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# Vadose zone water content characterization of a heterogeneous limestone by 3D-SNMR

Clémence Ryckebusch, J-M. Baltassat, A. Legchenko, P. Kessouri, N. Amraoui, J. Deparis, M. Abbas, M. Azaroual

Contact : [c.ryckebusch@brgm.fr](mailto:c.ryckebusch@brgm.fr)

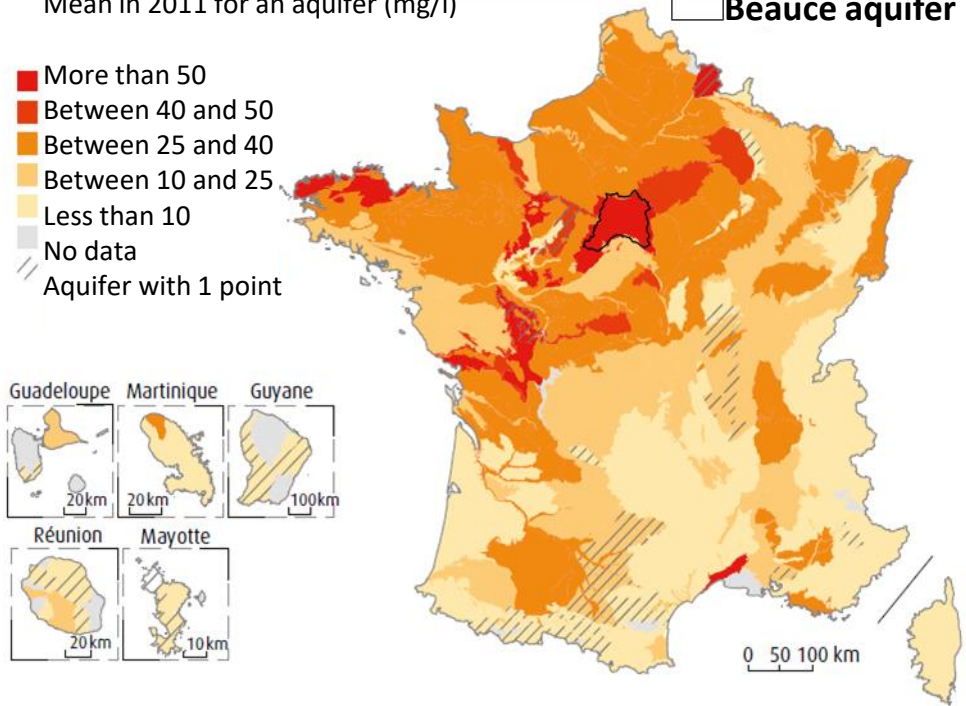
# Context of the study

## Map of nitrate mean concentration in aquifers, 2011 (Database : ADES)

Mean in 2011 for an aquifer (mg/l)

Beauce aquifer

- More than 50
- Between 40 and 50
- Between 25 and 40
- Between 10 and 25
- Less than 10
- No data
- Aquifer with 1 point



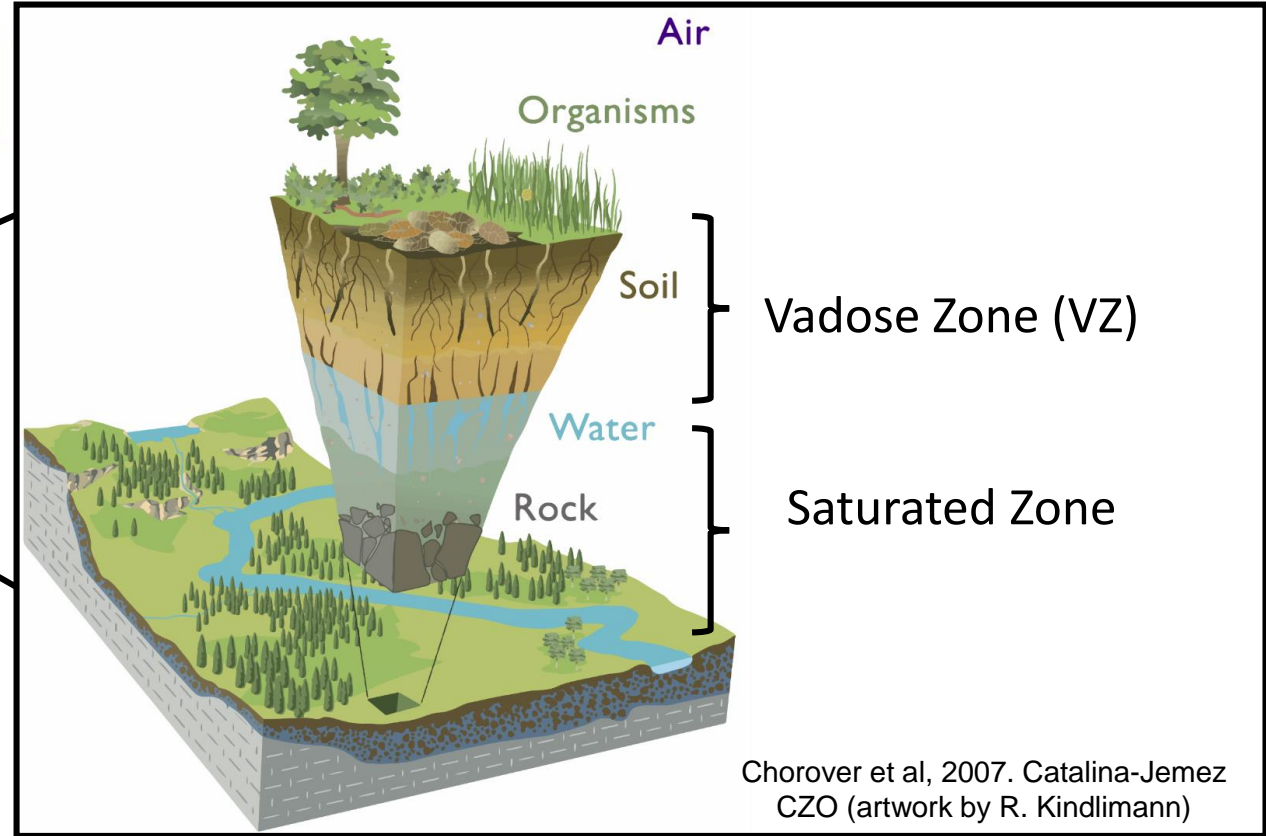
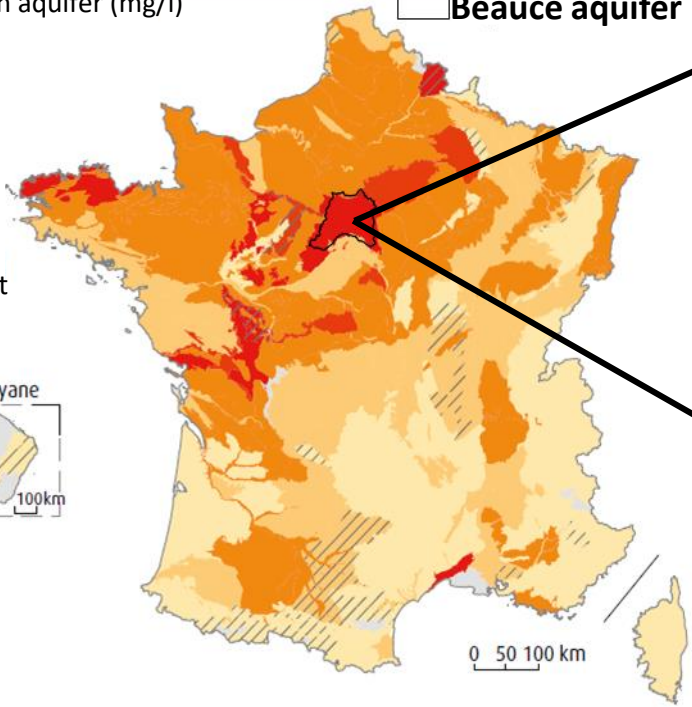
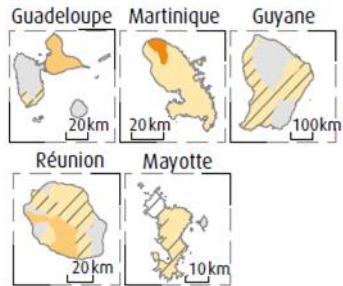
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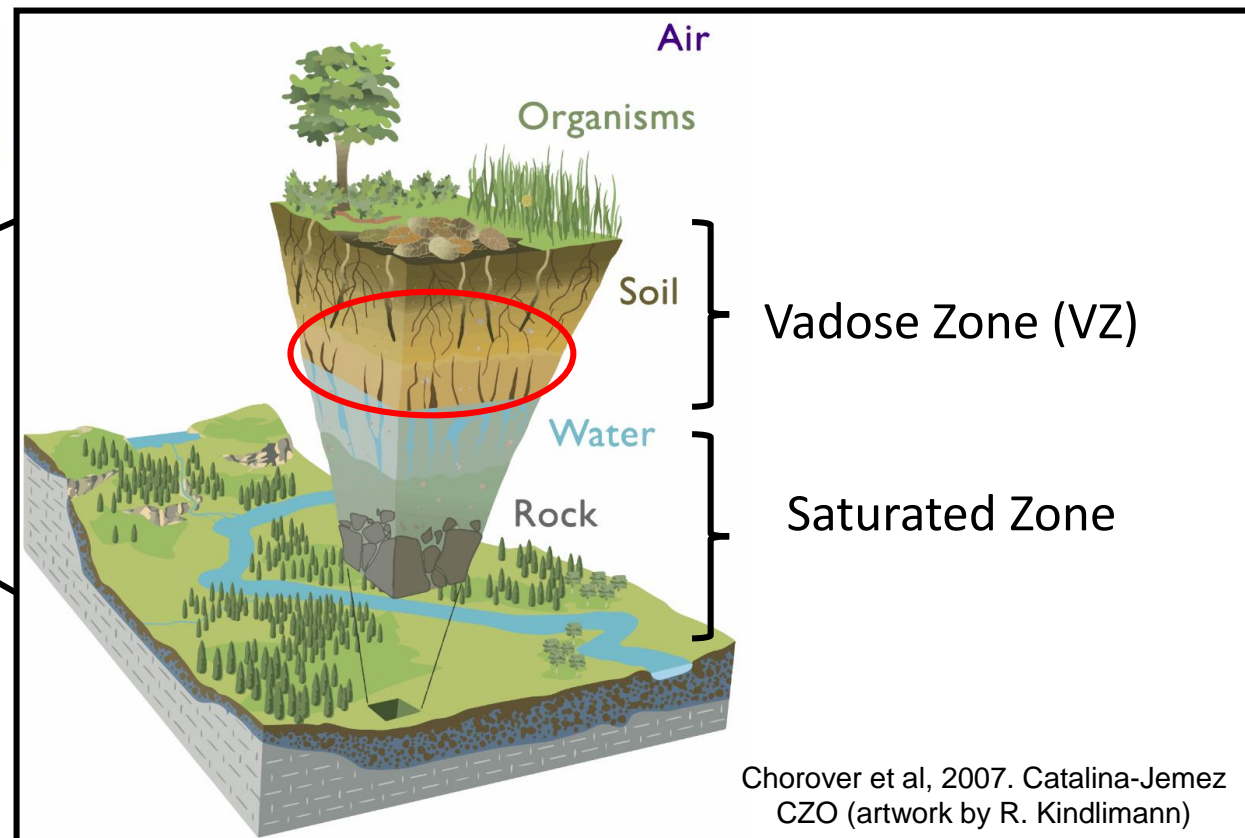
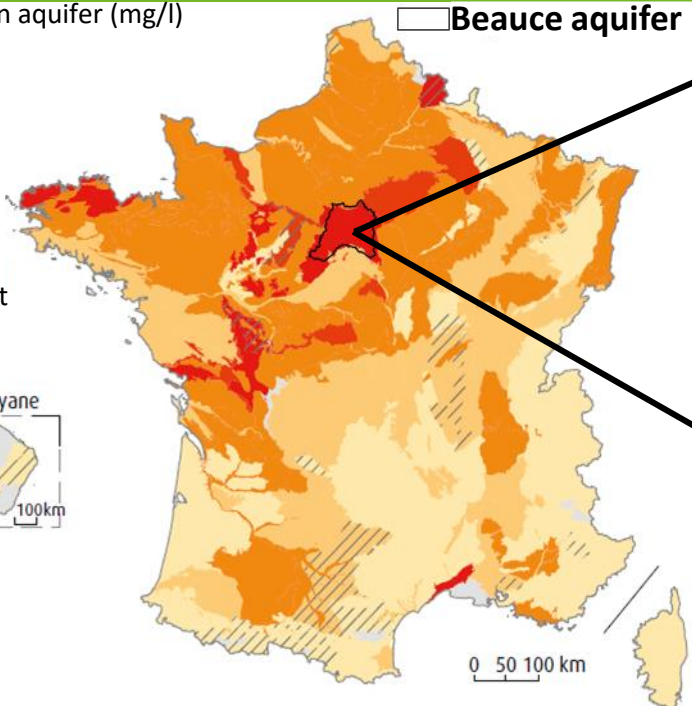
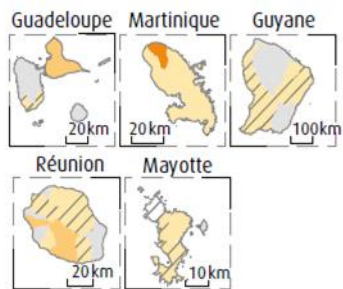
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### Problem

