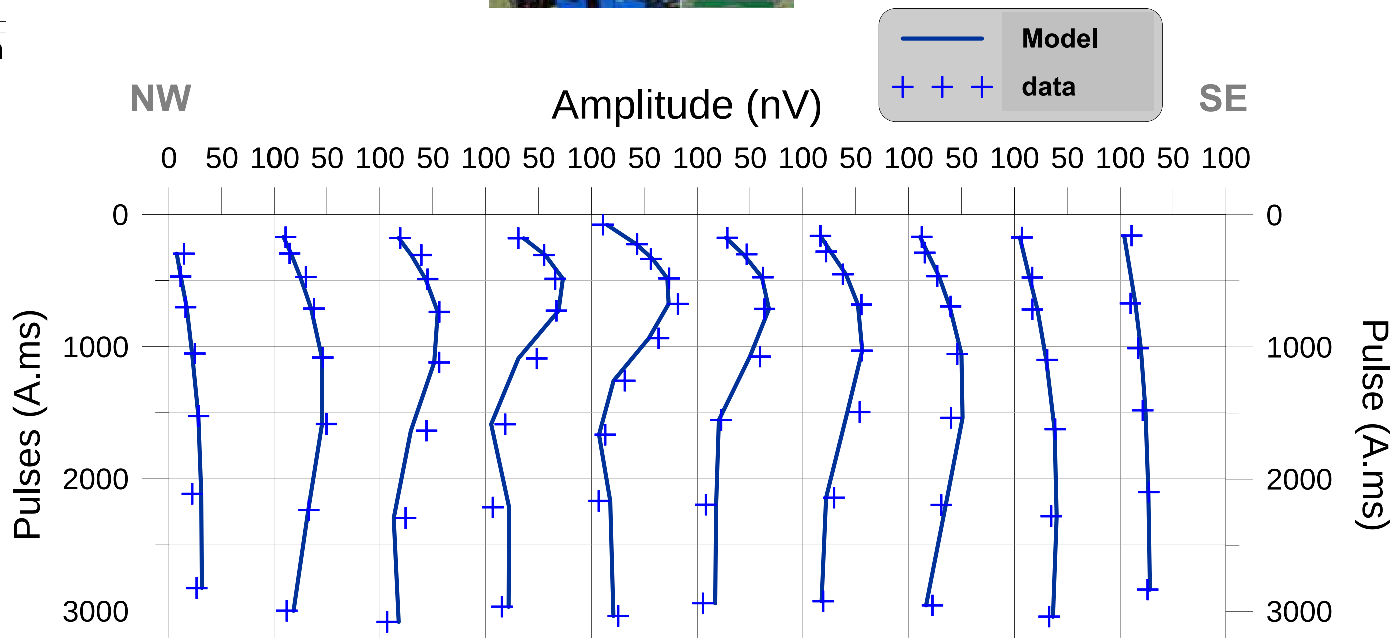
deviation from 0 to 60° for a W-E conduit

Impact of error in the 2D assumtion on inversion result

Magnetic Resonance - Rocamadour



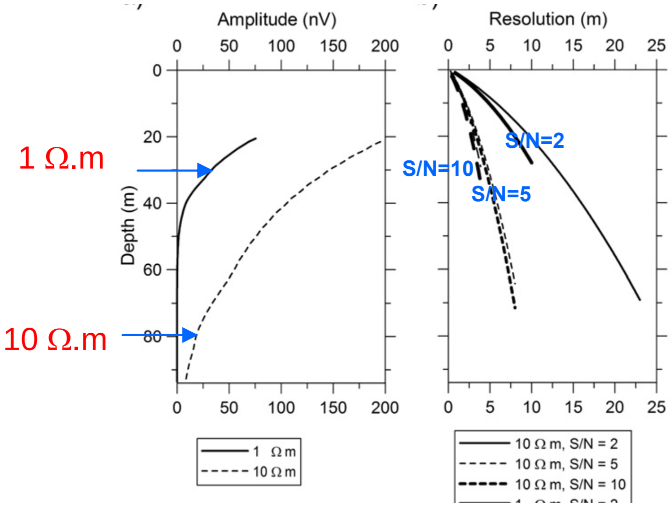




(Boucher, Girard et al., 2006, J. of Hydrology)

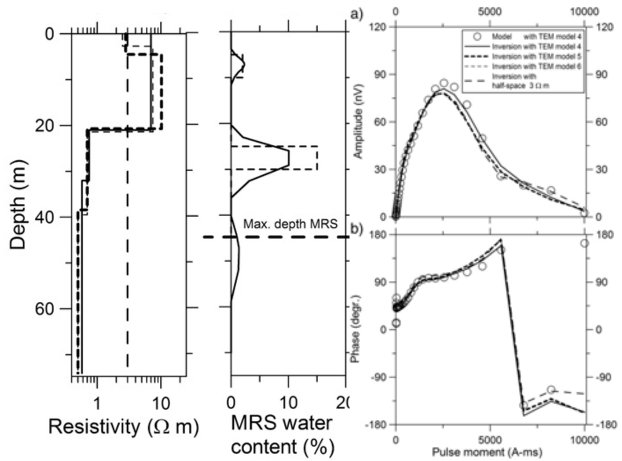
Magnetic Resonance - in highly conductive media

Improvement of the standard model by including elliptical polarization of magnetic field in MRS equations



For a 25 nV threshold, instrumental noise ~ 5 nV

- max. depth 80 m (10 Ω.m)
- decreases to 30 m for a 1 Ω.m half-space



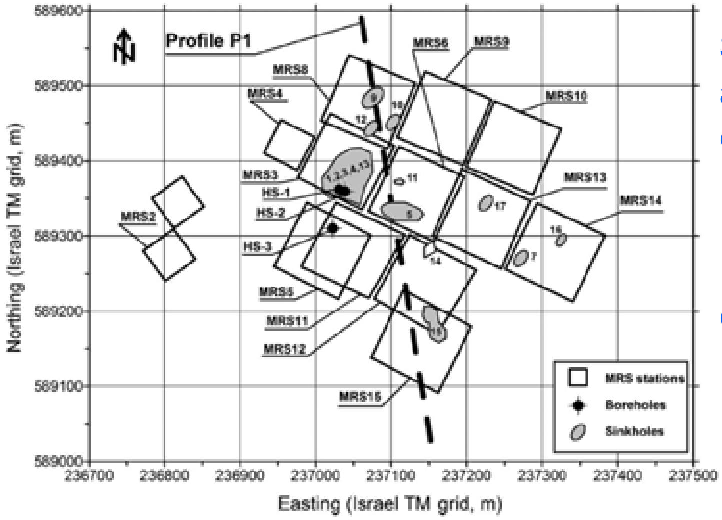
Here, uncertainty in the resistivity model due to TEM inversion does not affect MRS result.

Note that an increase in S/N from 5 to 10 has almost no effect on inversion (water content 1D distribution).

⇒ intrinsic resolution limit of the method

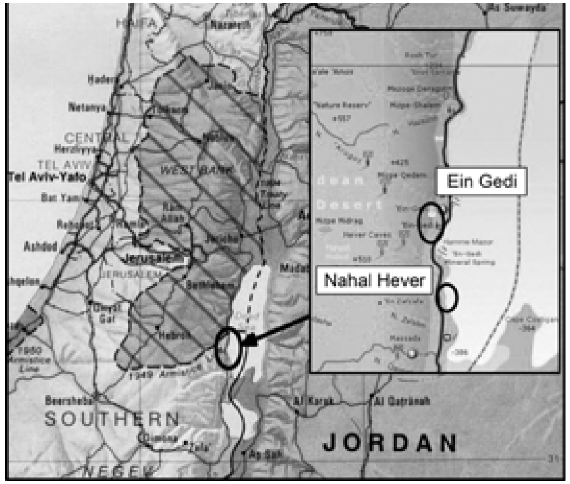
(Legchenko, Ezersky, Girard, JAG 2008)

Magnetic Resonance - in highly conductive environment

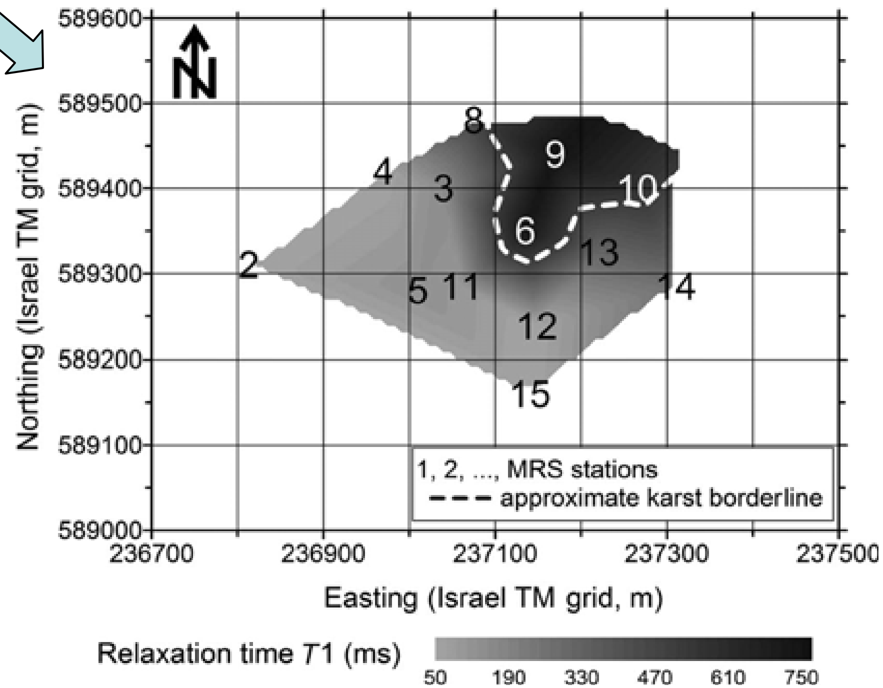


Location of MRS stations, boreholes, and visible sinkholes

Sinkhokes formation along the Dead sea coast



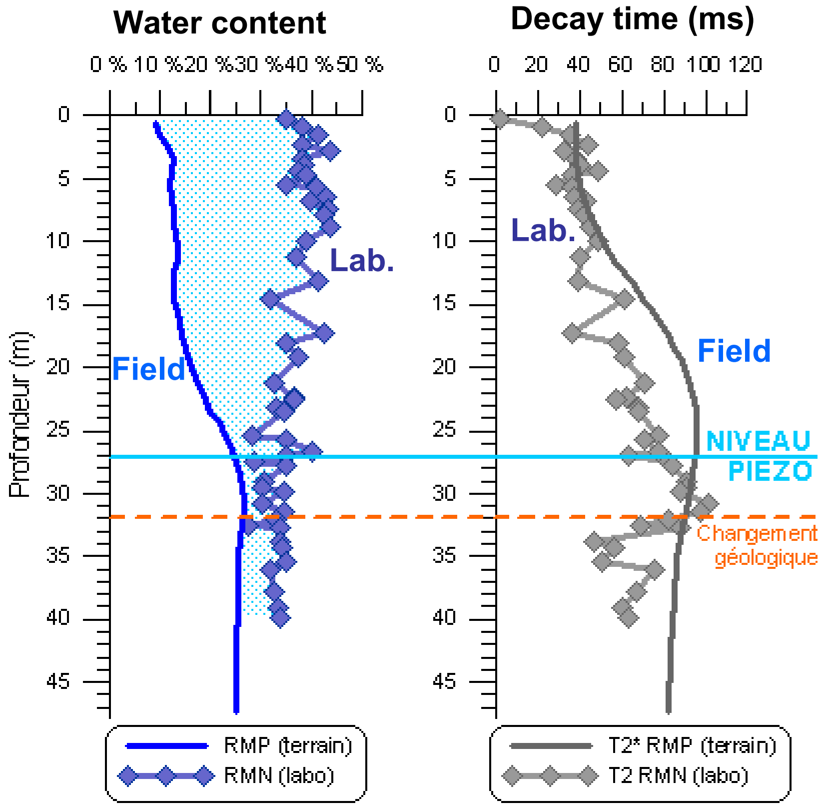
Due to salt layer dissolution



Apparent T1 decay time used as an index of cavern collapse

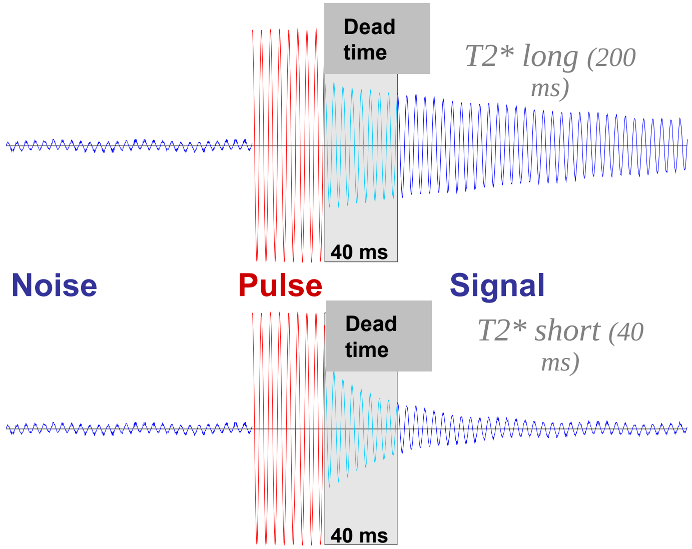
(Legchenko et al., Geophysics 2008)
NATO science for Peace program

Magnetic Resonance - application in chalk vadoze zone



MRS in chalk always depicts a continuous increase in water content and decay time

Maximum observed in the saturated zone



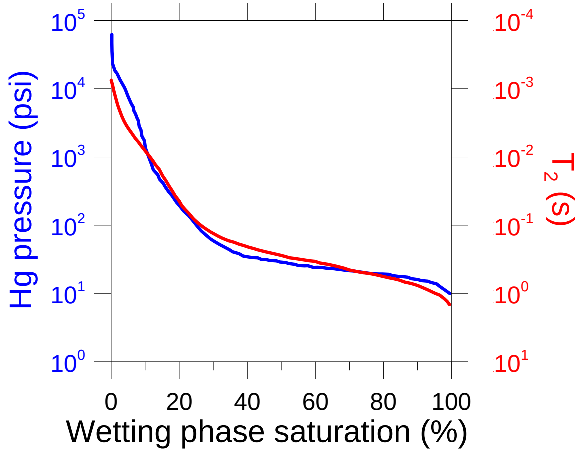
- Apparent variation of MRS water content due to effect of instrumental dead time when varying the decay time

- Variation on decay time confirmed by lab measurement

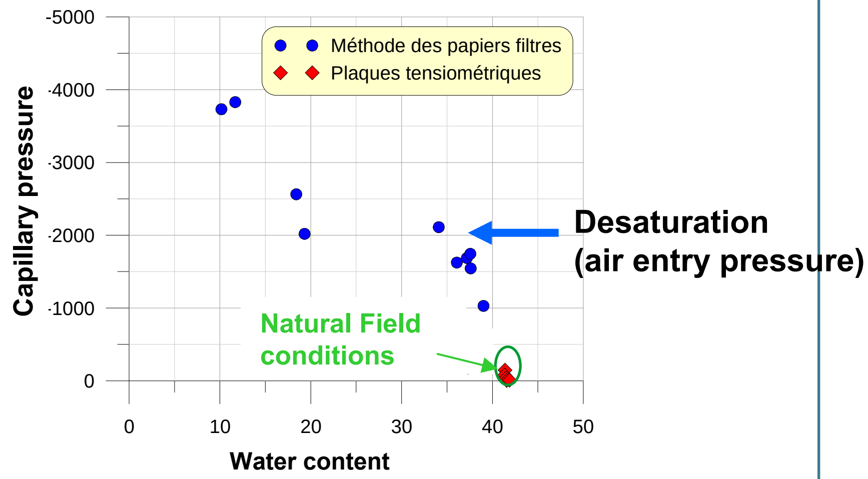
Flood1 project

How to interpret decay time log ?
Is the decay time a useful tool for monitoring the unsaturated zone ?

Magnetic Resonance - application in chalk vadoze zone



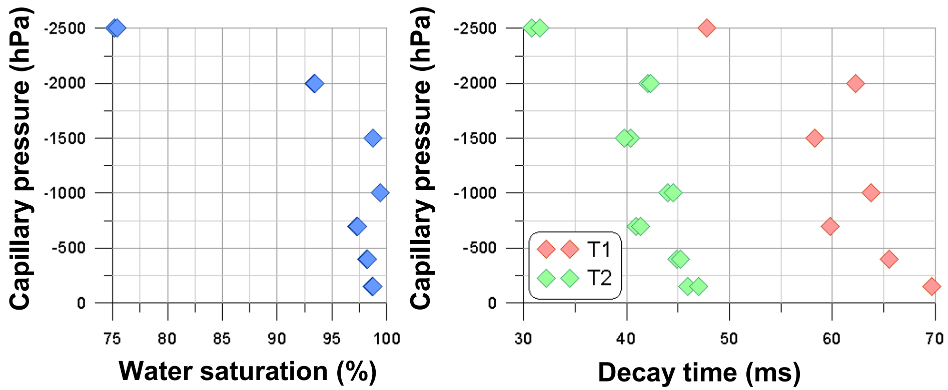
Hg porosimetry **in sandstone**
relationship to decay time
(Kleinberg 1996)



Retention curve **in chalk**
(flood1 - ANTEA)

Is there a decay time / capillary pressure relationship in chalk, as observed in sandstone ? Yes

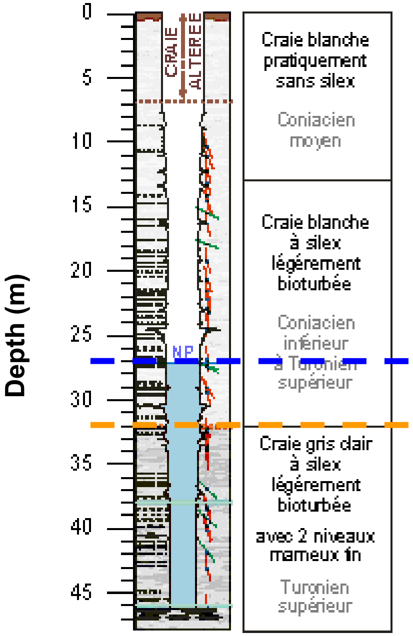
Does this relationship shows detectable variations in the range of natural site ? No



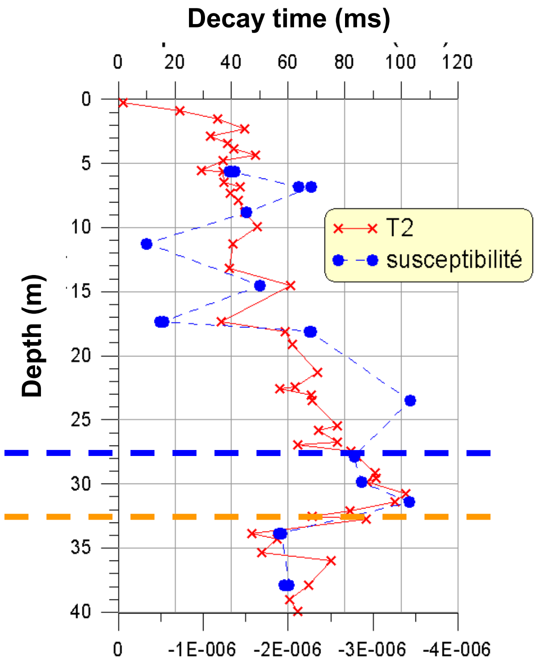
Water saturation and decay time variation with capillary pressure in chalk

Flood1 project

Magnetic Resonance - application in chalk vadoze zone



Geological log at Warloy-Baillon monitoring site



Magnetic susceptibility and decay time T2 on coring

What generates the decay time variation inside the chalk ?

Desaturation ? No.

Pore size variations ? No

…

Despite the very low magnetic properties of chalk,
correlation with magnetic susceptibility is striking !

MRS as a non-invasive tool to measure magnetic susceptibility in chalk !

(magn. susceptibility is a climatic marker of deposit conditions in chalk)

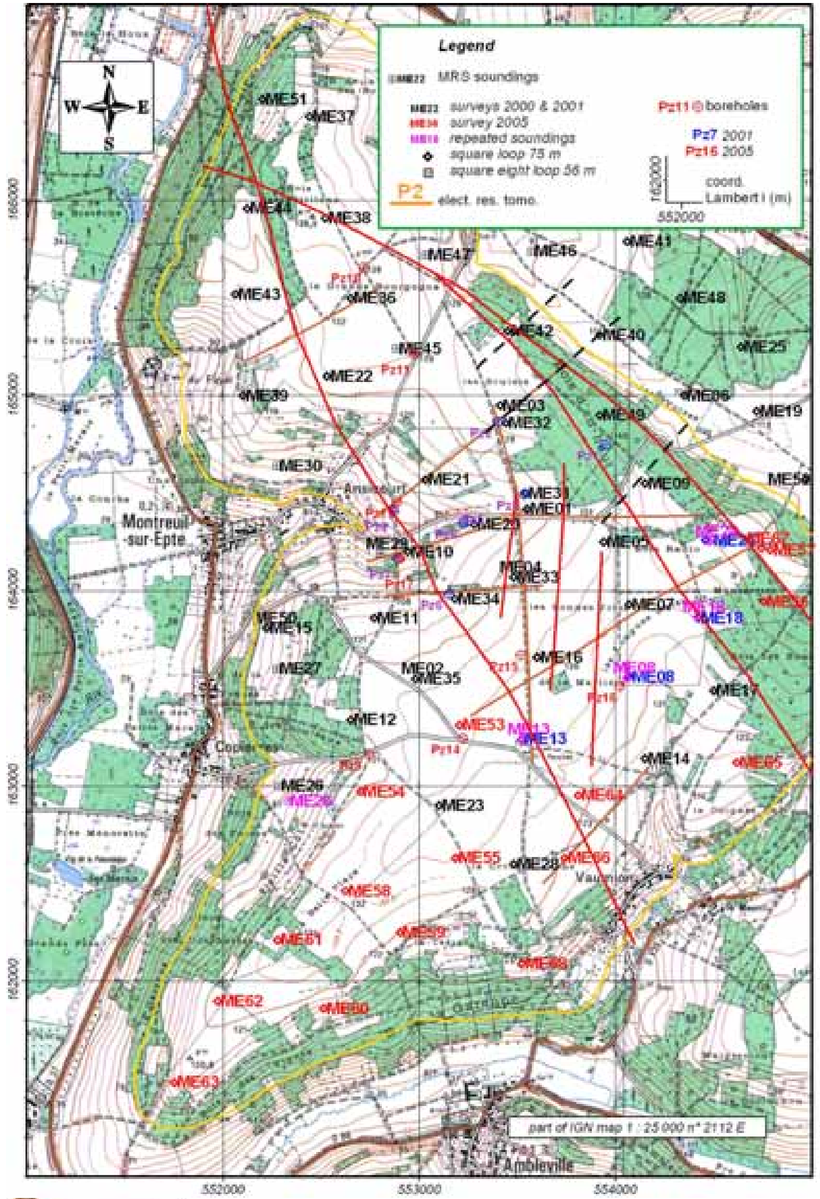
Flood1 project

MRS and ERT - basin scale hydrodynamic study

Position map of the geophysical measurements on the Brévilles spring catchment

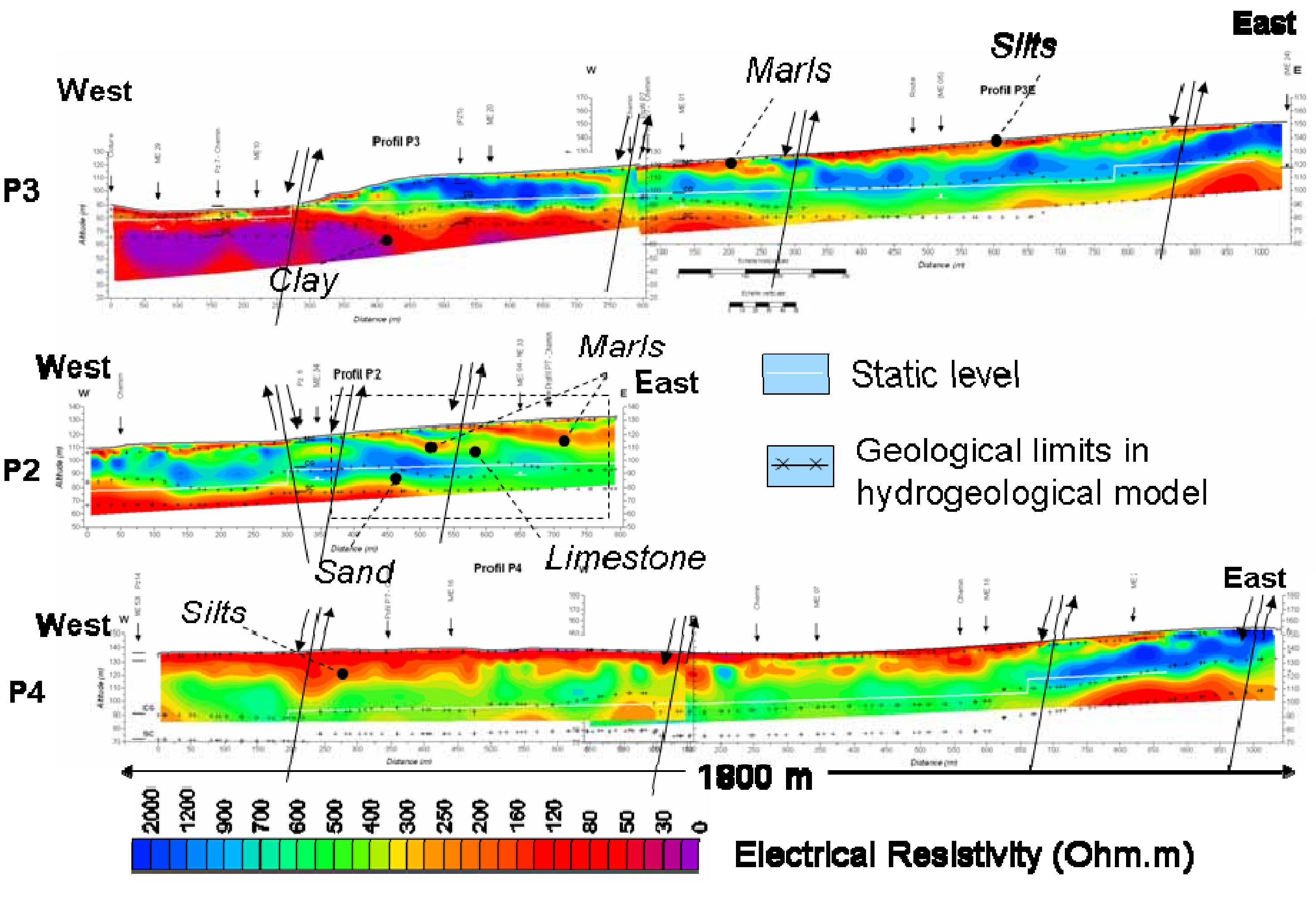
- 4 km x 6 km,
- the main faults (red)
- outcrop of the cuisian sand (yellow) surrounding the basin.

> Main targeted aquifer : cuisian sand aquifer



Aquaterra project

MRS and ERT - basin scale hydrodynamic study

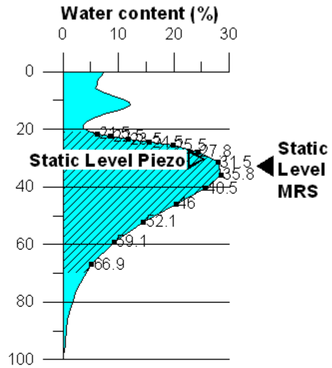


Metric shallow marls layers clearly imaged > vertical displacement used for structural interpretation

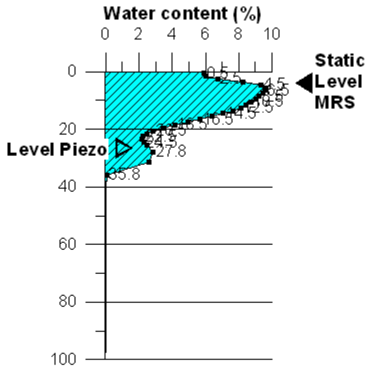
Very good correlation with geology, but no detection of aquifer

Aquaterra project

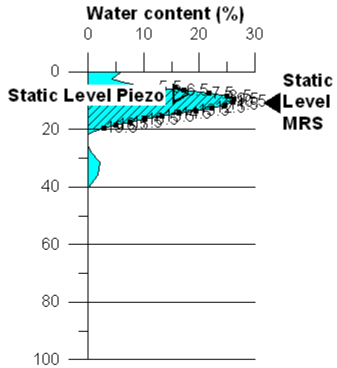
MRS and ERT - basin scale hydrodynamic study



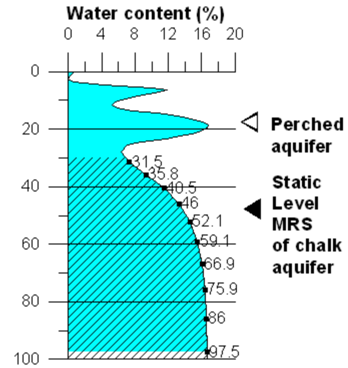
MRS name : ME31
Borehole name : Pz3
Static level MRS : 31.5 m
Static level Piezo: 31.8 m
Borehole transmissivity : $3.0e^{-4}$ m^2/s
MRS transmissivity : $4.0e^{-3}$ m^2/s



MRS name : ME49
Borehole name : Pz1
Static level MRS : 6.5 m
Static level Piezo: 37.7 m
Borehole transmissivity : m^2/s
MRS transmissivity : $5e^{-4}$ m^2/s



MRS name : ME10
Borehole name : Pz7-17
Static level MRS : 9.5 m
Static level Piezo: 7.7 m
Borehole transmissivity : m^2/s
MRS transmissivity : $4e^{-4}$ m^2/s



MRS name : ME48
Borehole name :
Static level MRS : 50 m
Static level Piezo: m
Borehole transmissivity : m^2/s
MRS transmissivity : m^2/s

25m ***saturated sand***

Desaturated sand *(dry borehole + near fault)*

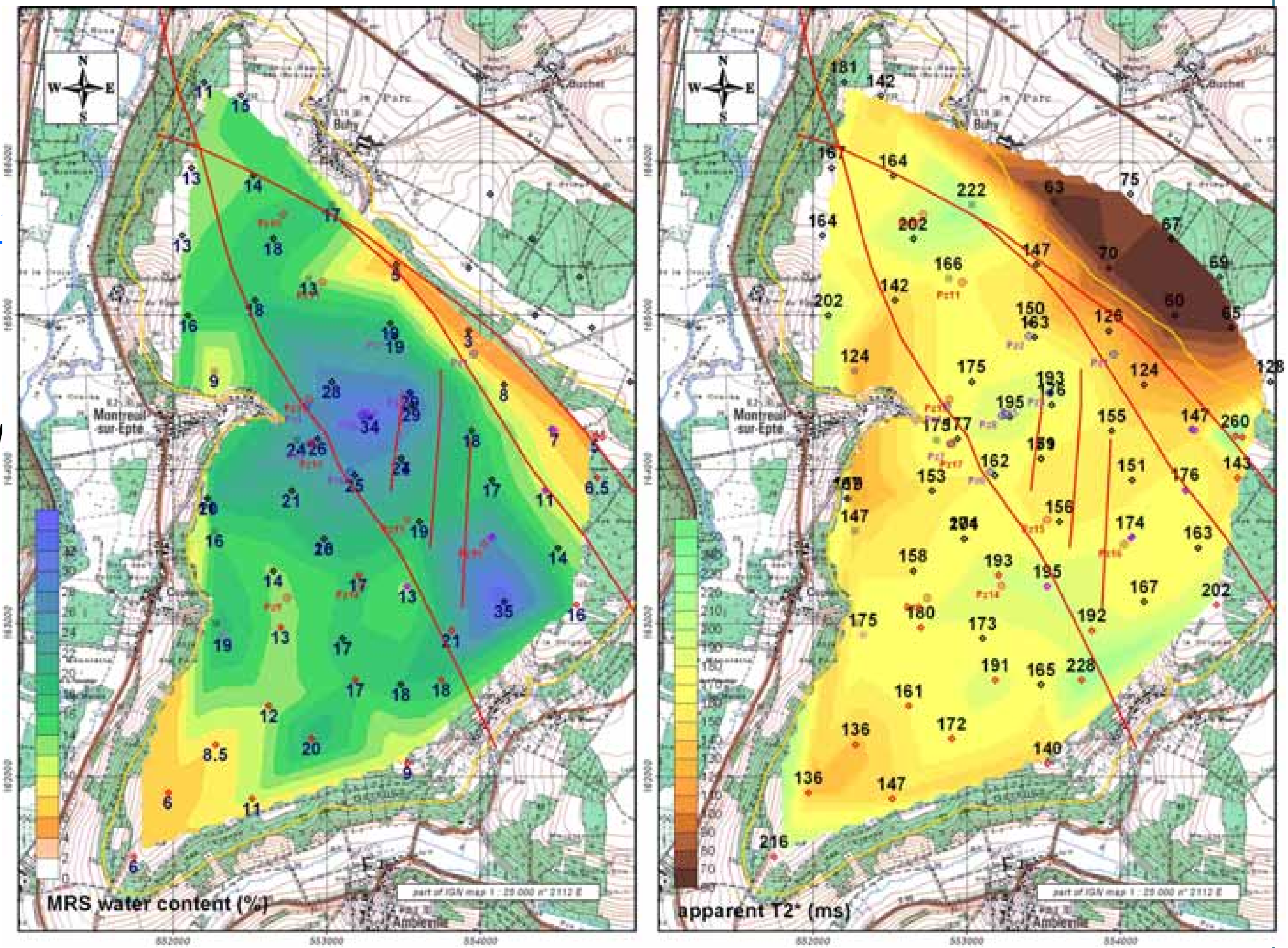
Shallow aquifer *in W part, saturated zone (<10 m)*