- Sampling and instrumentation to study the deep vadose zone
- Heterogeneity and complex behavior in vadose zone



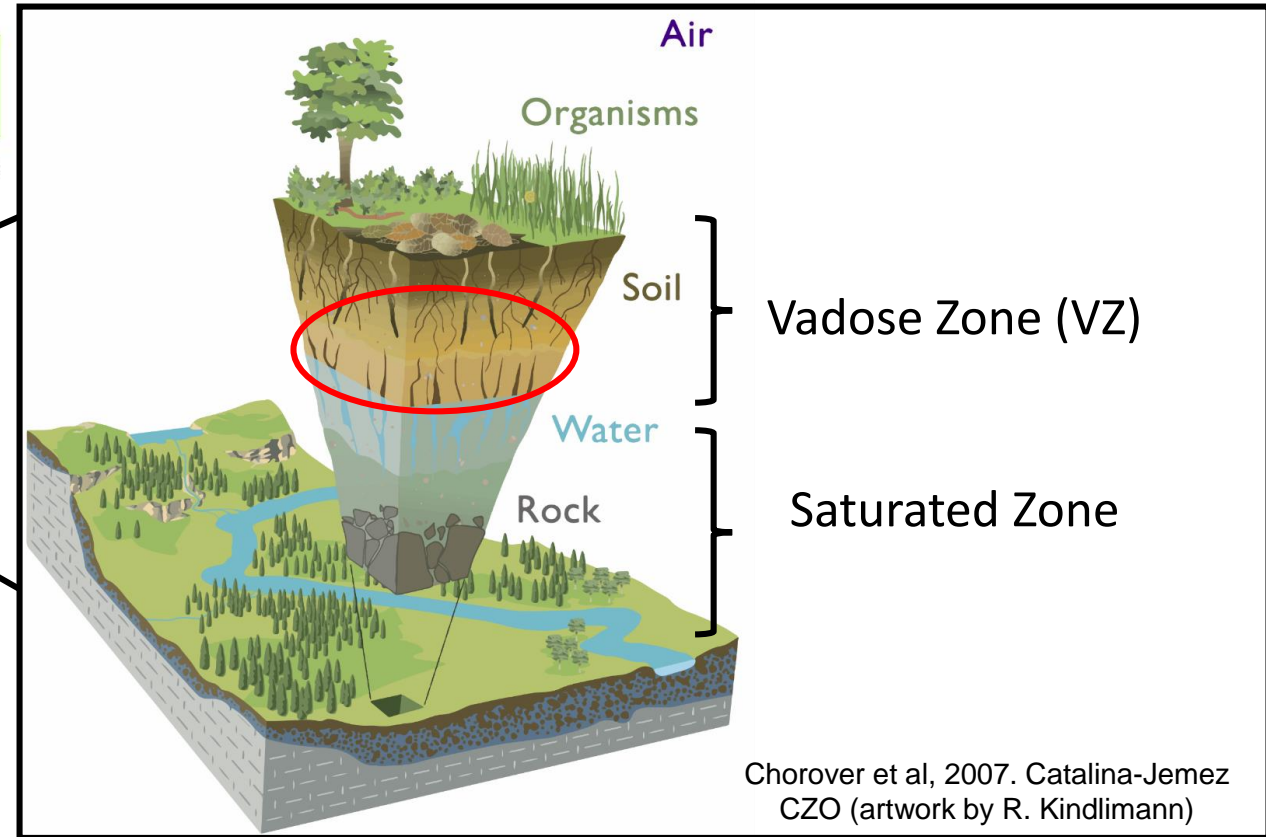
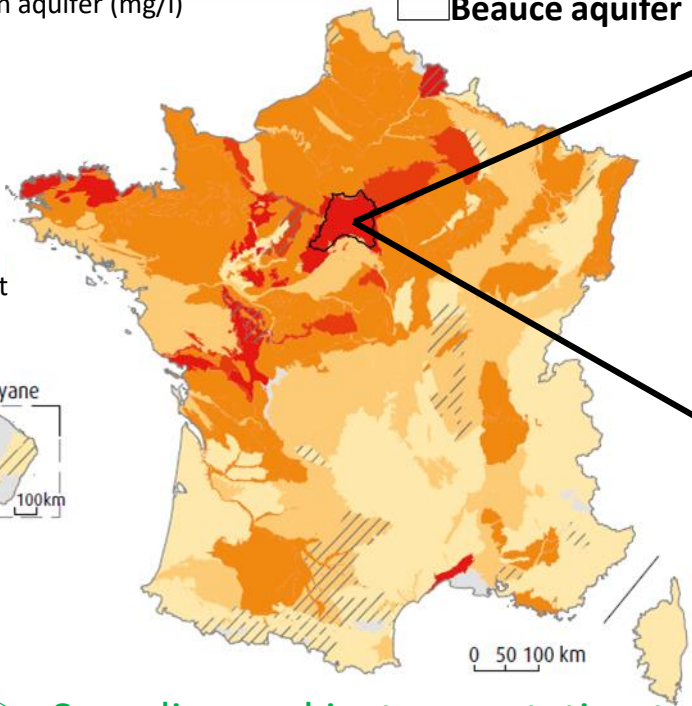
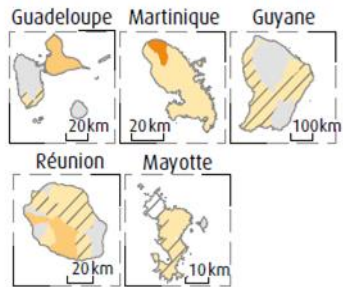
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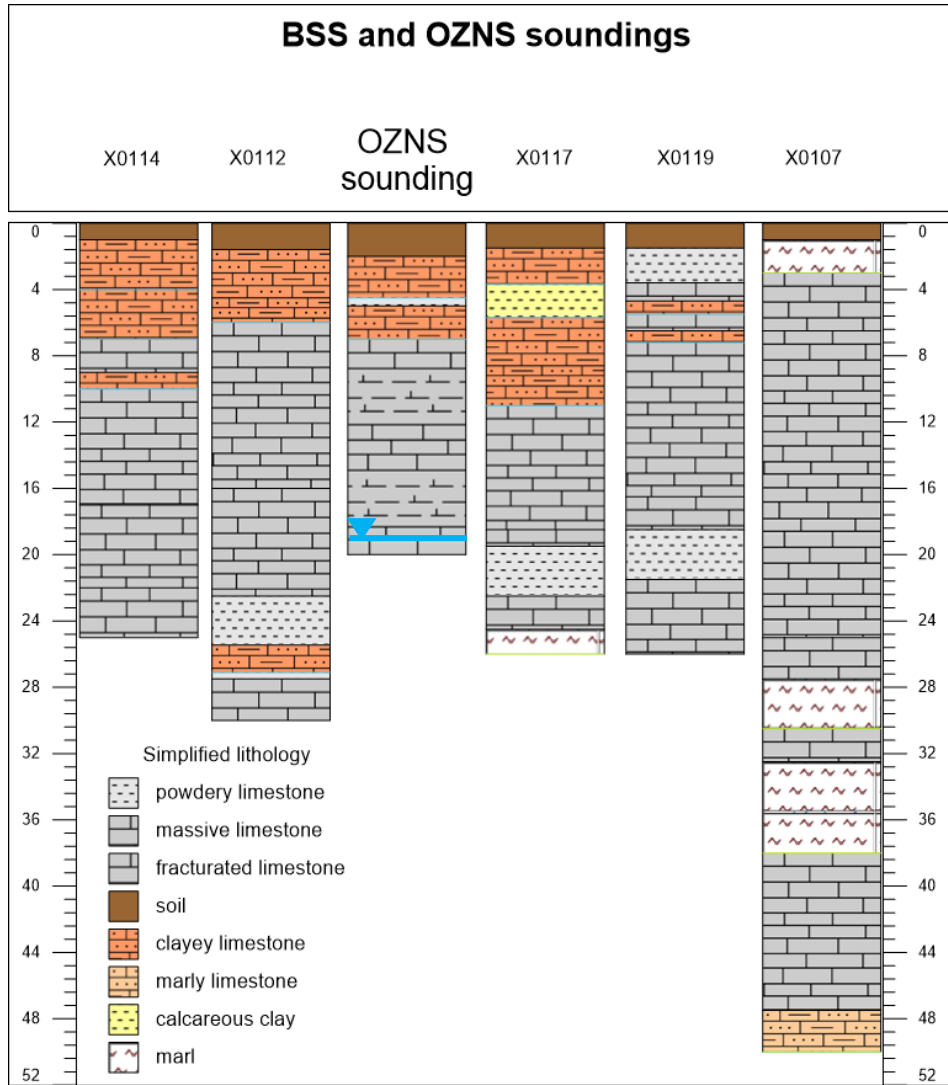
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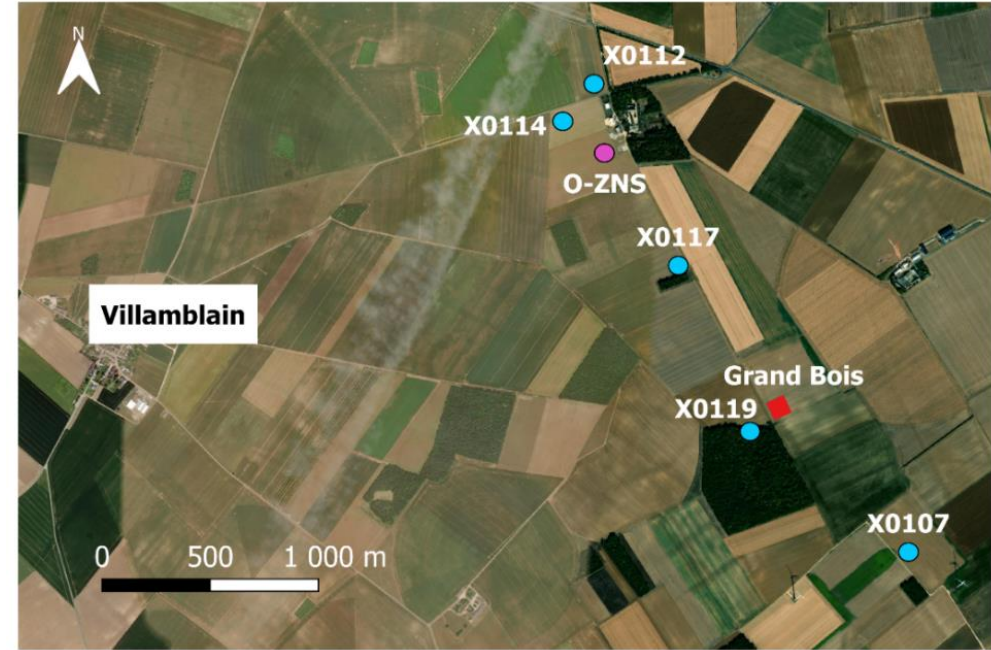
### Objective

- **Thesis** : Improve the vadose zone flow characterization and modeling by coupling Surface Nuclear Magnetic Resonance (SNMR) monitoring and hydrogeological modeling
- **This study** : Characterize the water content spatial heterogeneities in 3D VZ and 3D aquifer with a joint interpretation of 3D-SNMR and 3D electrical data