Thick **chalk** zone

Aquaterra project

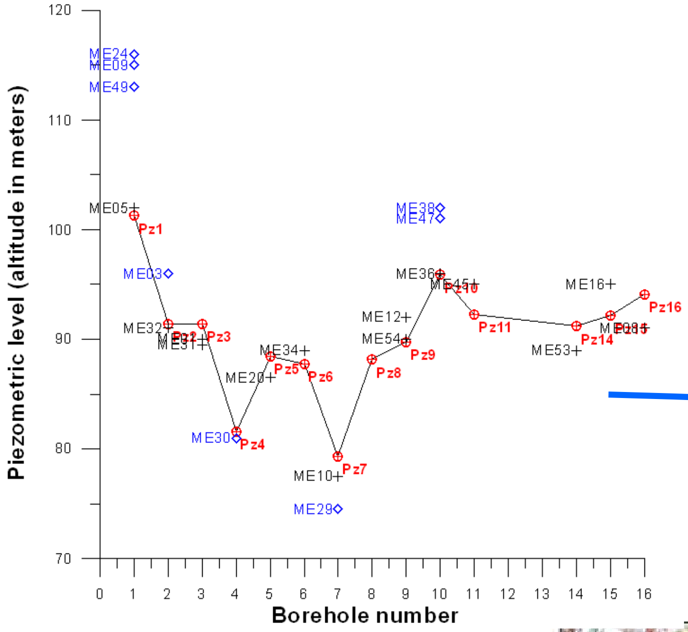
MRS and ERT - basin scale hydrodynamic study

- > Mean water content and T2 mapping
- > Domains delimited
  - *Desaturated zones*
  - *Saturated zones*
  - *Eastern zone with chalk*



Aquaterra project **MRS water content** **Apparent T2* (ms)**

MRS and ERT - basin scale hydrodynamic study



MRS accuracy enhanced via local calibration (left)

MRS used to extrapolate piezometric map outside the borehole network
⇒ provide an initial state for the basin hydrodynamic modelling

Water level map from MRS

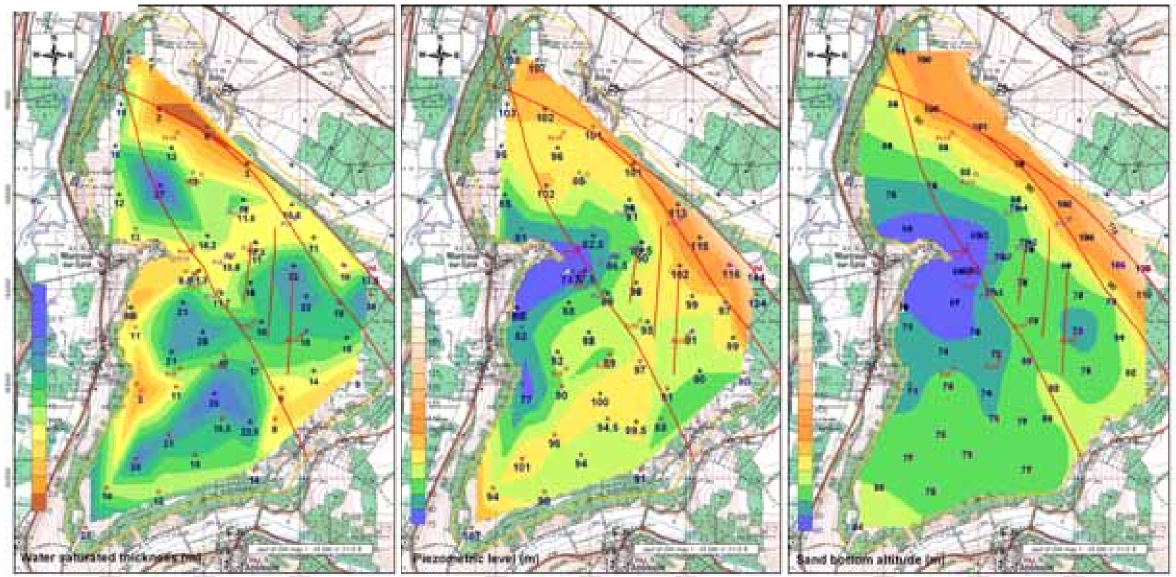
Zpiezo

Aquifer bottom from outcrop

Z_{bottom}

Thickness of saturated aquifer from MRS and geology

$$T_{saturated} = Z_{piezo} - Z_{bottom}$$

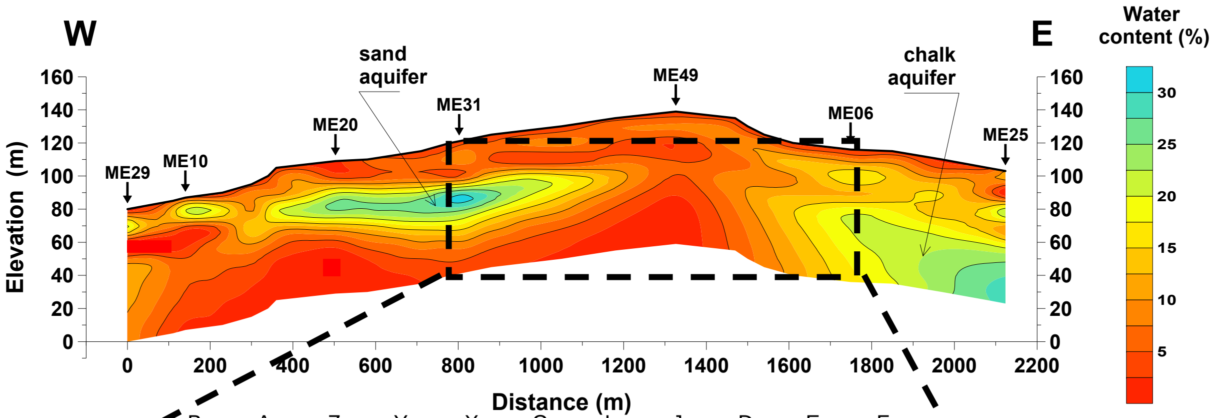


Aquaterra project

MRT and ERT - basin scale hydrodynamic study

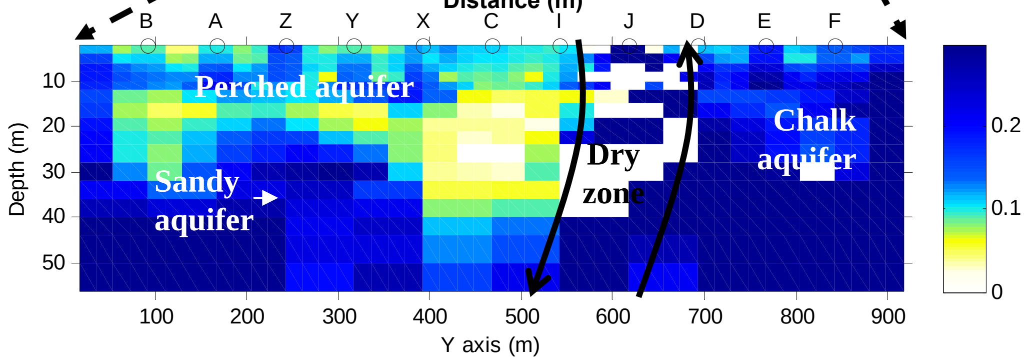
East-west MRS water content

Interpolation of 1D results derived from 7 soundings (2 km)



Aquaterra project

2D MR tomography using 11 side to side 75 m square loops

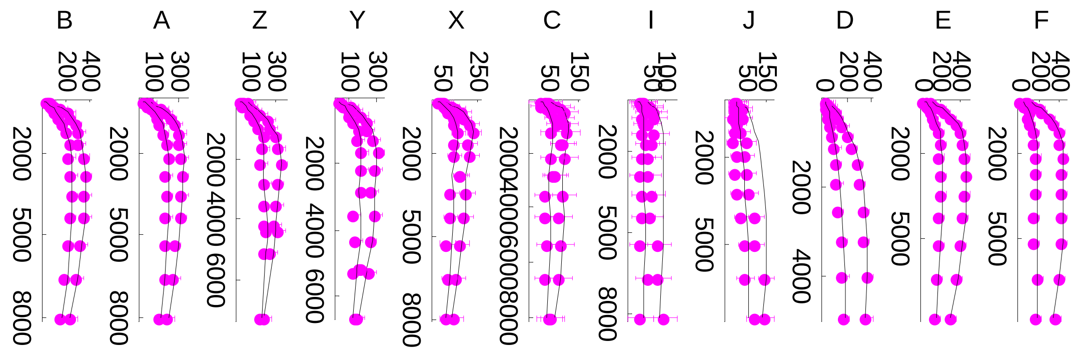


Water content

ReMaPro project

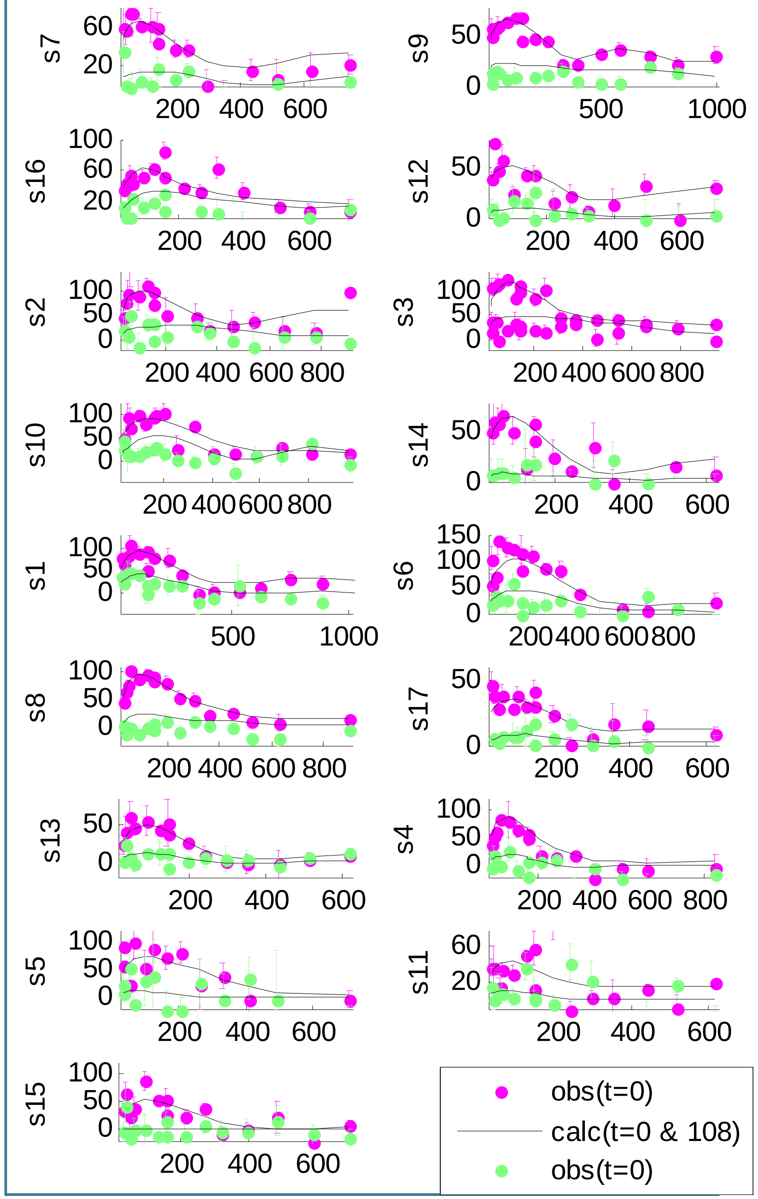
> Eastern limit of the basin delimited

> Image Heterogeneity in the shallow limestone

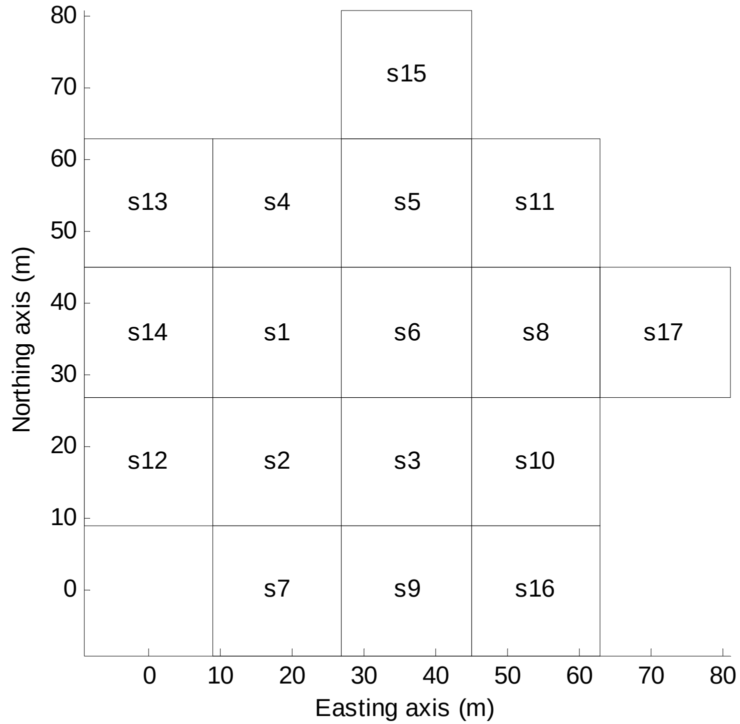


Data fit

MRS become MRT (ex. 3D peat bog experiment)

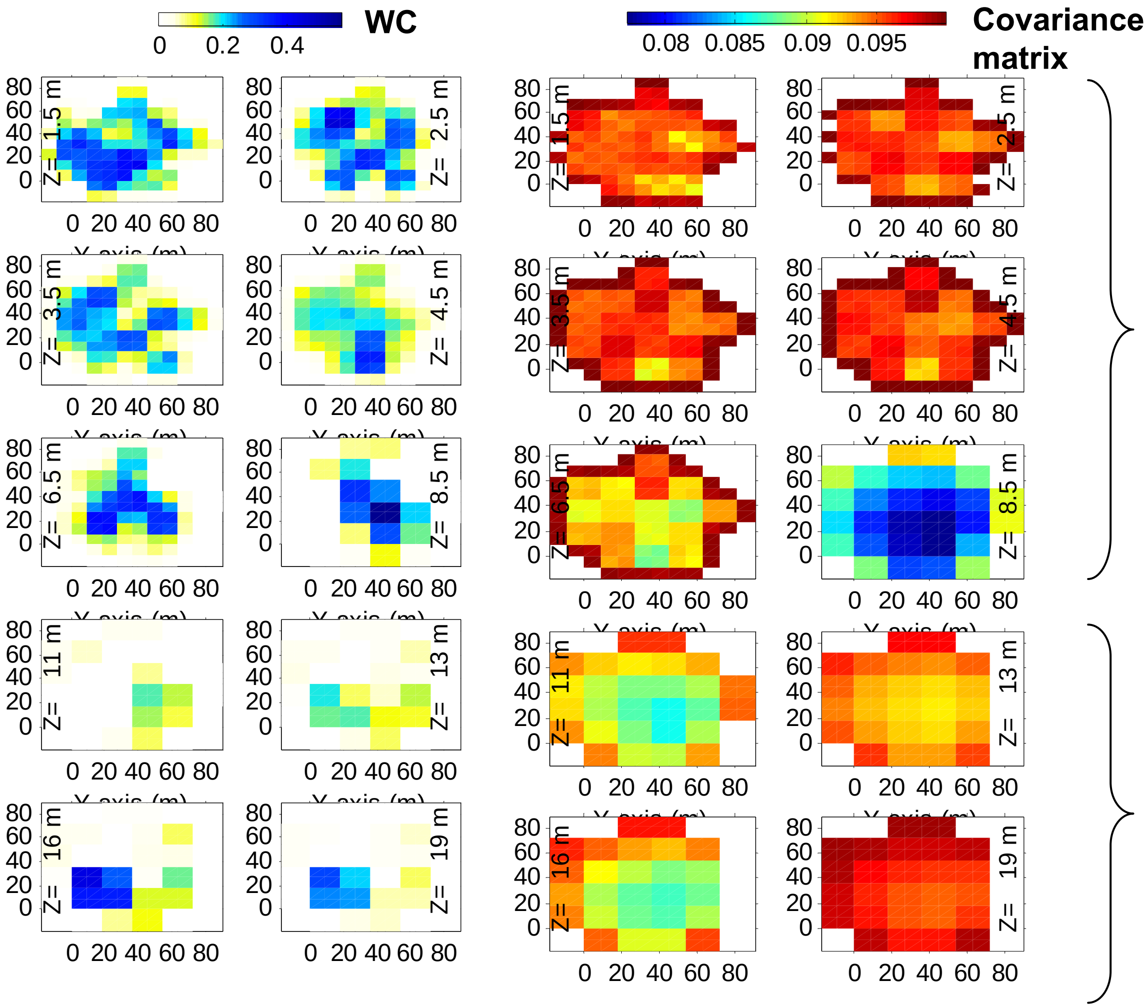


80 m x 80 m experimental zone
(using 19 m square loops)



Low SN ⇒ use FID1 only ⇒ WC

MRS become MRT (ex. 3D peat bog experiment)



➢High water content

1 m thick blocks

« 4 cells per loops »

➢low water content

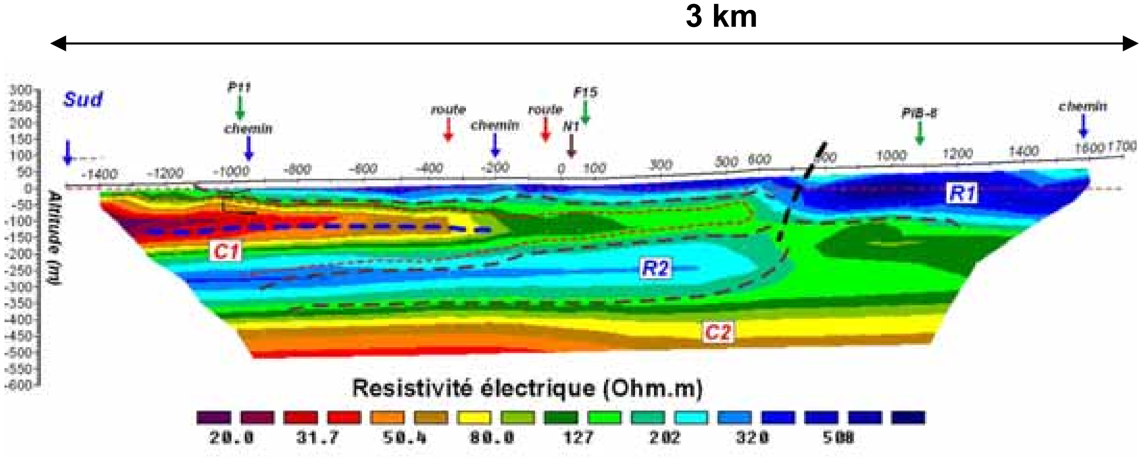
3 m thick blocks

« 1 cell per loops »

➢Lack of sensibility deeper

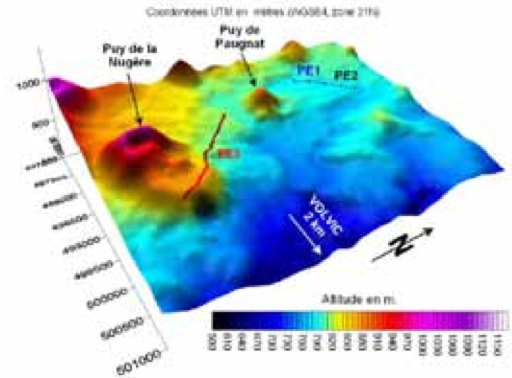
ERT - water resources exploration in complex environment

2 examples of electrical prospection in coastal volcanic environment

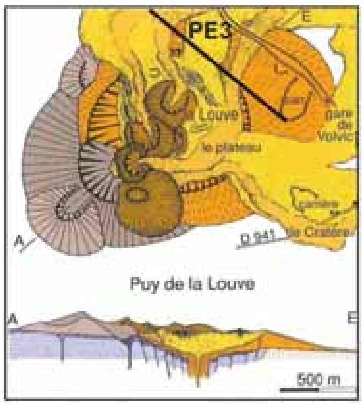


2D ERT for saline intrusion imaging (coastal aquifer, la Reunion)
electrode spacing 100m (dipoles 100, 200 and 400 m)

(rapport BRGM/RP-56612-FR, 2008)



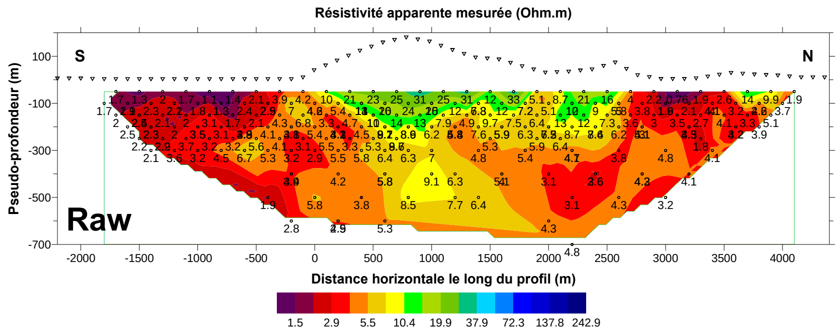
Commercial applications for
Danone Water resource
Volvic, Puy de la Nugère (2009)
Poland (2008), etc…

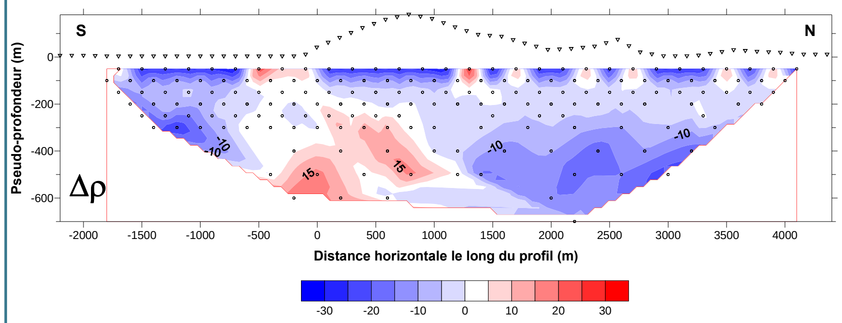


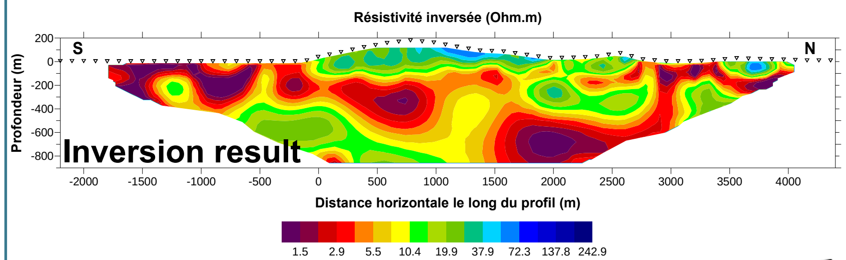
ERT - water resources exploration in complex environment

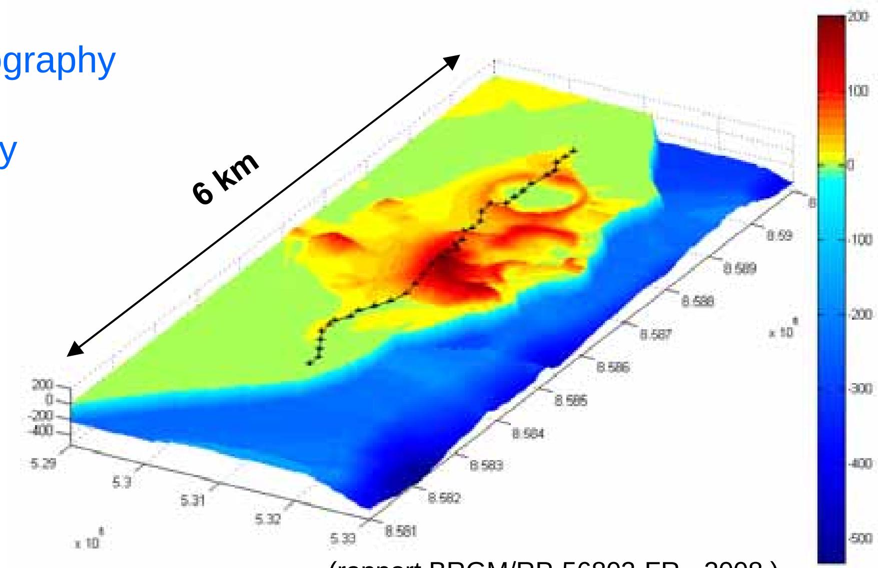
Correction of 3D topography effect before 2D tomography

Removing 3D effect modelled with a 3D topography but constant resistivity ρ_0









(rapport BRGM/RP-56802-FR - 2008)

$$\rho_{corrected} = \frac{\rho_{measured}}{\rho_{synthetic}} \times \rho_0$$

ρ_0 sea (0.2 Ohm.m)
ρ_0 ground (5 Ohm.m)

Here, topography effect uncorrelated with resistivity anomalies… validity of inversion result reinforced

Dipoles length	Level	Data nb
200	1,2,3,4,5,6	141
400	1,2,3,4,5,6	69
800	1,2,3	16
Total		226

CSEM - for monitoring deep CO_2 injection

Originality

- Using borehole casing to inject current to face depth of targeted reservoir (> 800 m)

  ~ Mise à la Masse (MAM) with cylindrical divergence…

- Source : Long Electrode Mise à la Masse

  Long history of such array (Mining, oil prospecting, geothermy)

- Good lateral resolution through surface measurement of electric and magnetic field

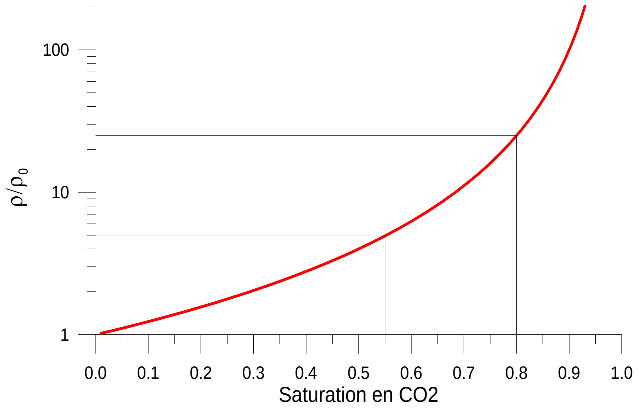
CO2 supercritic ~ gaz (purely resistive)

Generalized Archie law

$$\rho \approx \rho_w \Phi^{-m} S_w^{-2}$$

If water resistivity, porosity… unchanged (valuable at short term)

$$\rho / \rho_0 \approx S_w^{-2} \approx (1 - S_{CO_2})^{-2}$$



Pessimistic :	S_{CO2} = 55 % ⇒ S_W = 0.45 ⇒ $\rho/\rho0 \approx 5$
Average :	S_{CO2} = 69 % ⇒ S_W = 0.31 ⇒ **$\rho/\rho0 \approx 10$**
Optimistic :	S_{CO2} = 80 % ⇒ S_W = 0.20 ⇒ $\rho/\rho0 = 25$

CO_2ReMoVe

(Bourgeois and Girard, 2010, Oil & Gas Sc. & Tech.)

CSEM - for monitoring deep CO_2 injection

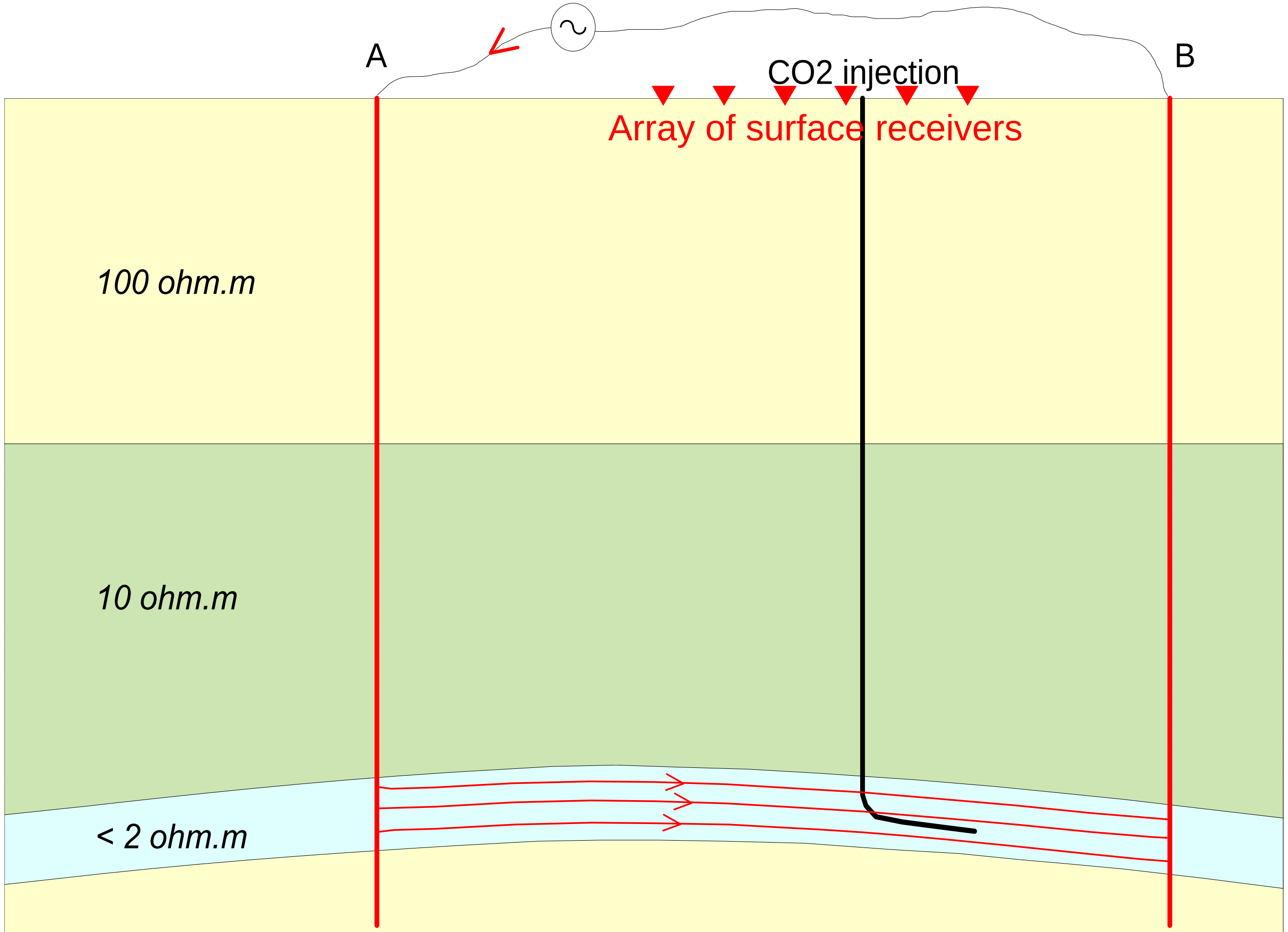
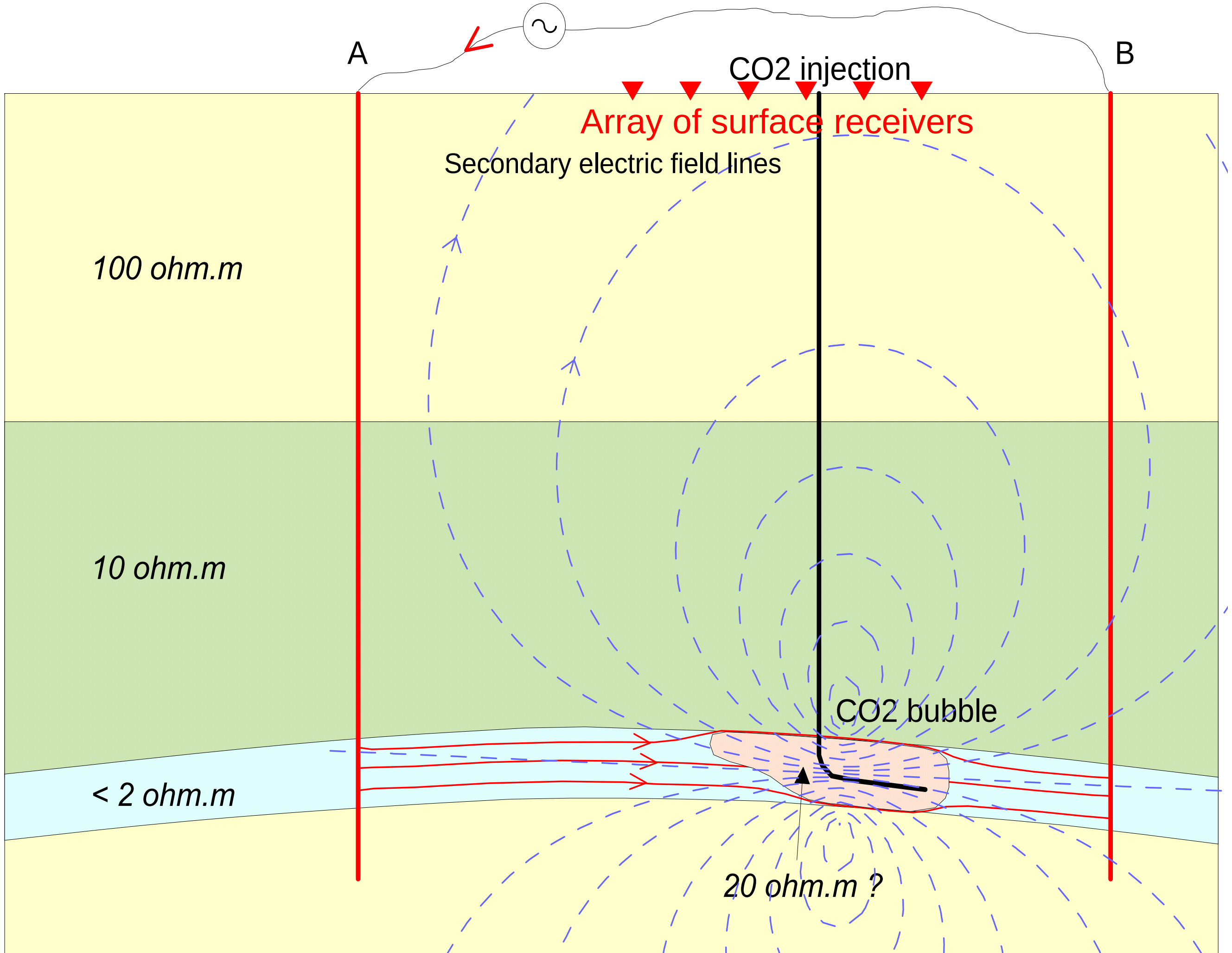


Diagram of the "LEMAM" borehole-to-surface electric array proposed for CO_2 monitoring in saline aquifers (intermediate between "mise-à-la-masse" and "rectangle" arrays)