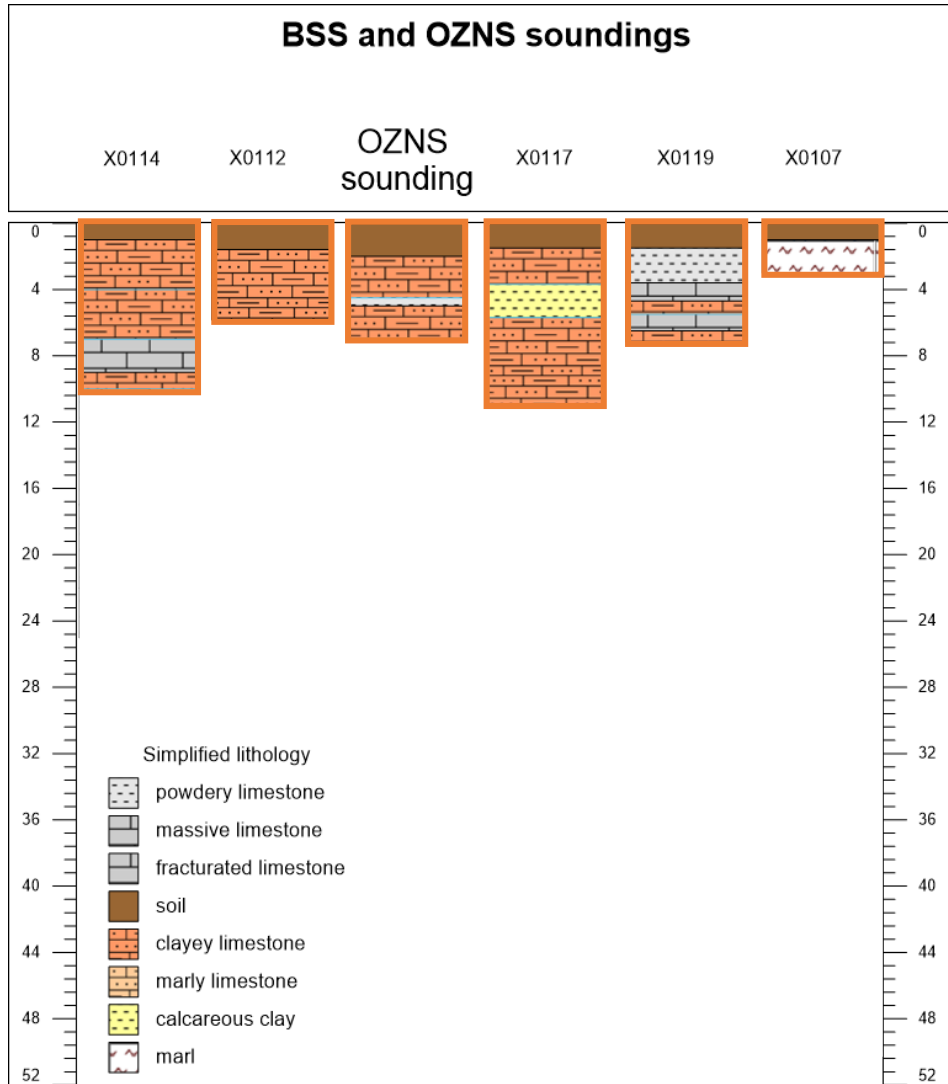
# Study site



## Villamblain study sites and BSS soundings (ID X01--)



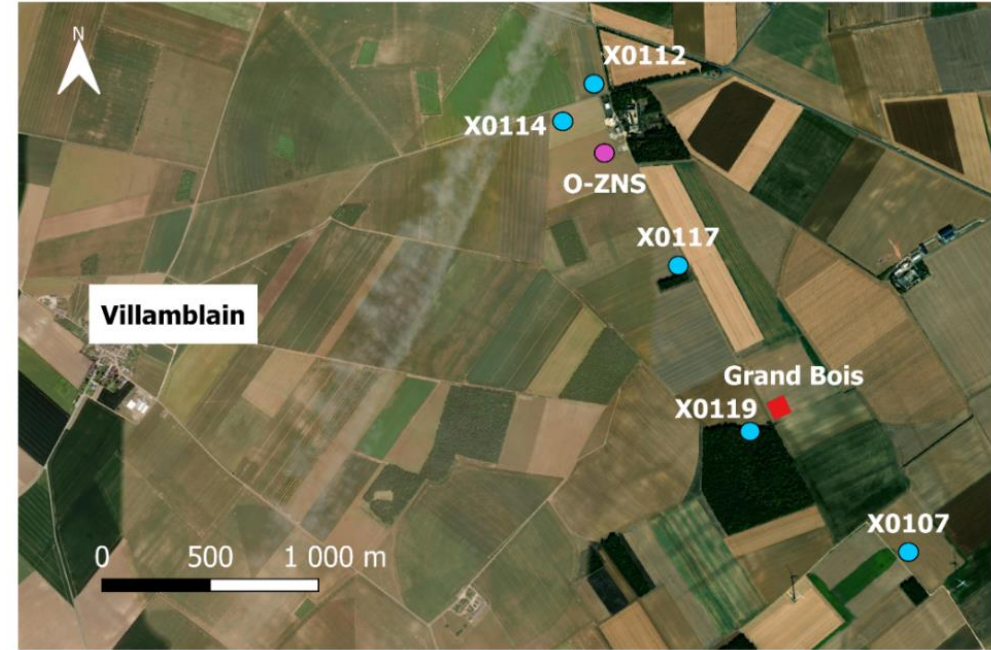
# Study site



Simplified  
geology

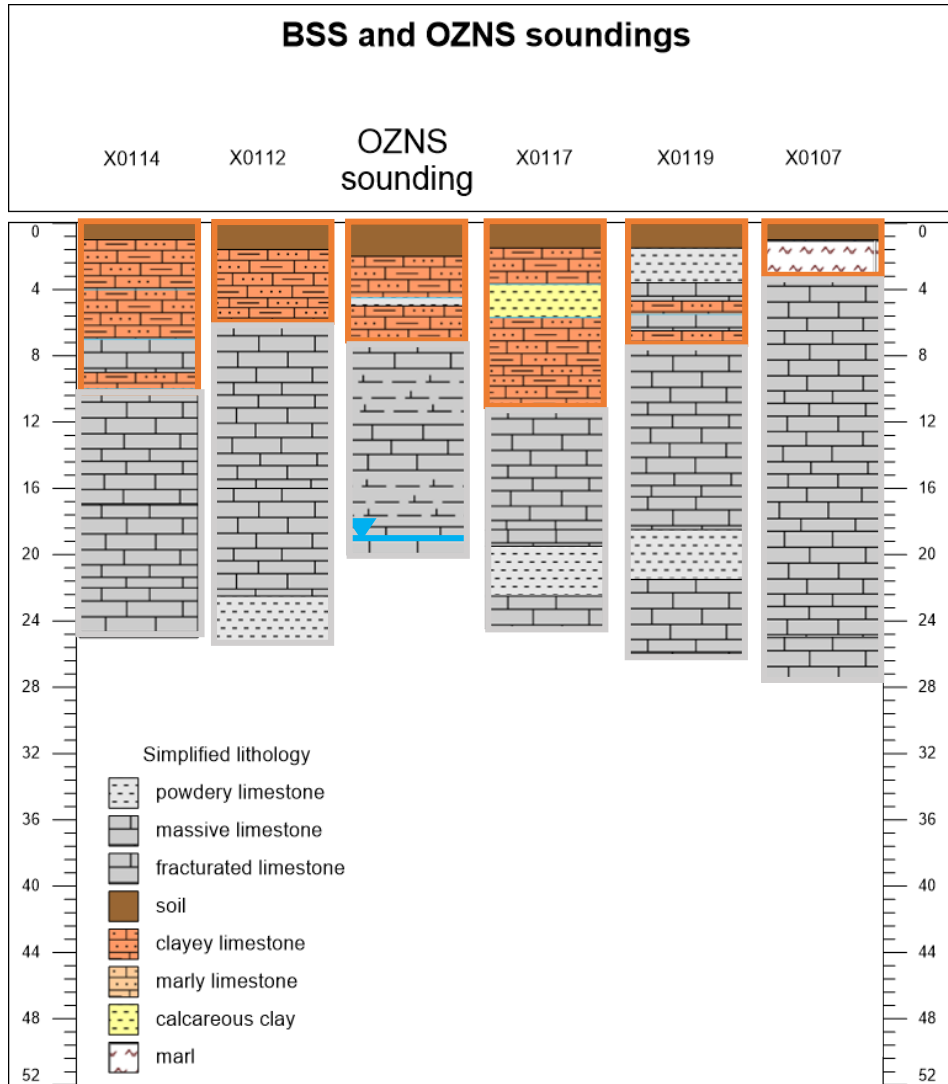
Highly weathered  
limestone

Villamblain study sites and BSS soundings (ID X01--)

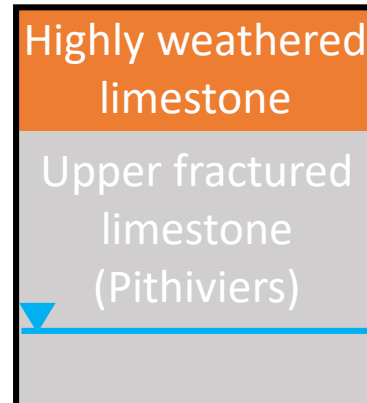




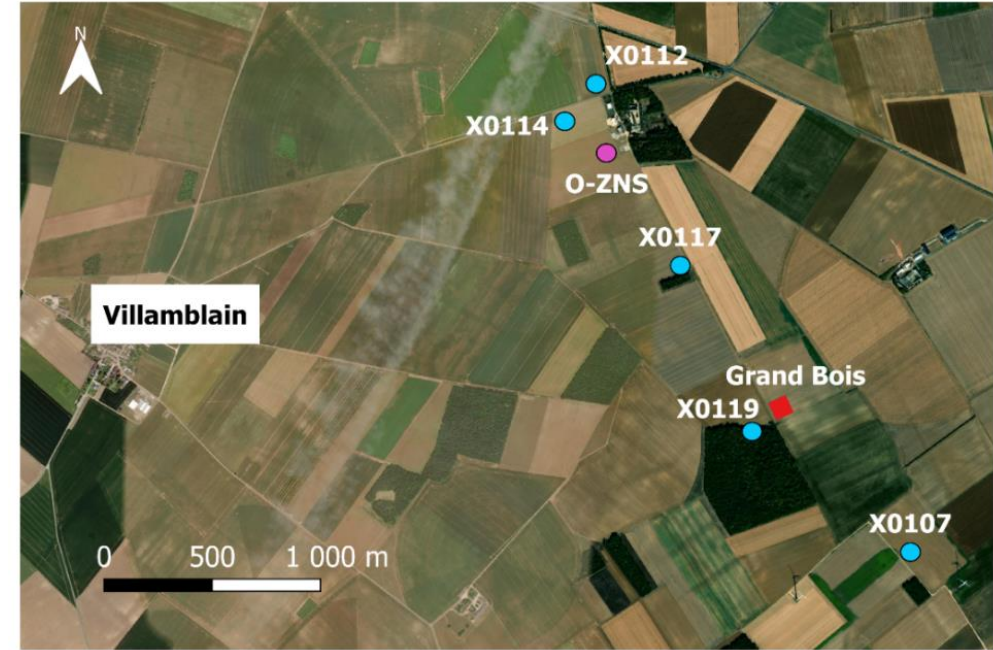
# Study site



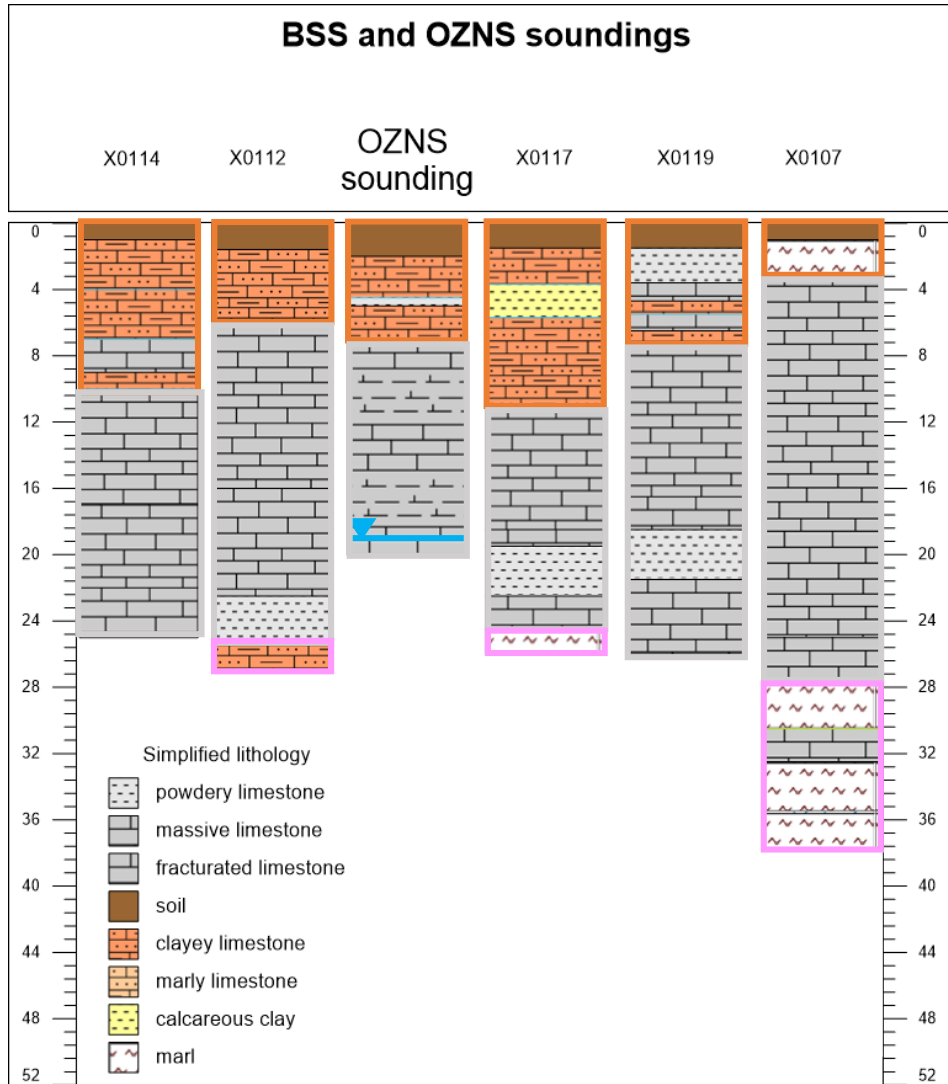
## Simplified geology



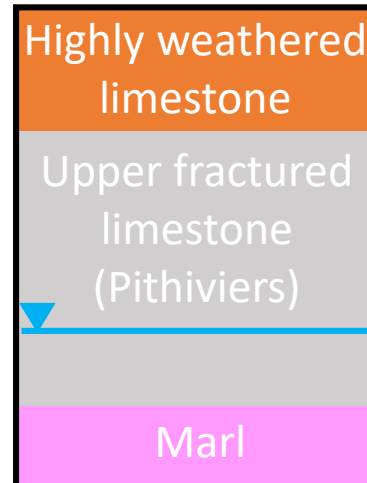
## Villamblain study sites and BSS soundings (ID X01--)