CO_2ReMoVe

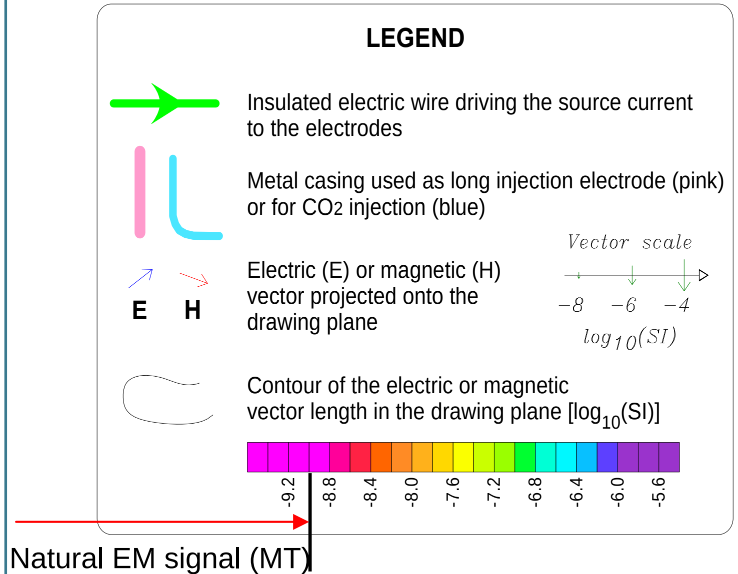
CSEM - for monitoring deep CO_2 injection

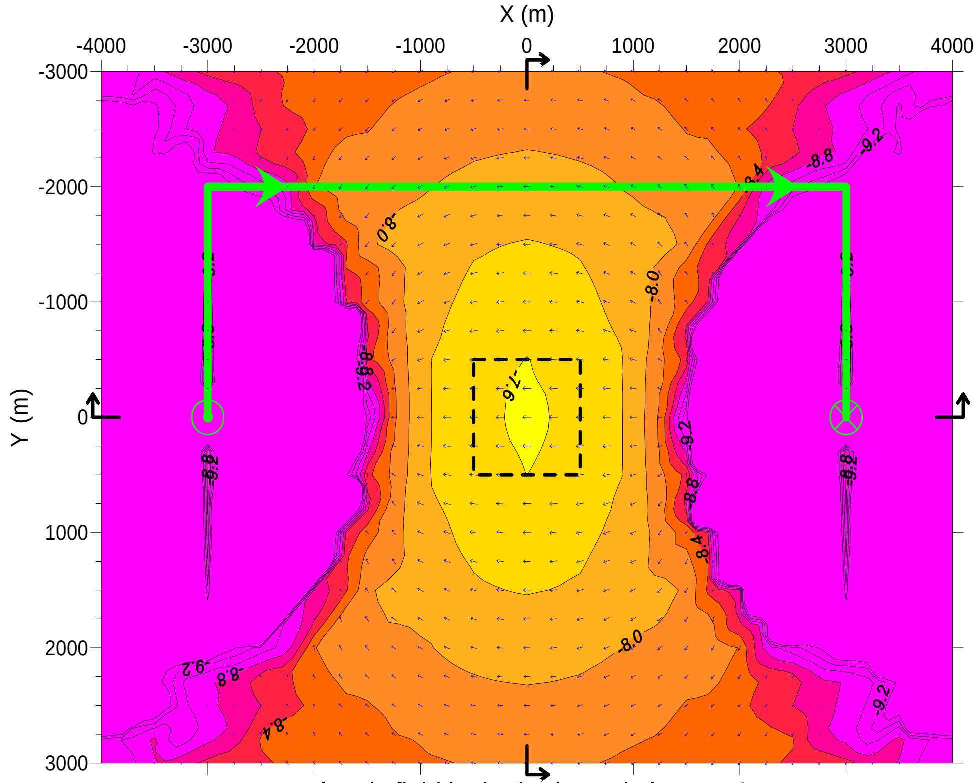


The current lines are diverted away by the resistivive CO2 "bubble"
The effect is more pronounced seen from above, in the horizontal plane of the aquifer layer
The current distorsion modifies the electric potentials measured at the surface

CO_2ReMoVe

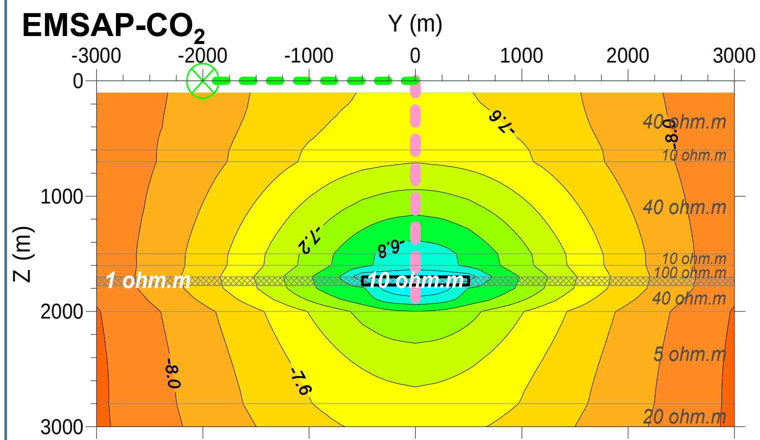
IN-PHASE SECONDARY ELECTRIC FIELD @ 0.5 Hz
from a small CO_2 bubble (1km×1km×70m)
for a current injection via a pair of metal-cased wells
("DOUBLE-LEMAM" ARRAY)



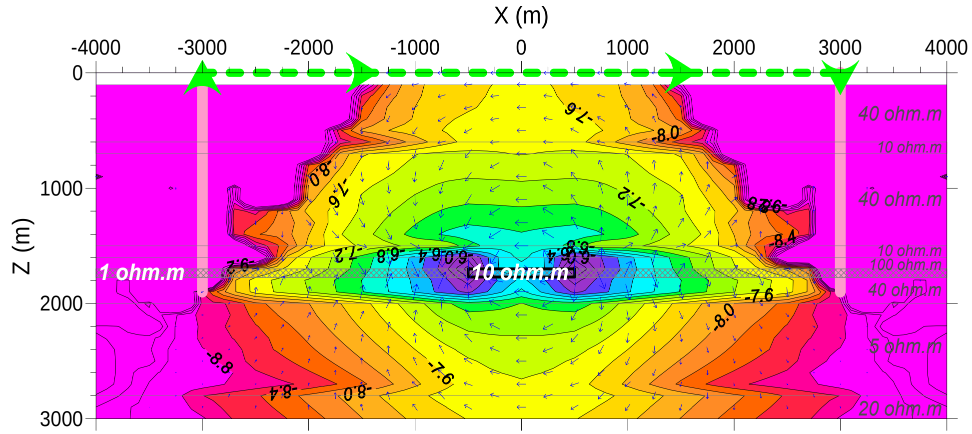


Electric field in the horizontal plane Z=0

EMSAP-CO_2



Electric field in the vertical plane X=0



Electric field in the vertical plane Y=0

NORMALIZED ELECTRIC RESPONSE (IN-PHASE)
from a small CO_2 bubble (1km×1km×70m) @ 0.5 Hz
for a current injection via a pair of metal-cased wells
("DOUBLE-LEMAM" ARRAY)

LEGEND

Insulated electric wire driving the source current to the electrodes

Metal casing used as long injection electrode (pink) or for CO_2 injection (blue)

Electric (E) or magnetic (H) vector projected onto the drawing plane

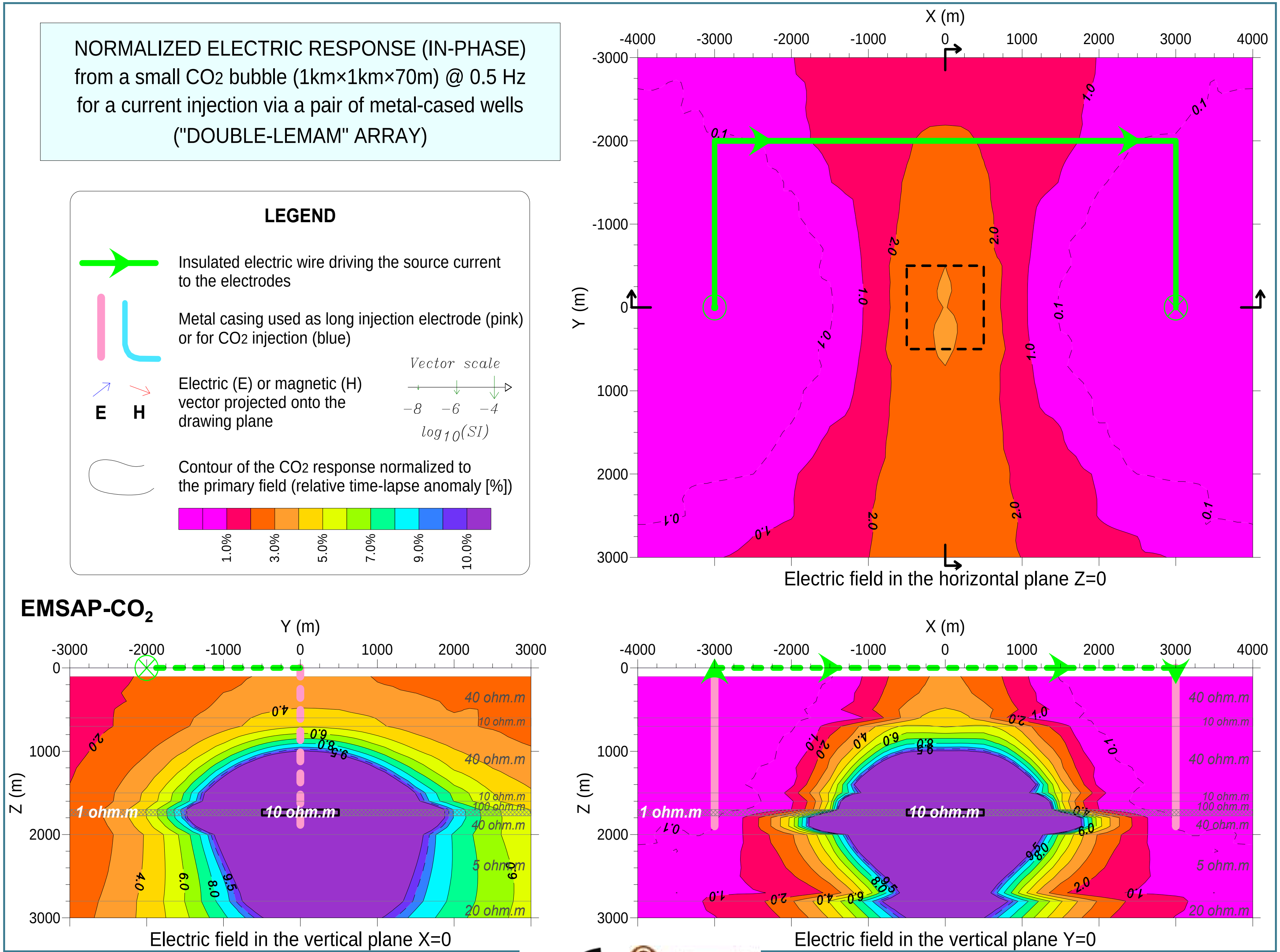
E H

Vector scale
−8 −6 −4
$log_{10}(SI)$

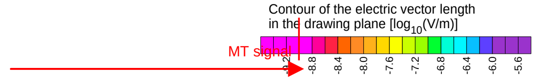
Contour of the CO_2 response normalized to the primary field (relative time-lapse anomaly [%])

1.0% 3.0% 5.0% 7.0% 9.0% 10.0%

EMSAP-CO_2

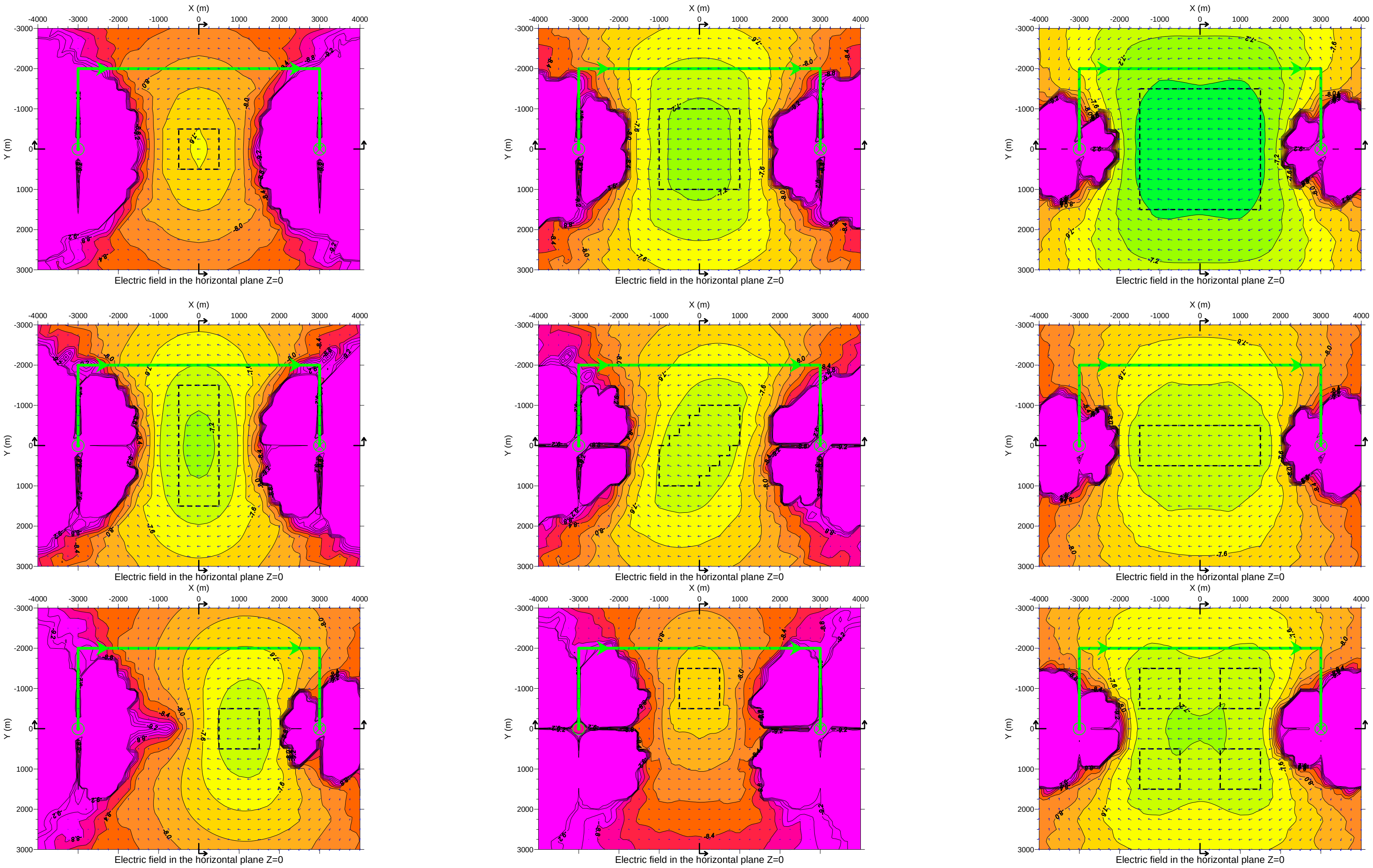


CSEM - for monitoring deep CO_2 injection



(Bourgeois, Rohmer, Girard, 2009)

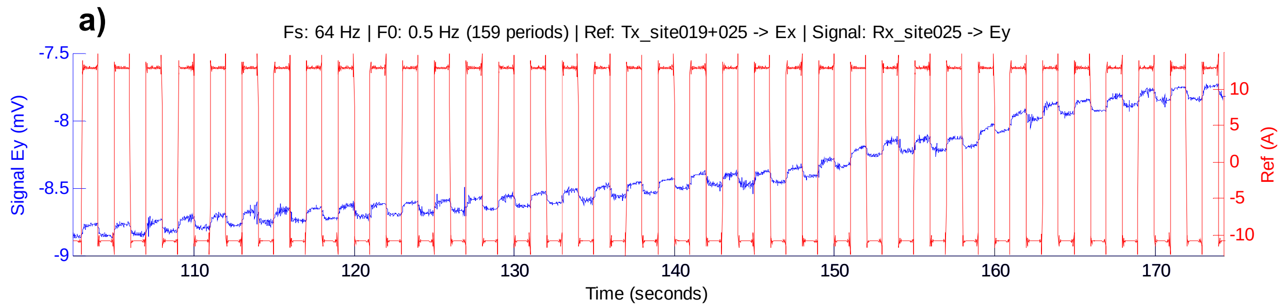
Natural EM signal (MT)

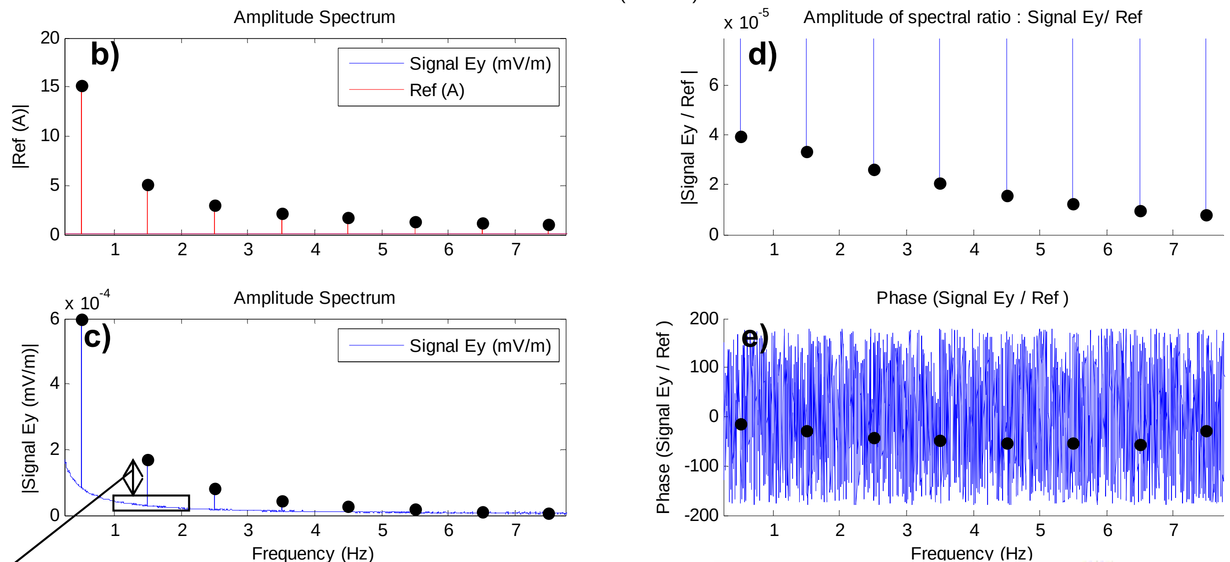


Time-Lapse response on in-phase electric field (0.5 Hz) for a 70 m thick CO2 plume, 10 Ω.m (S_{CO2}=70%), confined in a 1 Ω.m reservoir, 1700 m depth, using LEMAM array.

EMSAP-CO_2

CSEM





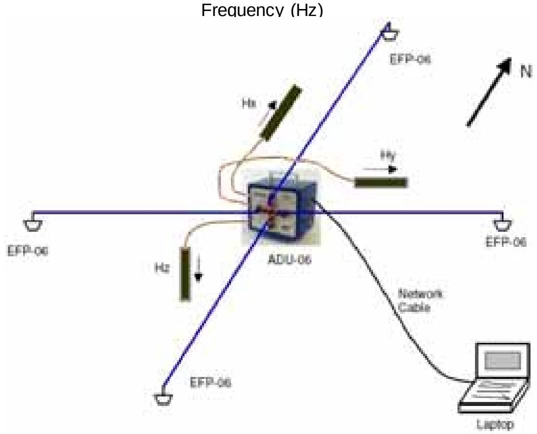
Tx current monitored

E/I , H/I amplitude

Ex, Ey
Hx,Hy,Hz
monitored

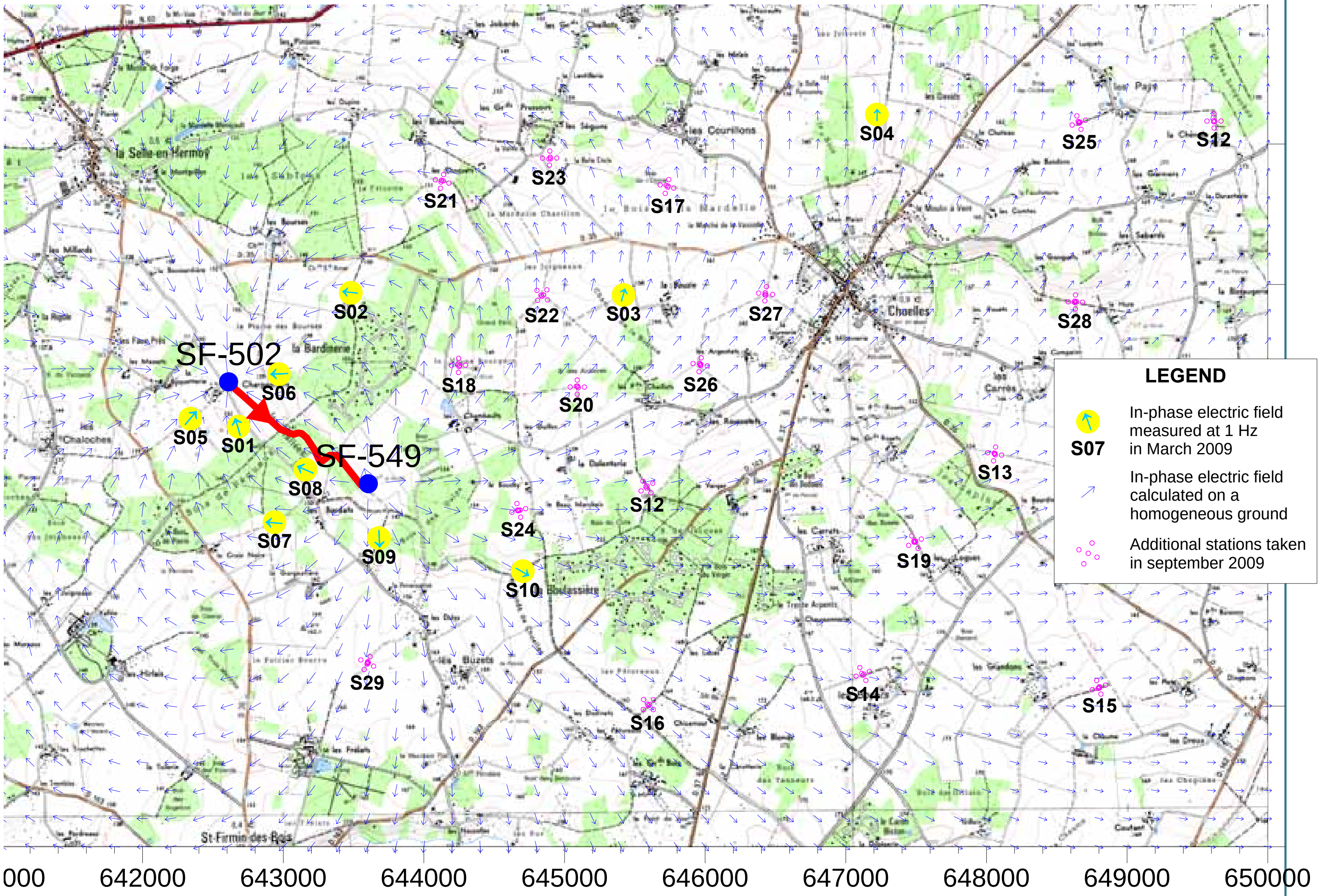
E/I , H/I phase

Signal / Noise ratio



EMSAP-CO_2

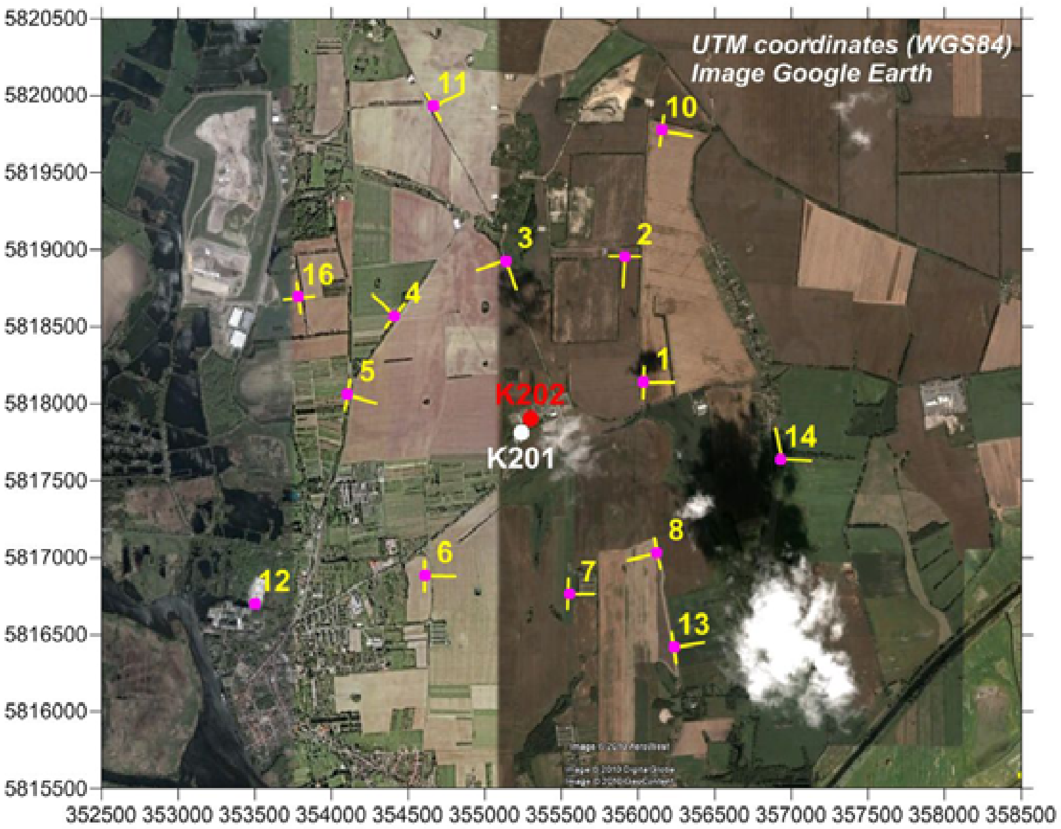
Test site for repetition, near Montargis (Toreador Energy France)
-> 29 stations repeated 3 times (Mar 09, Sep 09, Mar 10)



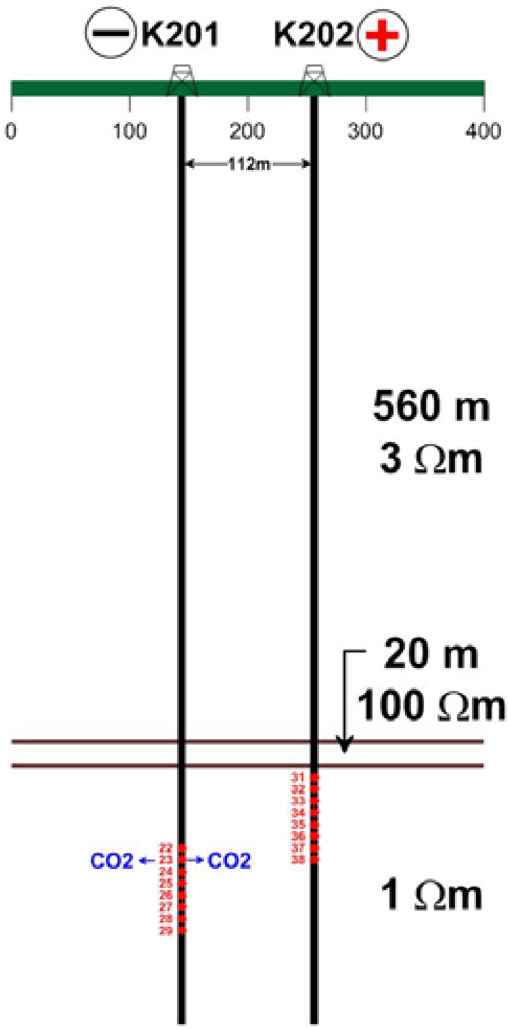
CSEM - monitoring CO_2 injection at Ketzin pilot site

Double "Mise à la masse" (dipôle) configuration

X-Y VIEW



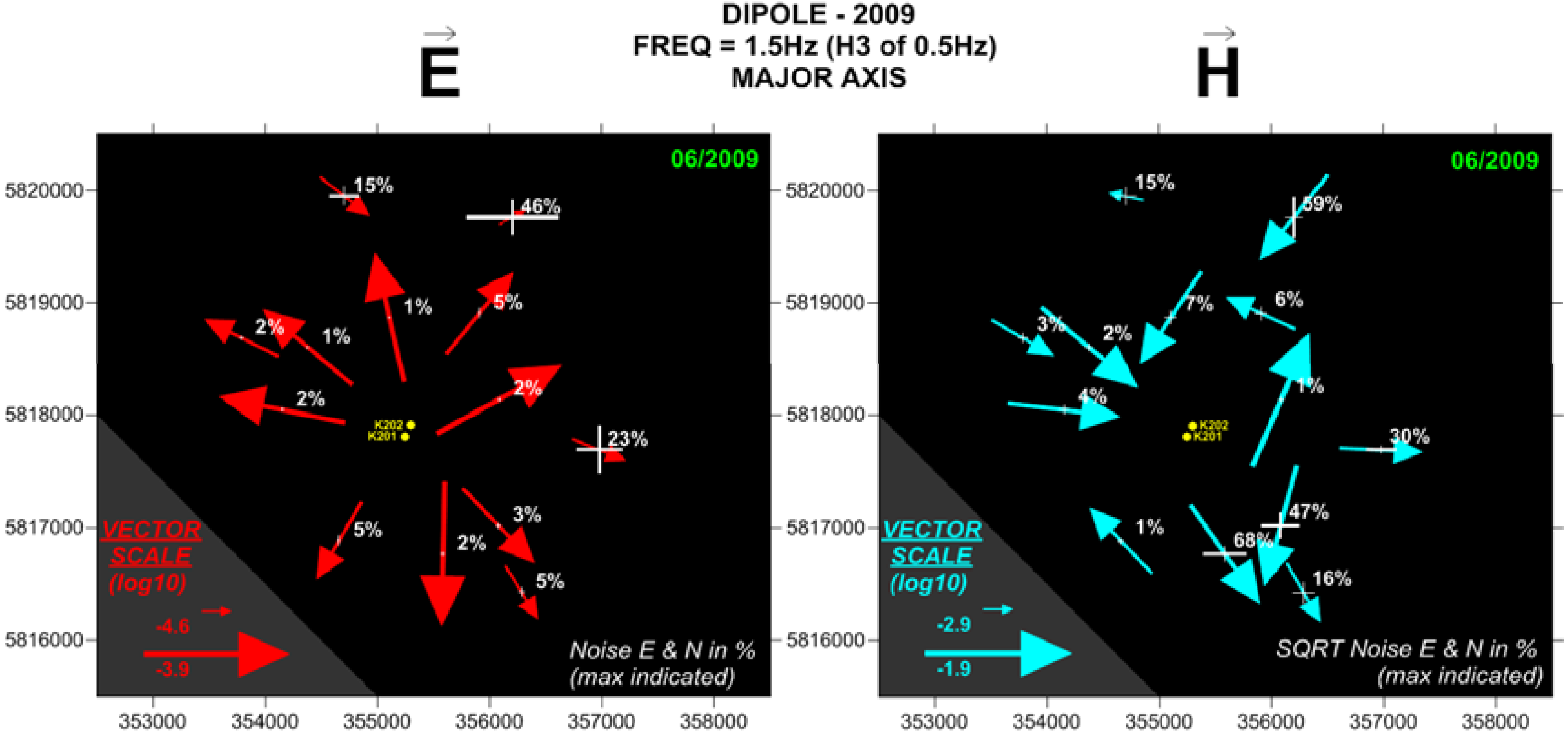
X-Z VIEW



CO_2ReMoVe

(Girard et al., EGU 2009)

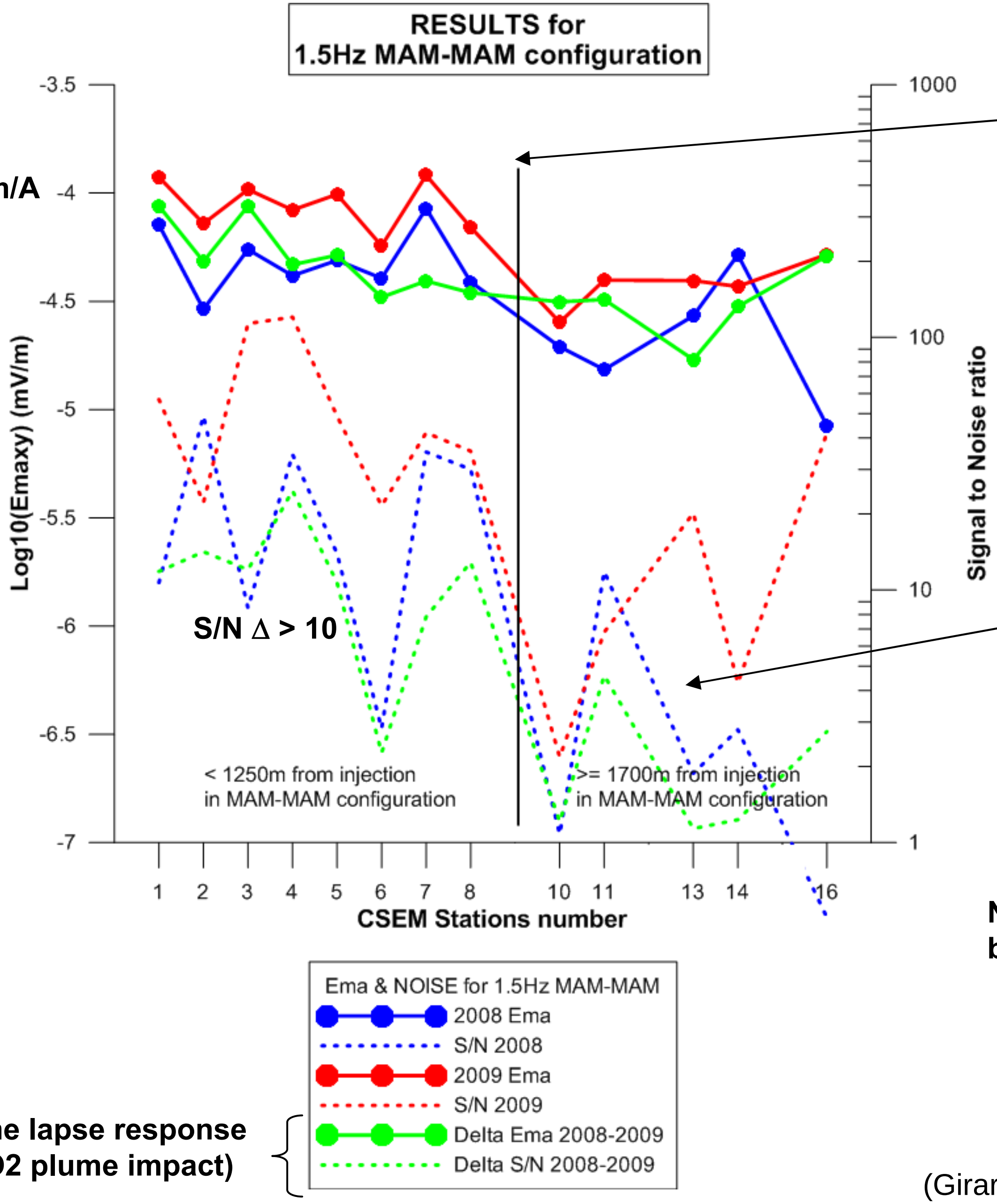
CSEM - monitoring CO_2 injection at Ketzin pilot site