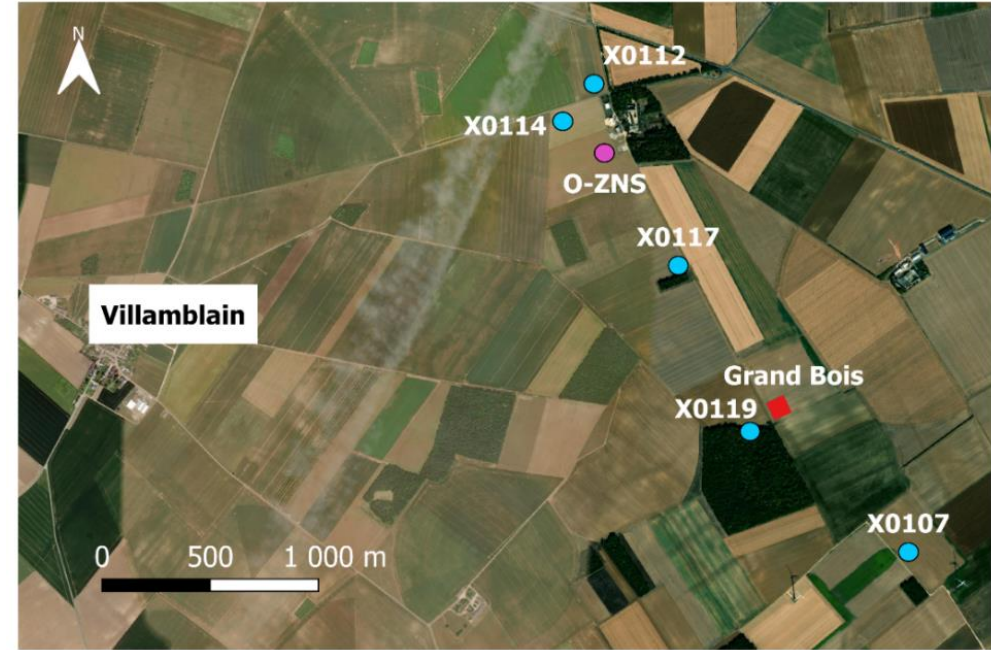
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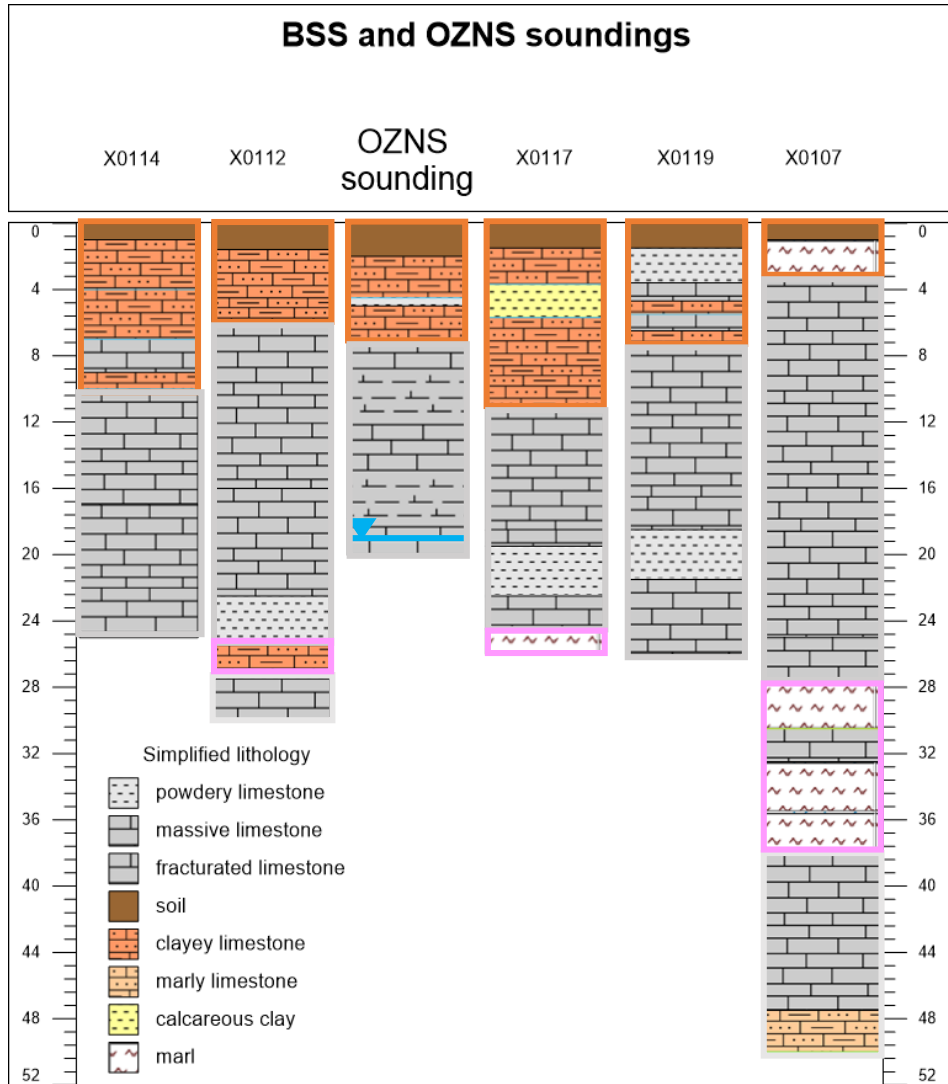
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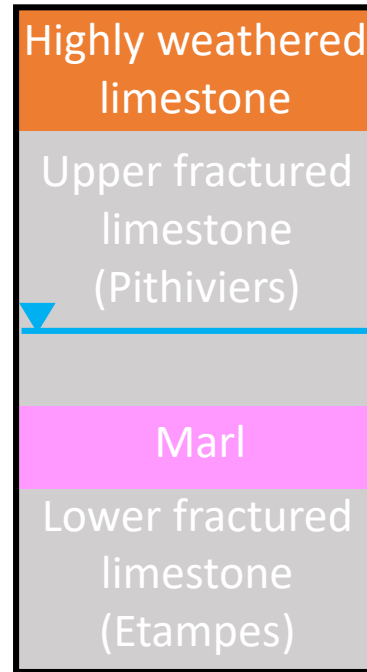
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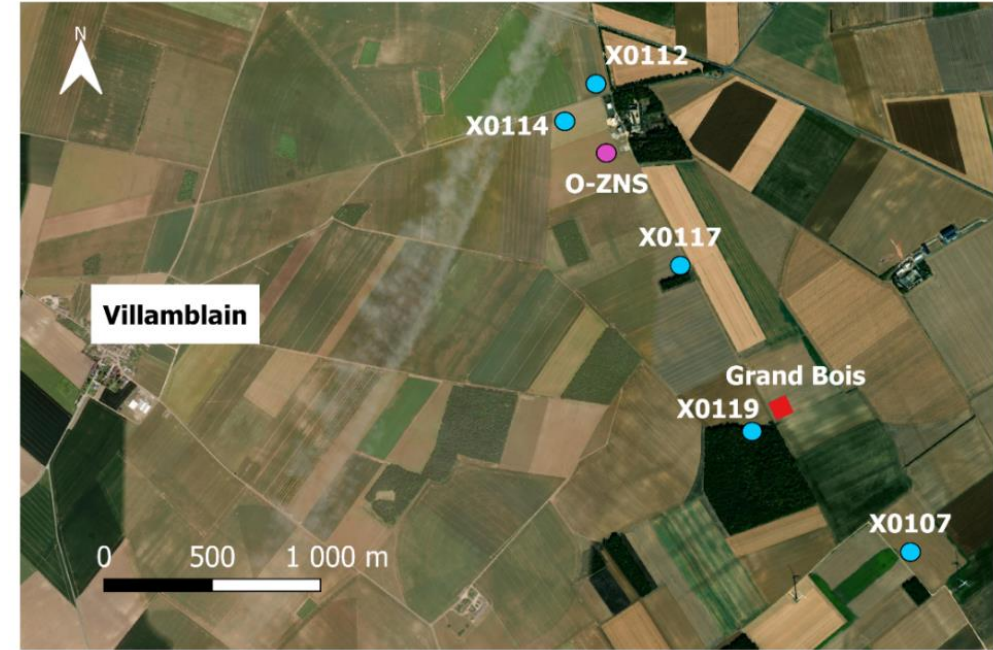
# Study site



## Simplified geology



## Villamblain study sites and BSS soundings (ID X01--)



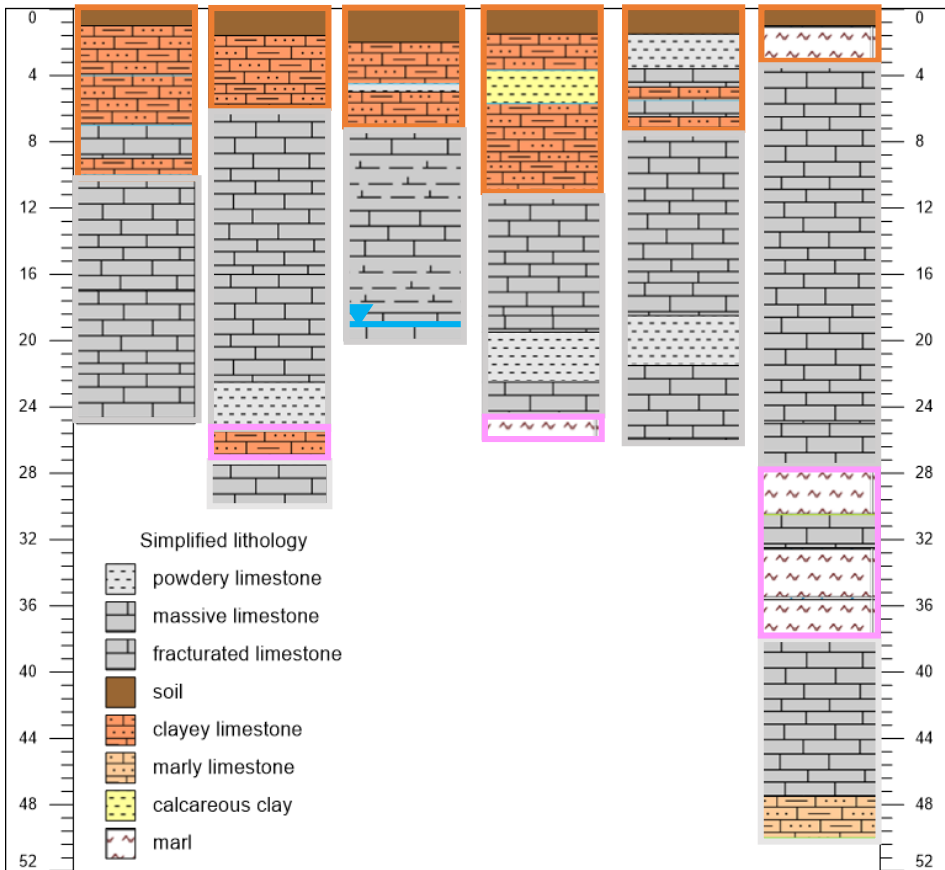
➤ Weathered and highly heterogeneous limestone in VZ