Measured surface Electric and Magnetic Field

CO_2ReMoVe

(Girard, Coppo, Bourgeois, GHGT10)



$\sim 10^{-4}$ mV/m/A

$\Delta \sim 6.10^{-5}$ mV/m/A

Note decrease of S/N with distance to transmitter

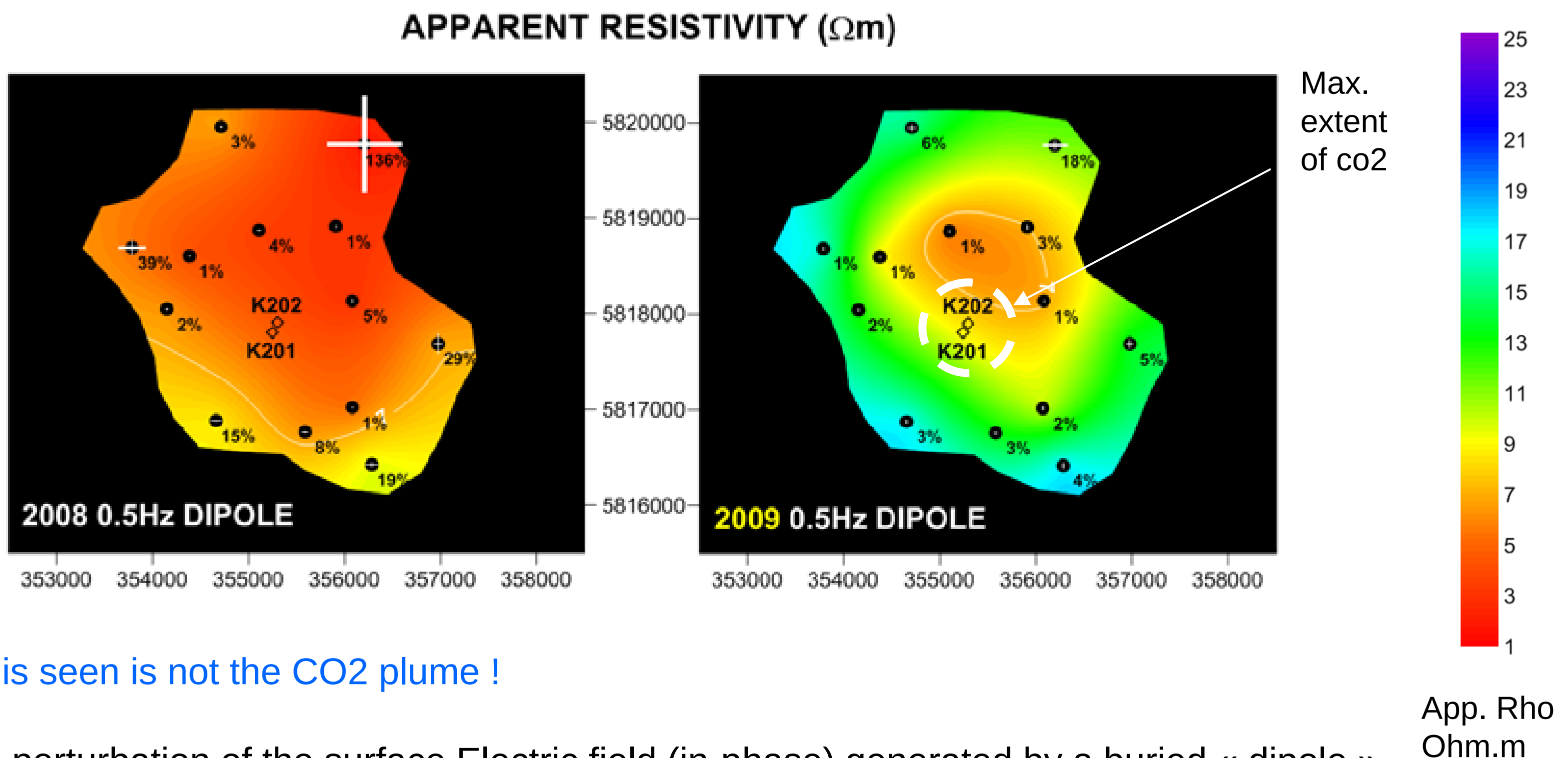
Note decrease of S/N with harmonic number (especially in 2008 – blue)

Note, that 2009 data quality is better

Time lapse response (CO2 plume impact)

(Girard, Coppo, Bourgeois, GHGT10)

CSEM - monitoring CO_2 injection at Ketzin pilot site



! What is seen is not the CO2 plume !

But the perturbation of the surface Electric field (in-phase) generated by a buried « dipole » when a resistivity variation happens close to TX

~

⇒ modification of the « radiation » pattern of the TX field

⇒ Current work on inversion

(Girard, Coppo, Bourgeois, GHGT10)

CO_2FieldLab - Appraisal phase: Geophysical investigation

CO_2FieldLab
(2009-2013)

CO_2 Leaking
Pilot Site

Verket ridge

2 lines for
Appraisal
Geophysics

BRGM in charge
of appraisal
geophysics

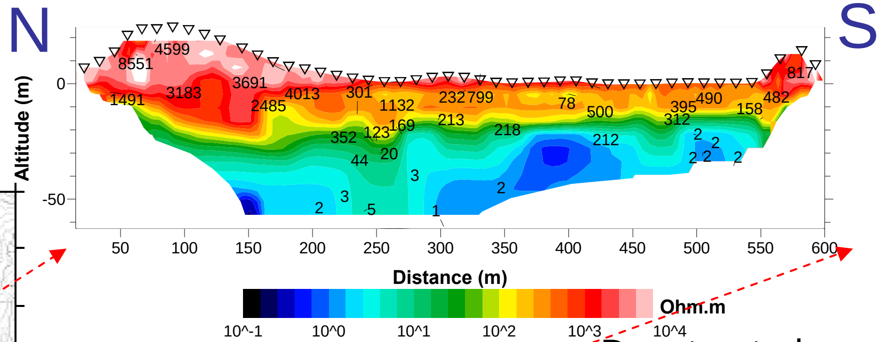
Geosciences Montpellier · imageau · SINTEF · Schlumberger · brgm Géosciences pour une Terre durable · StatoilHydro · Bureau Veritas 1828 · BGS

CO_2FieldLab - Appraisal phase:

– aquifer characterization in complex environment (2D seismic & ERT)

(Shallow investigation / Wenner - Schlumberger Array)

Appraisal survey in Nov 2009

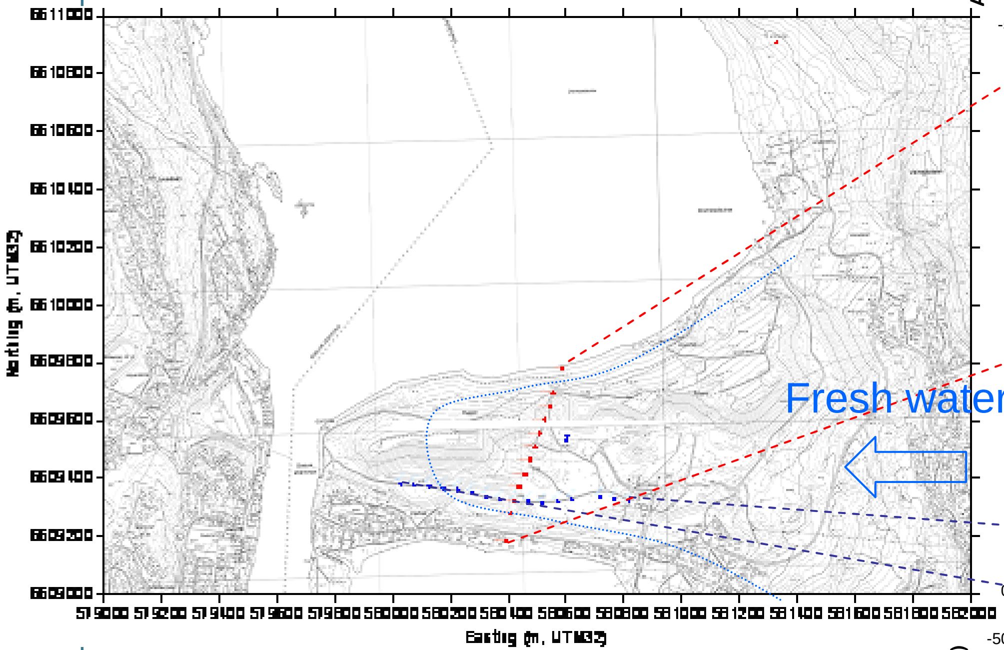


Sea water saturated

Rain water

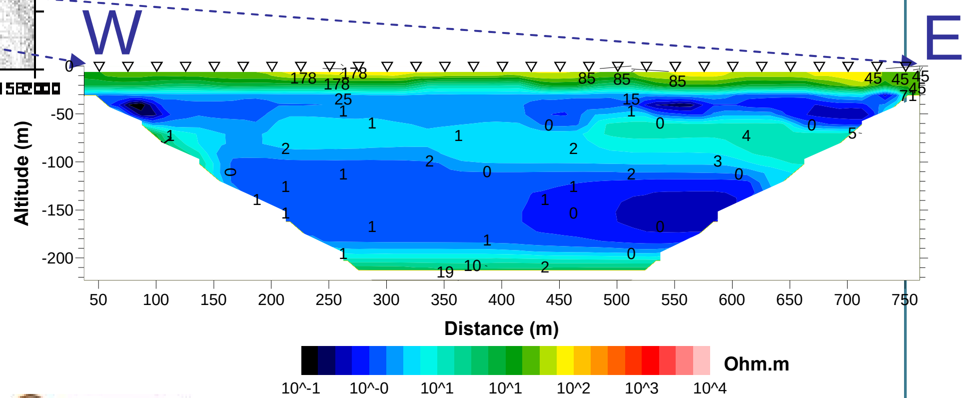
Desaturated sand

Preliminary interpretation before drilling



Fresh water flow

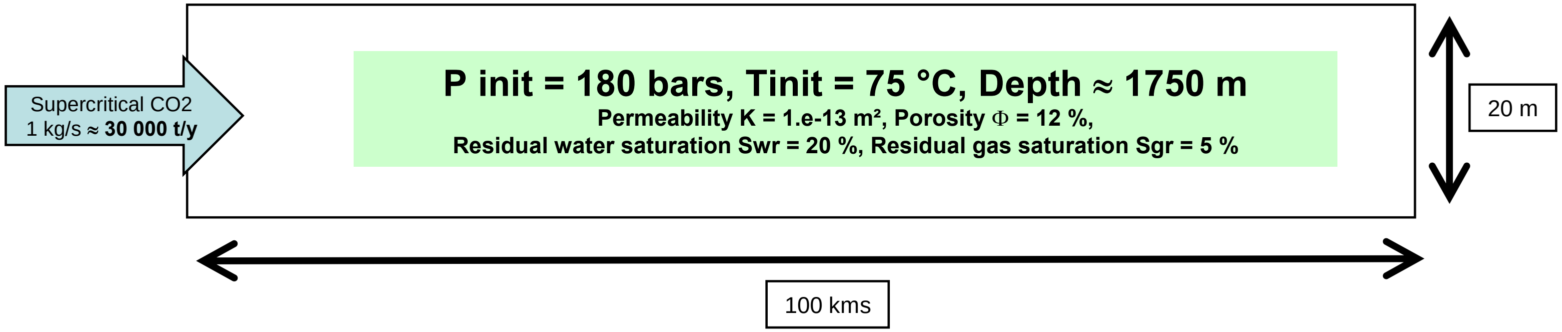
(Deeper investigation / Pole Dipole Array)



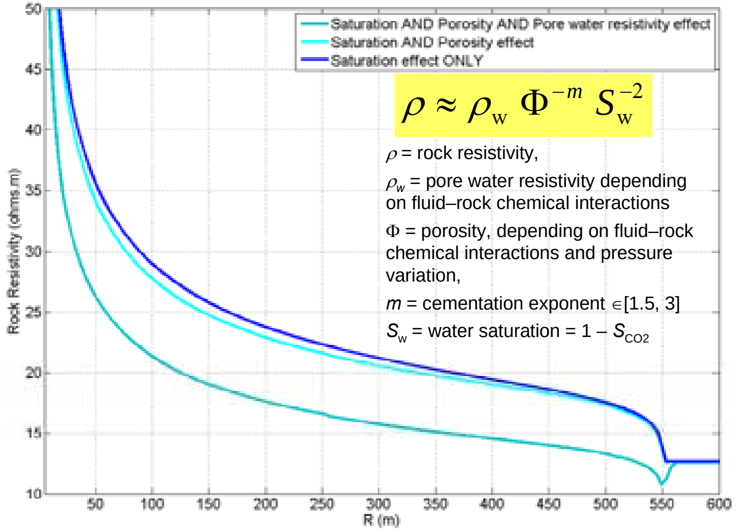
2D high resolution seismics performed end of February 2010

Current and future research project

⇒ coupling (reactive) transport modeling with EM modeling



Model parameters (after Andre et al., 2007) used to compute mineralization evolution in a limestone aquiferduring CO2 injection. Reactive transport modeling with TOUGHREACT (Xu and Pruess, 2001 / 2005).

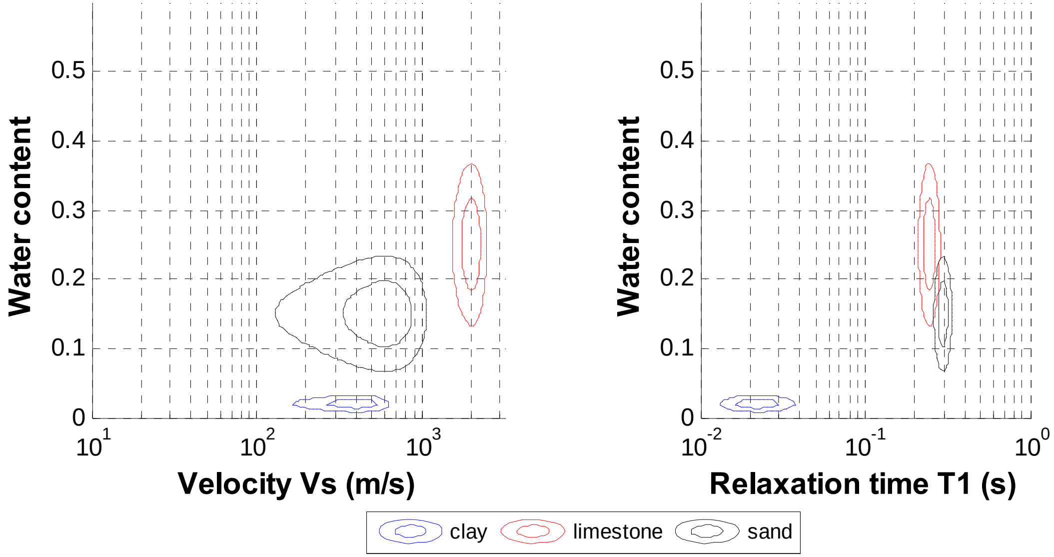


(Girard, Leroy, Audigane, Rohmer, Bourgeois, 2009- 2010)

Resistivity variation in the reservoir after 10 years of CO2 injection, in limestone aquifer, including CO_2 saturation, porosity change (dissolution / precipitation) and water conductivity variation !