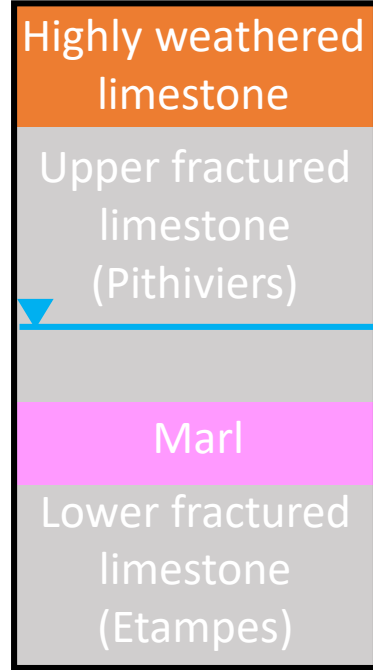
# Study site

## BSS and OZNS soundings

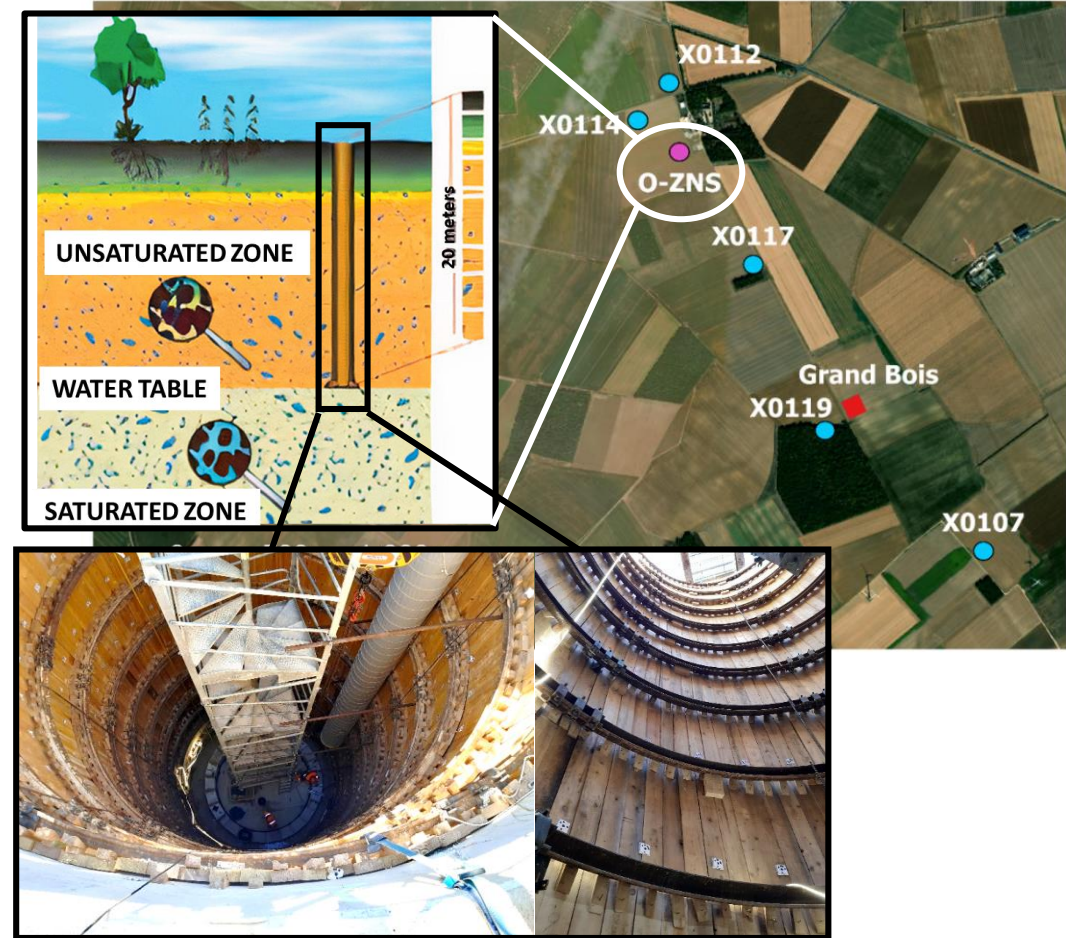
X0114    X0112    OZNS sounding    X0117    X0119    X0107



## Simplified geology



## Villamblain study sites and BSS soundings (ID X01--)

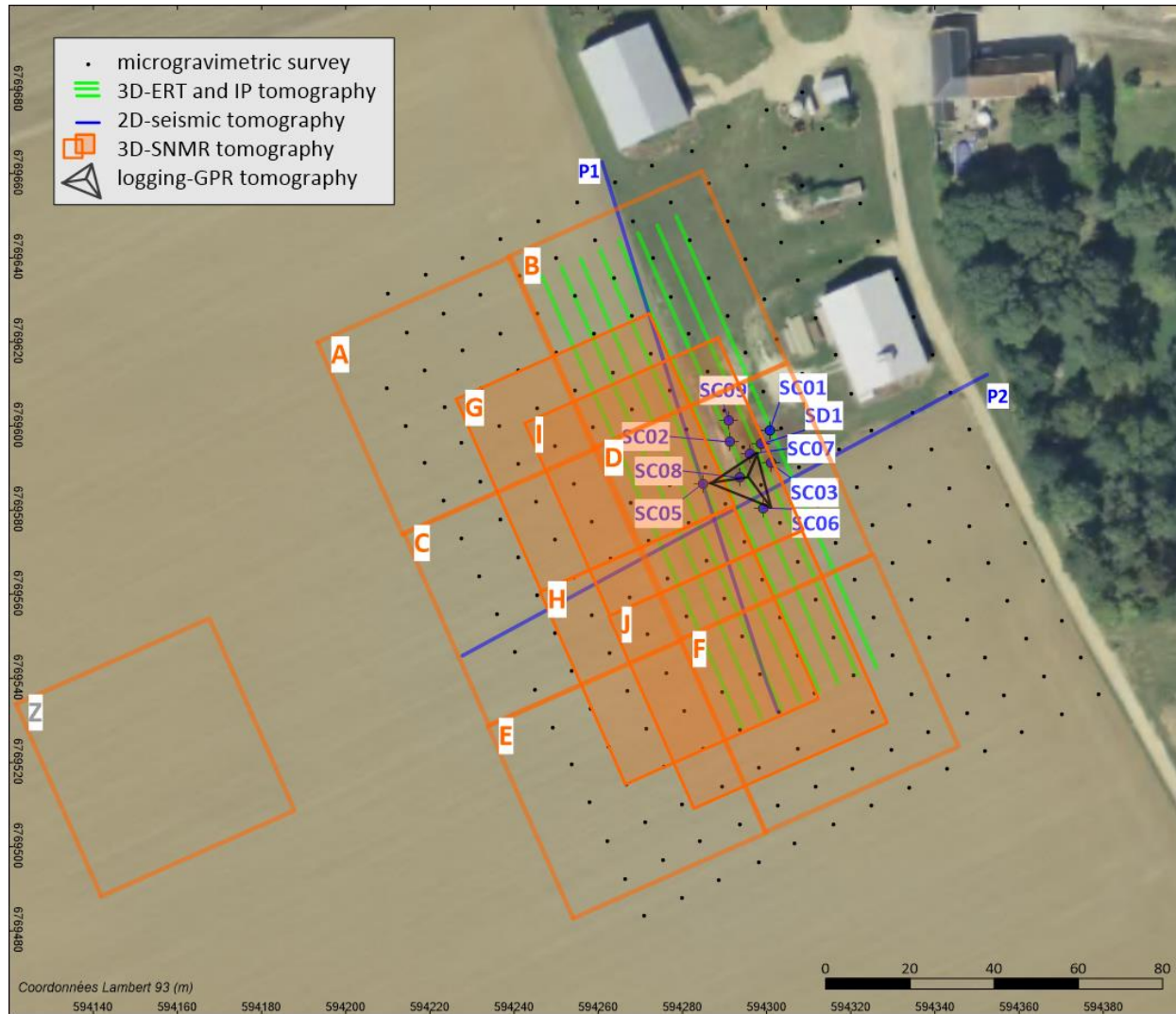


<https://plateformes-pivots.eu/o-zns/>

- Weathered and highly heterogeneous limestone in VZ
- O-ZNS study site

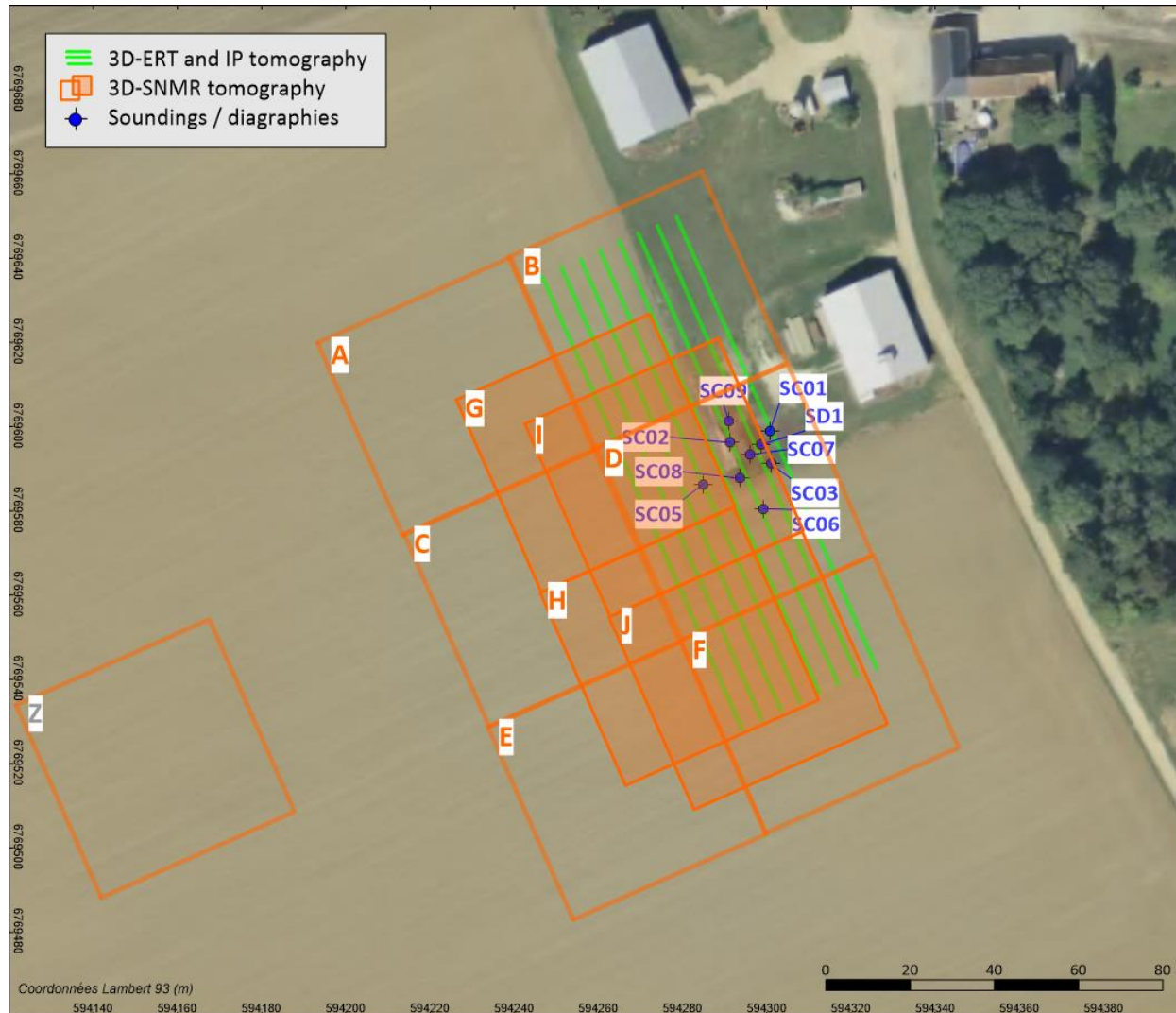


# Geophysical investigation and data processing



Map of geophysical investigations done simultaneously (09/2020) on OZNS study site before the well drilling

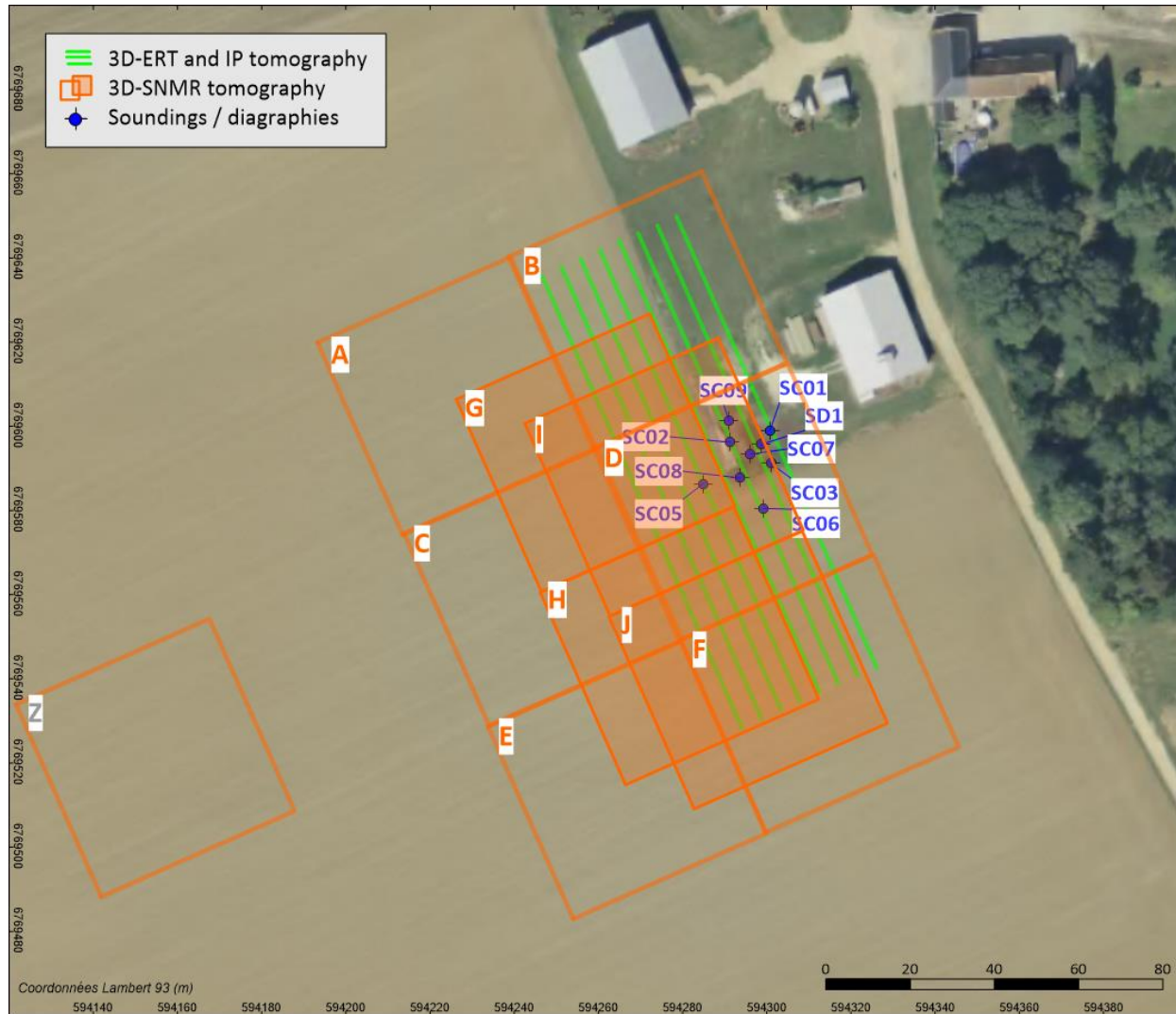
# Geophysical investigation and data processing



	SNMR	ERT/IP
Acquisition	10 soundings	8 profiles
Configuration	SQ 50m 2 tours Tx-Rx 16 pulses	48 electrodes 2.5m dipole-dipole
Device	Numis POLY (IRIS Instrument)	Syscal Pro switch (IRIS Instrument)
3D-inversion	Samovar	BERT

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## SNMR data

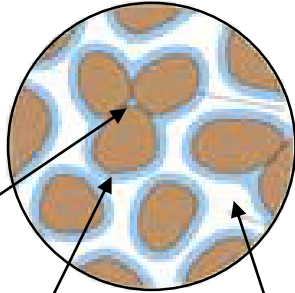
- S/N between 1.5 and 6.6 ; RMSE = 16.2 nV ;  
Noise level = 50 nV

## Electrical data

- ERT : RMSE = 7 %
- IP : preliminary result

# Data interpretation in the Beauce limestone context

Water in porous media

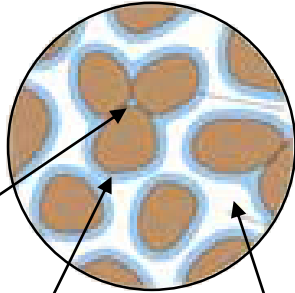


clay water	retention water	gravitational water
Total water content $w$ (%)		



# Data interpretation in the Beauce limestone context

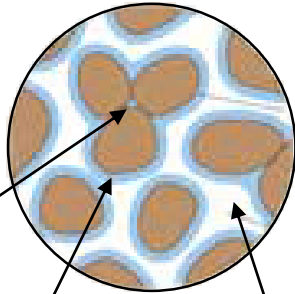
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clay water	retention water	gravitational water
Total water content $w$ (%)		
30	Relaxation time $T_2^*$ (ms)	1000

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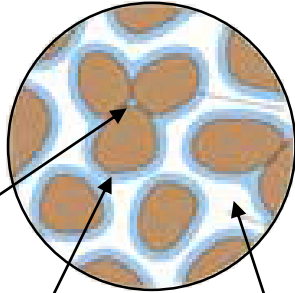
clay	retention	gravitational
water	water	water
	Total water content $w$ (%)	
	Relaxation time $T_2^*$ (ms)	1000
30		

SNMR detection threshold  
in Beauce limestone

Geophysical method	Parameter measured	Interpretation
SNMR	Water content	Decrease with clay content or with decreasing porosity
	Time relaxation	(Not used to date)

# Data interpretation in the Beauce limestone context

Water in porous media

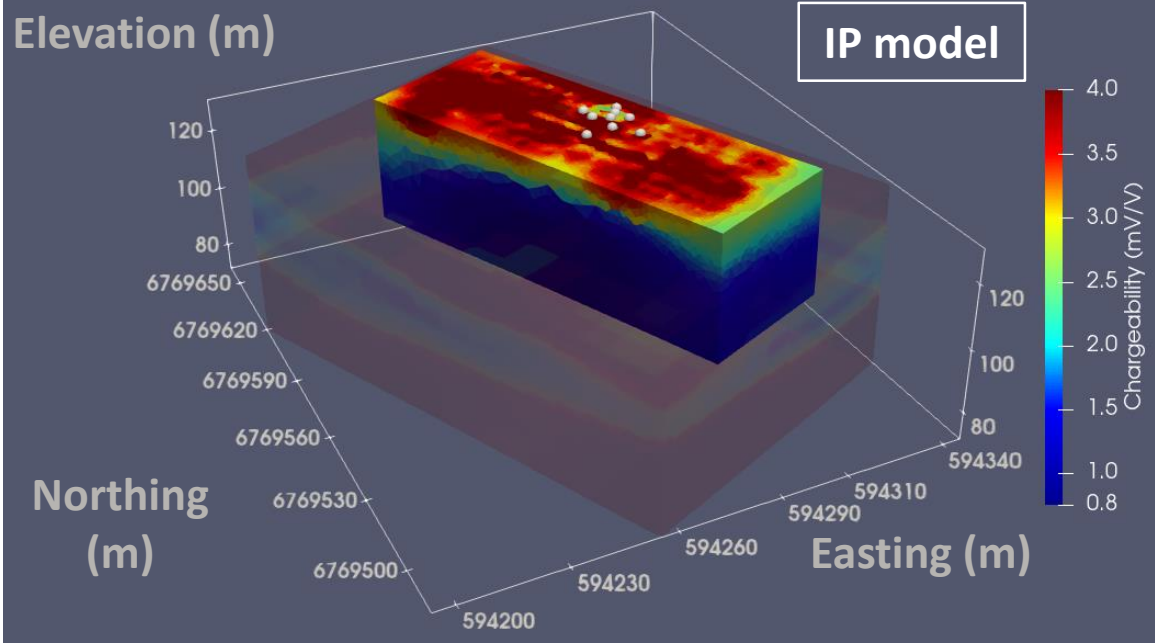
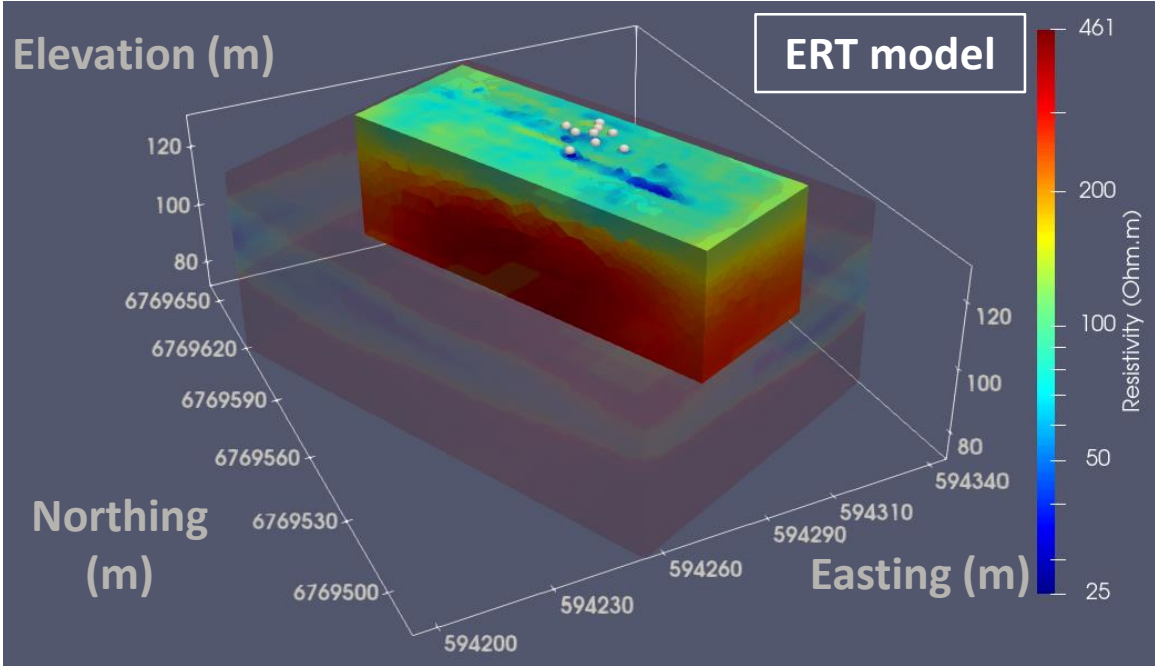
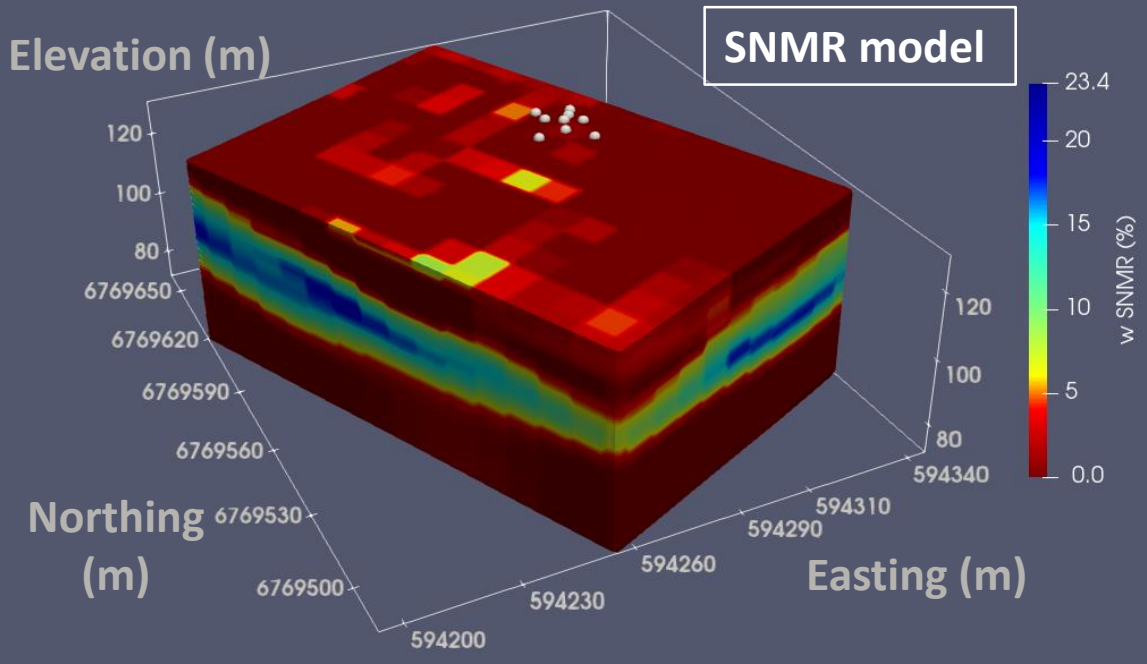