Current and future research project

⇒ stochastic inversion



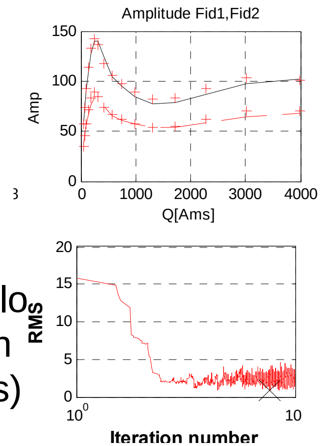
A priori knowledge
⇒ density probability function

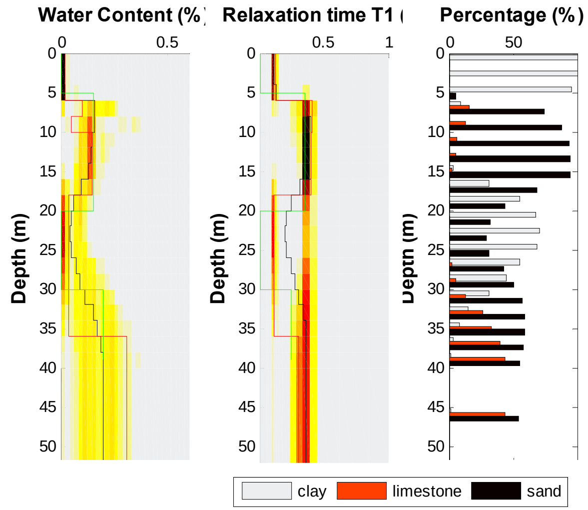
Here,
- Shear wave velocity,
- MRS water content,
- Decay time T1

for three « facies » :
clay, limestone, sand

Best fit

Monte Carlo
Exploration
(Metropolis)





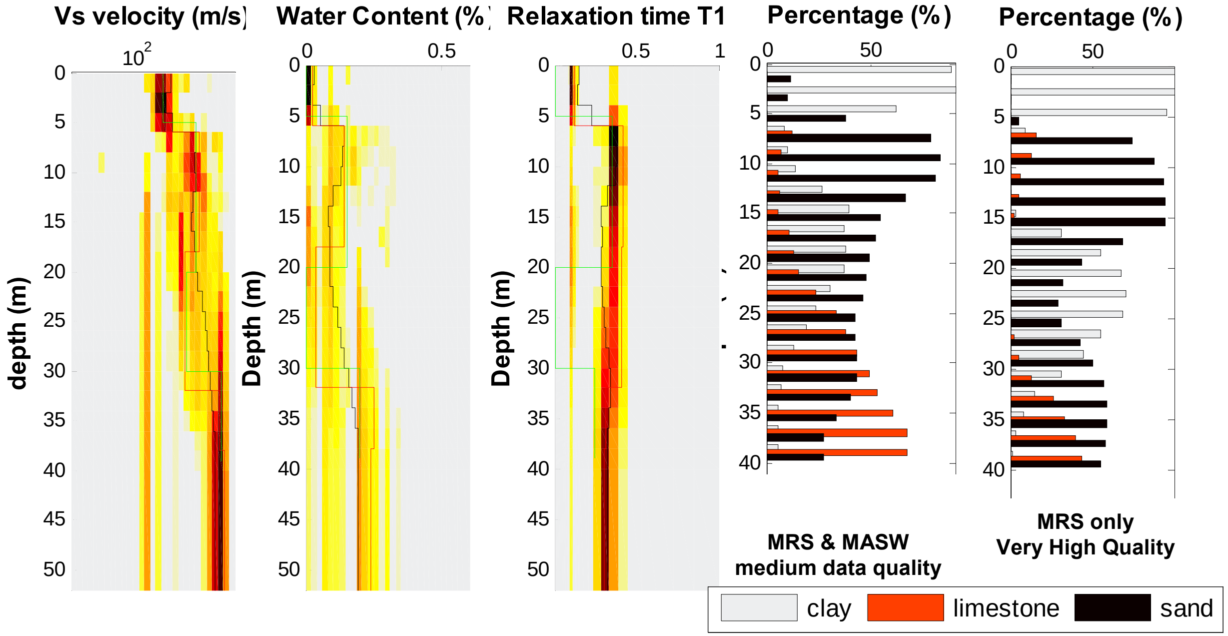
Stochastic inversion
of MRS data

Results
Water content, decay time T1
Probability of facies

(Girard, Roulle et al., MRS2009)

Current and future research project

⇒ joint stochastic inversion



Joint stochastic inversion of MRS and MASW data:

Complementarity in sensitivity

⇒ Seismic sensitive to limestone but blind to clay

⇒ MRS clearly detect clay but unable to discriminate second aquifer nature (sand or limestone)

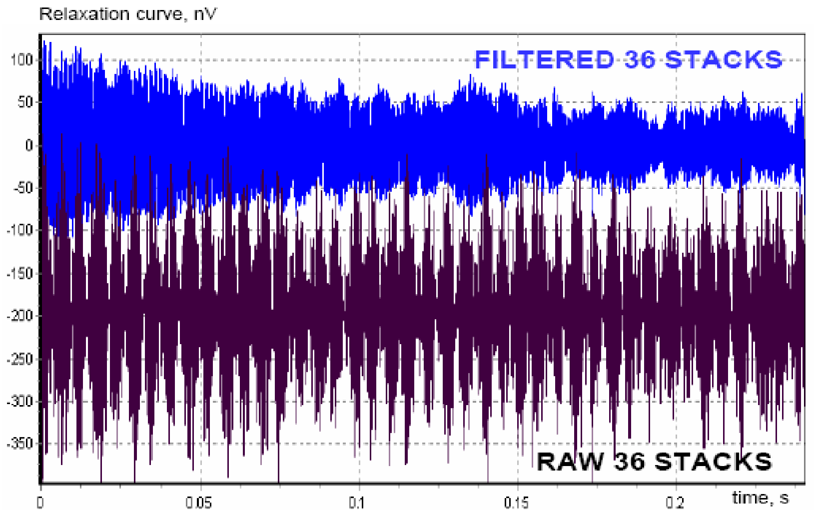
If joint inversion of medium quality data (realistic 10% noise)

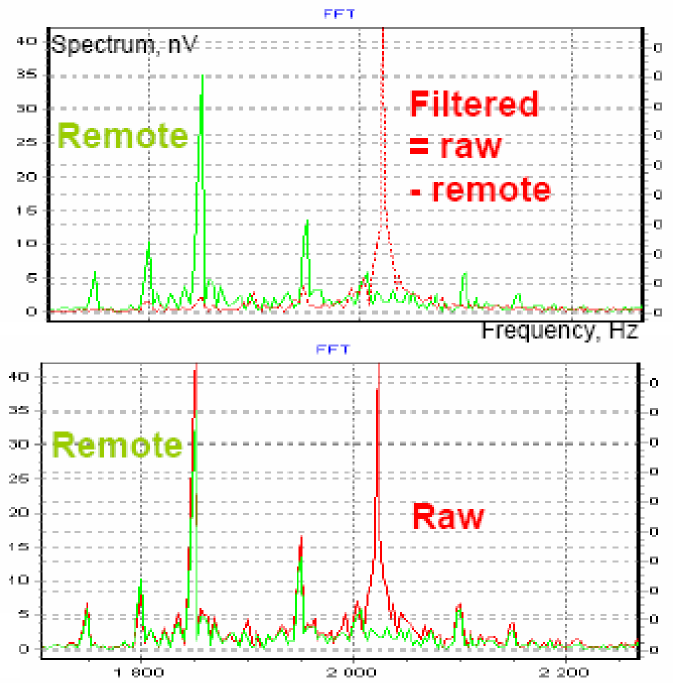
⇒ allows a good discrimination of all materials !

(Girard, Roulle et al., MRS2009)

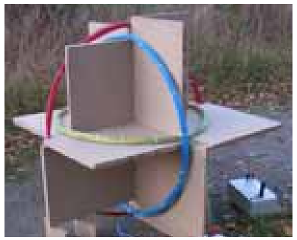
Current and future research project

⇒ Multi-channel MRS filtering





Ex of « remote » filtering : raw data (bottom) and filtered (top)



Site dependent efficiency (structure, stability, amplitude, etc…)

Filtering technics using Transfert Function estimation with N remote loops, or 3 component receivers, …

Separated loop acquisition time become attractive

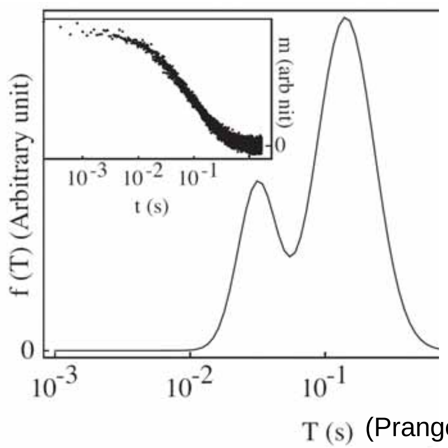
ReMaPro

(field demo at MRS2009)

Current and future research project

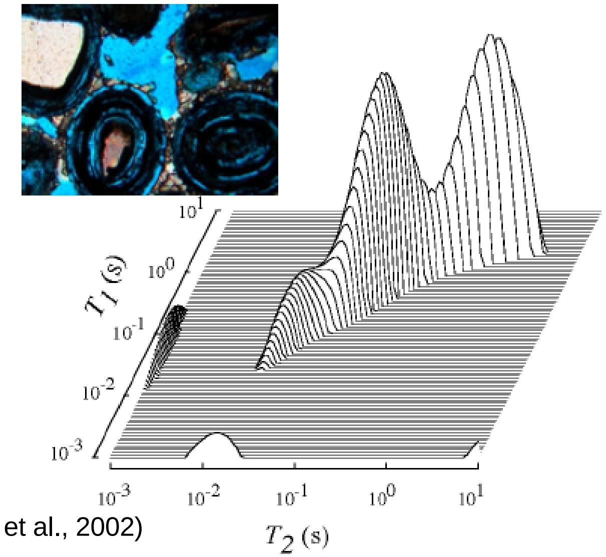
⇒ Spectral analysis of decay times

Progress in data quality + **Progress in speed**
> amount of data (varying sequences)



(Prange, 2010)

Oolitic



(Song et al., 2002)

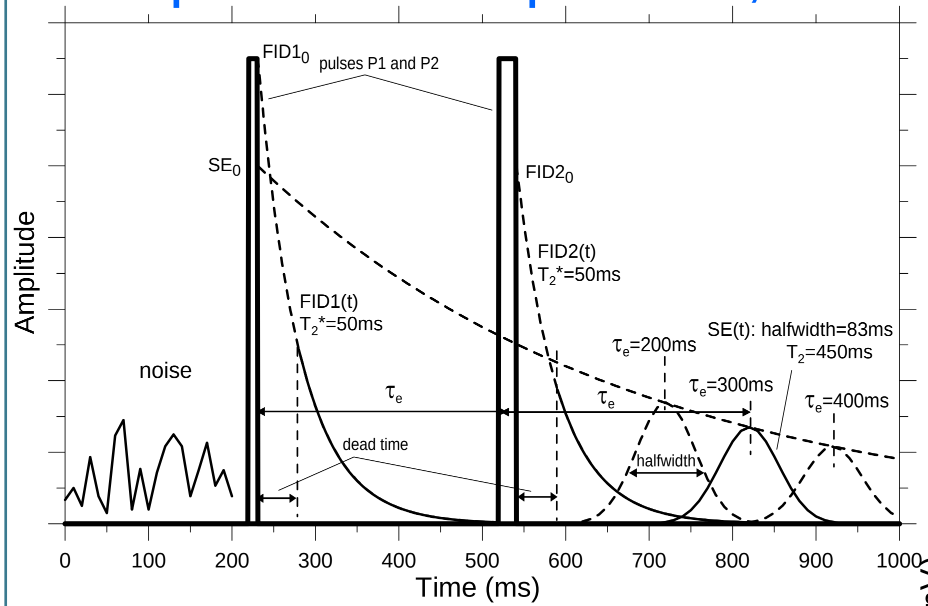
NMR signal decay is <u>multi-exponential</u>
⇒ Decay spectrum estimation

But ill posed problem… (MC, statistics)

T1 – T2 correlation spectra
(T2 – D maps…)

Current and future research project

⇒ Spin Echo sequences, …

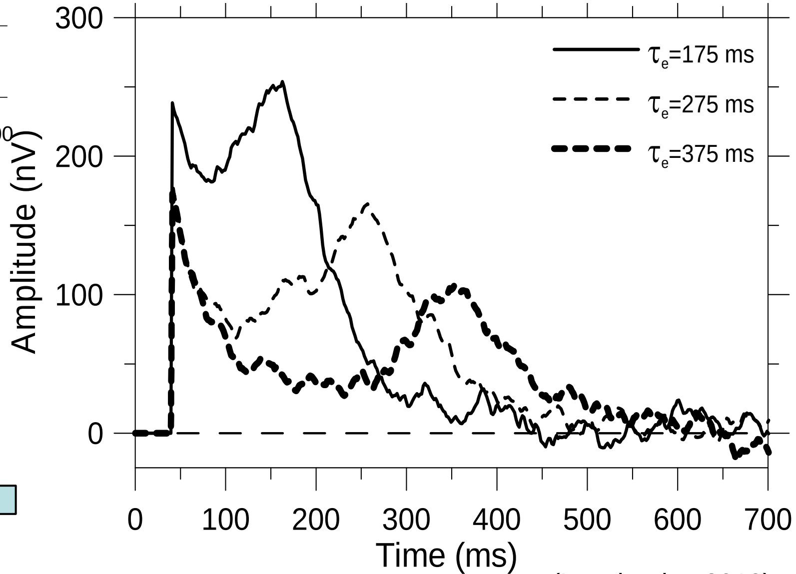


« Spin echo » sequence

Few attempts of SE field experiments

Feasibility recently demonstrated (India, Canada…)

Canada (St Marthe, August 2008).

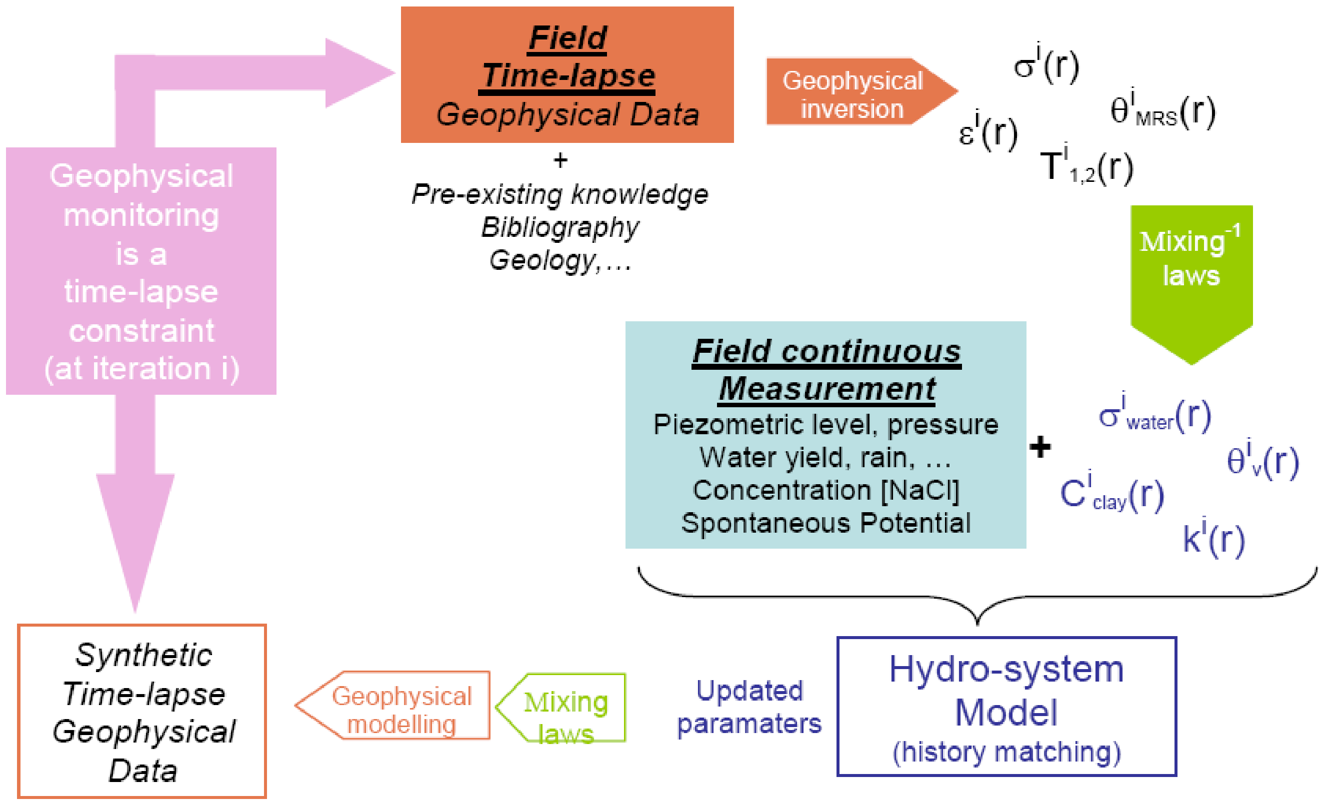


(Legchenko, 2010)

Measurements in magnetic environments
- volcanic geology…
- waste zone…

AMPERE - Une Approche Multi-Physique pour surveiller la qualité Environnementale des sols (Roches) et de l'Eau »

→ projet soumis à AO ANR Ecotech 2010



Workflow for a coupled hydro-geophysical approach (measurement & modelling) for monitoring the environment

Partenaires: brgm, eost , lthe, migp, Iris-Instruments, SAEME (Eaux Evian), China Univ. of Geosciences