clay	Retention	gravitational
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SNMR detection threshold  
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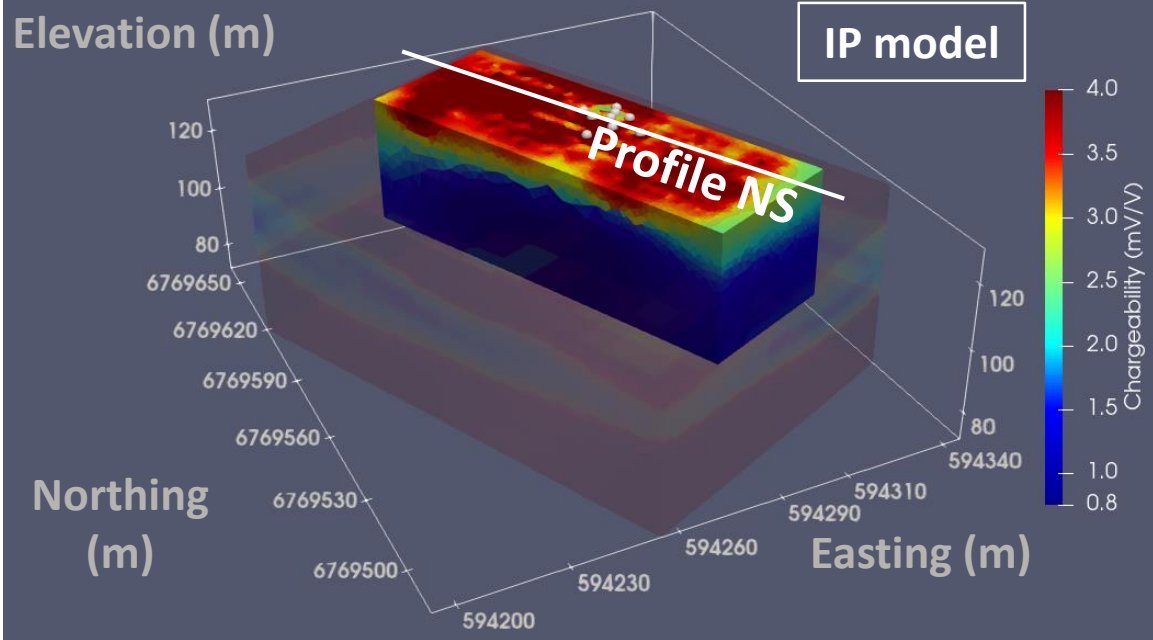
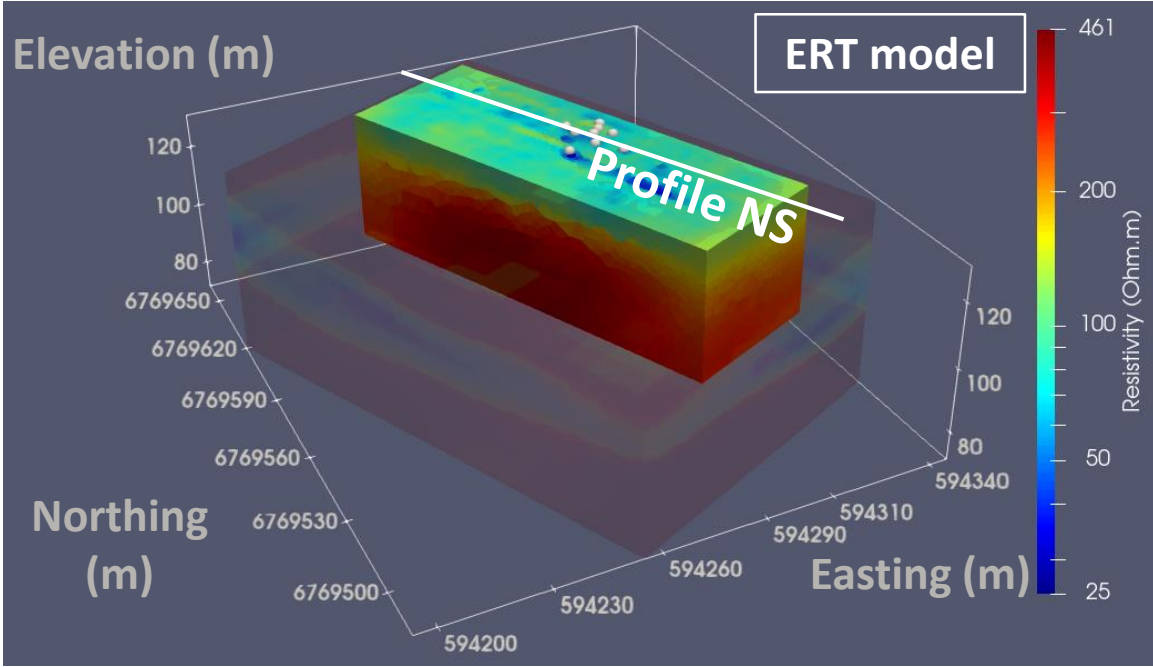
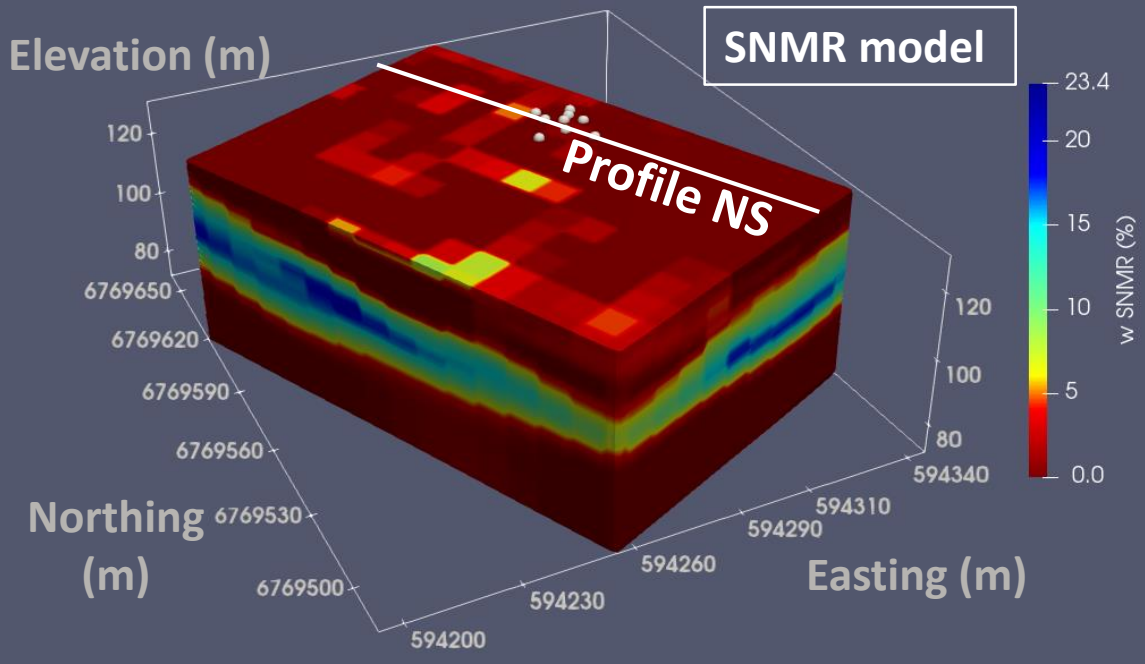
Geophysical method	Parameter measured	Interpretation
SNMR	Water content	Decrease with clay content or with decreasing porosity
	Time relaxation	(Not used to date)
ERT	Electrical resistivity	Decrease with clay content and/or limestone alteration
IP	Chargeability	Increase with clay content

# 3D SNMR and ERT/IP inverse models

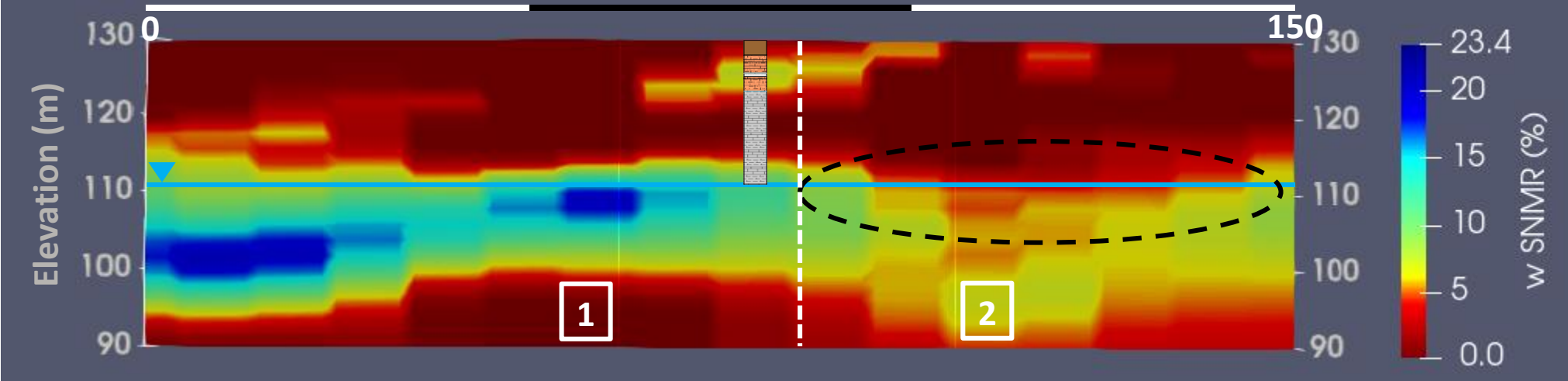




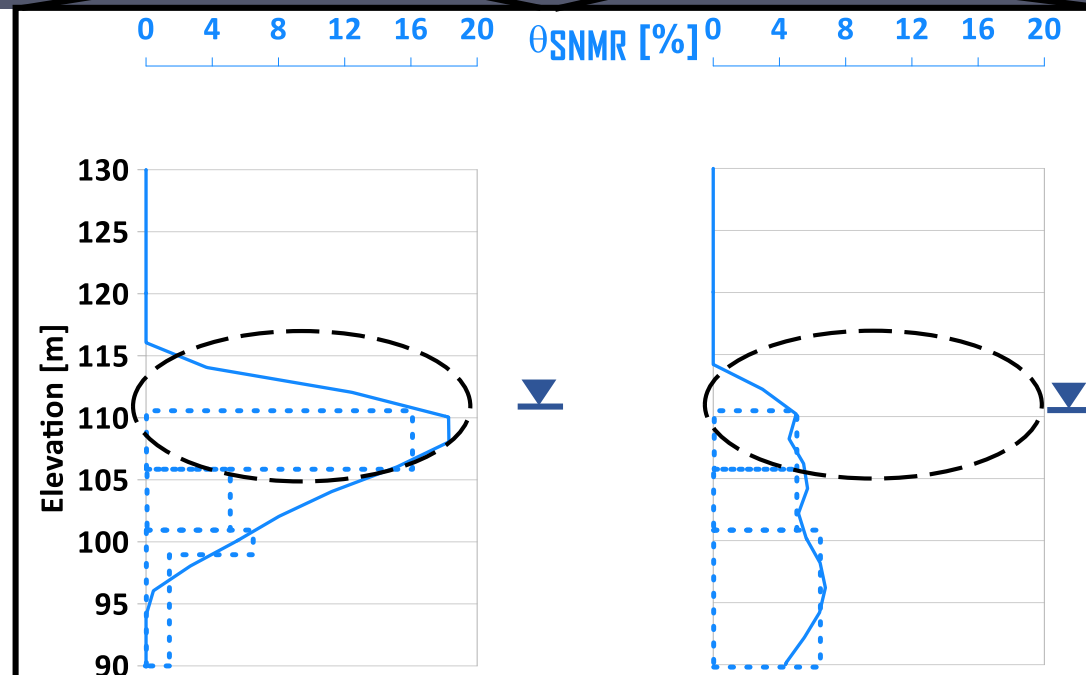
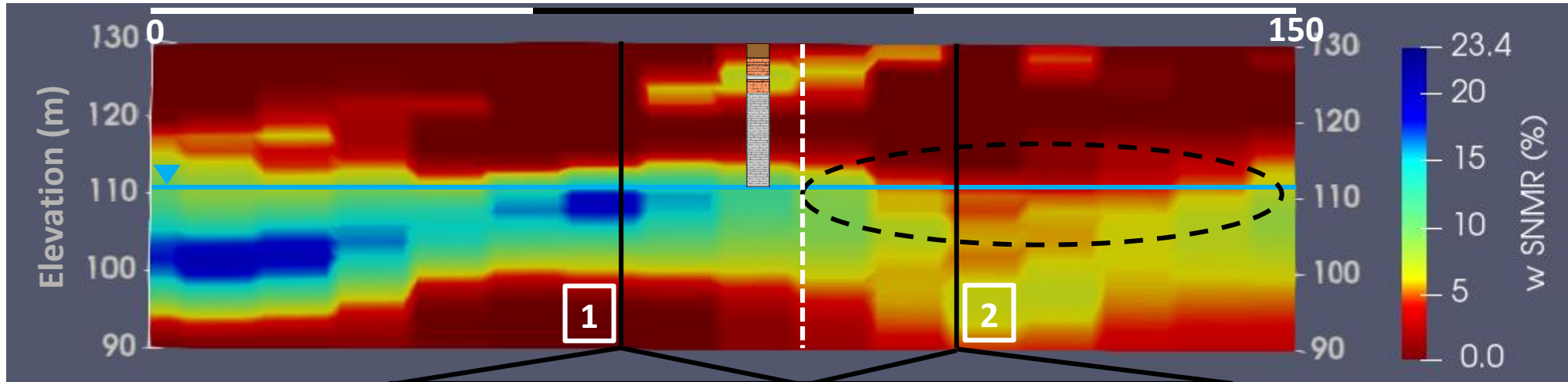
# 3D SNMR and ERT/IP inverse models



# Water content heterogeneities resulting from SNMR 3D inversion



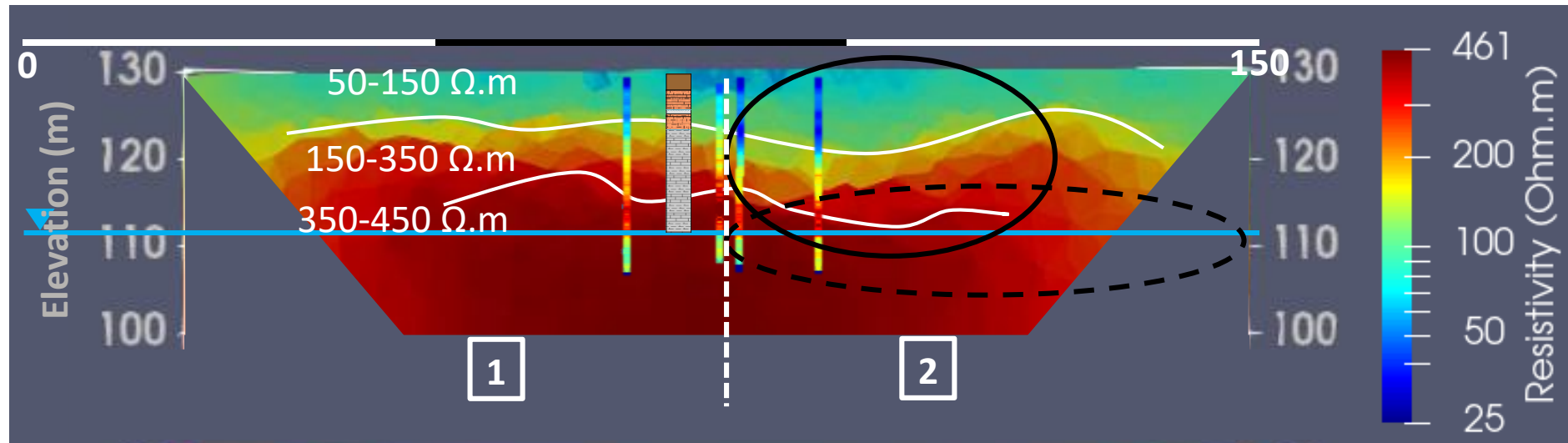
# Water content heterogeneities resulting from SNMR 3D inversion



## Legend :

- ▼ Water level
- Inverted water content
- ⋯ Schematic water content

# Identification of lithological heterogeneities from electrical 3D inversion results

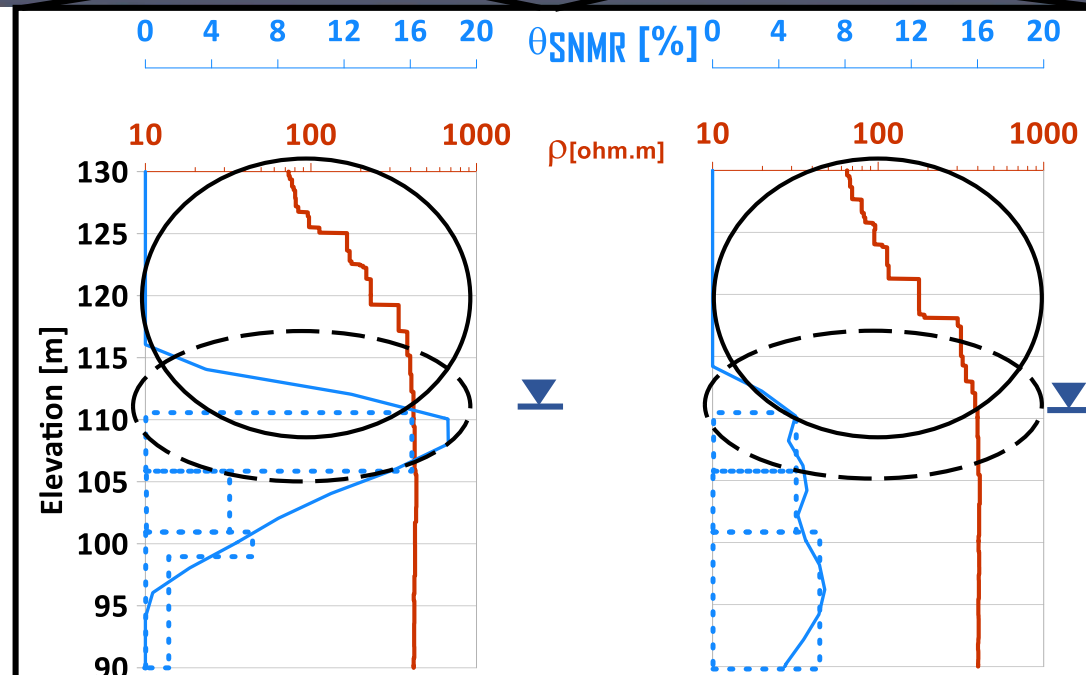
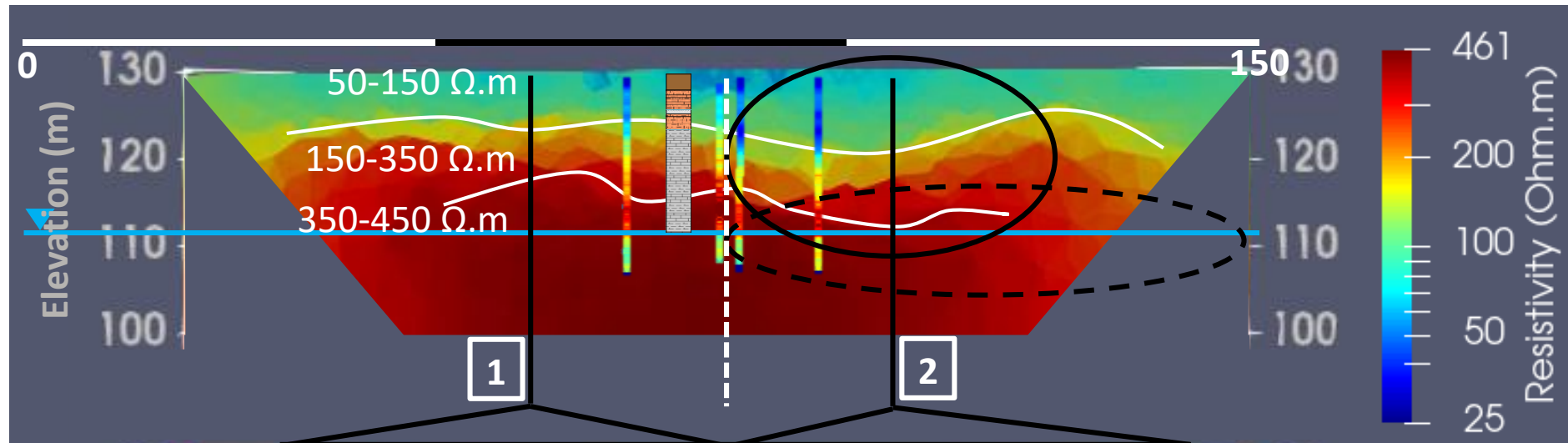


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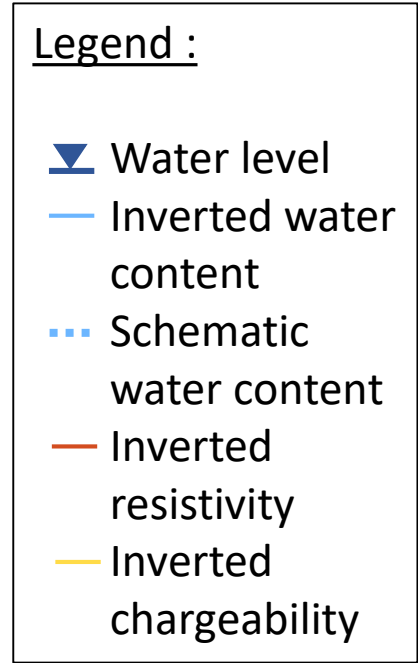
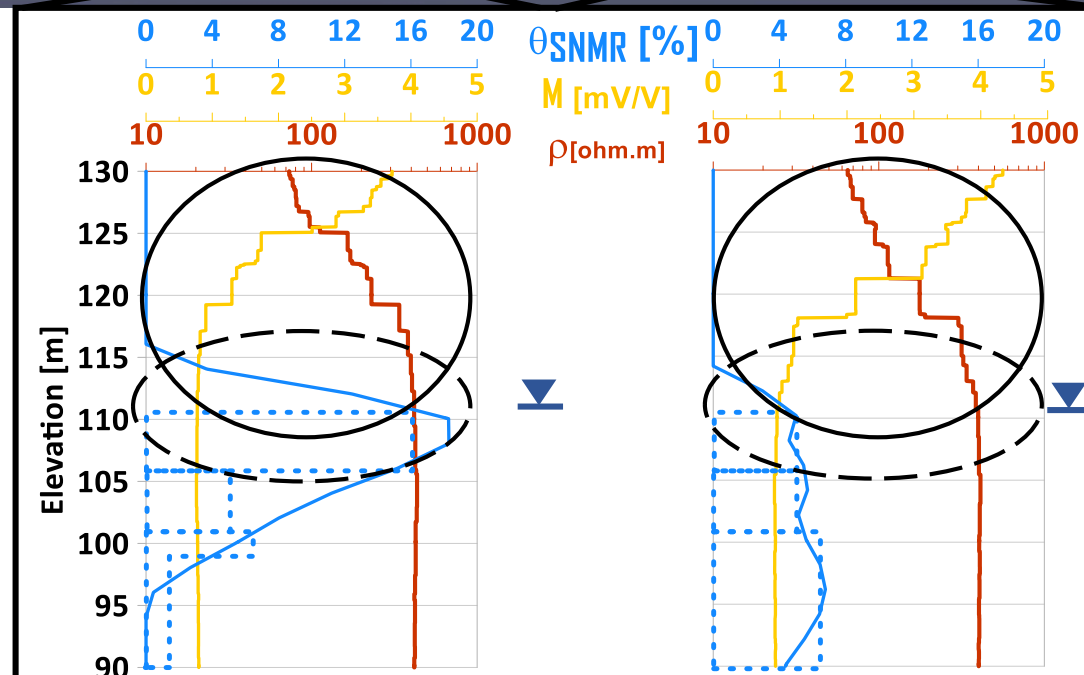
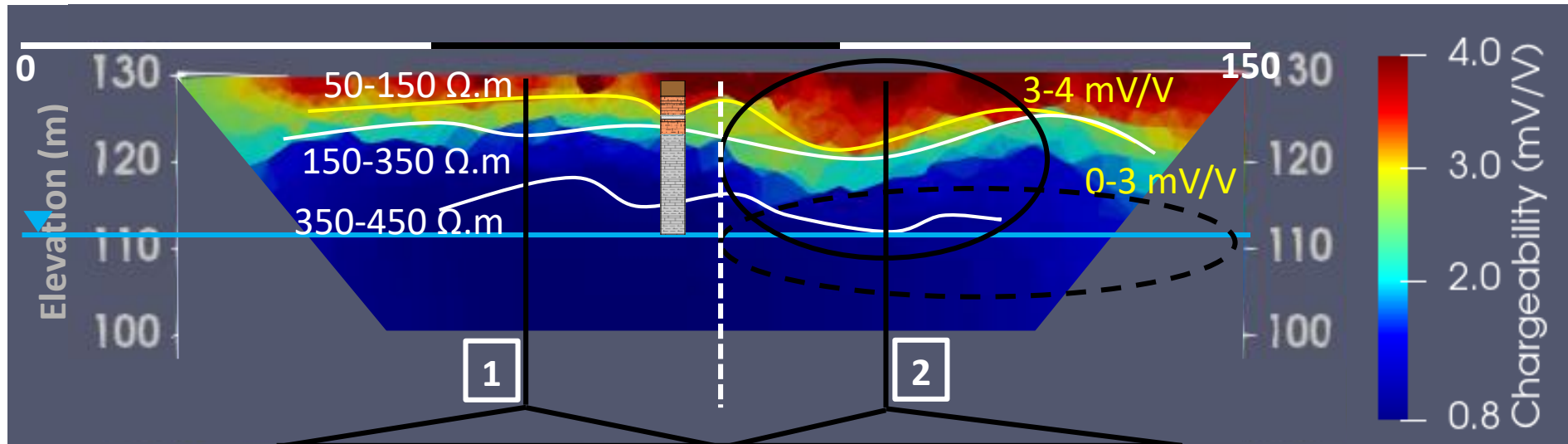
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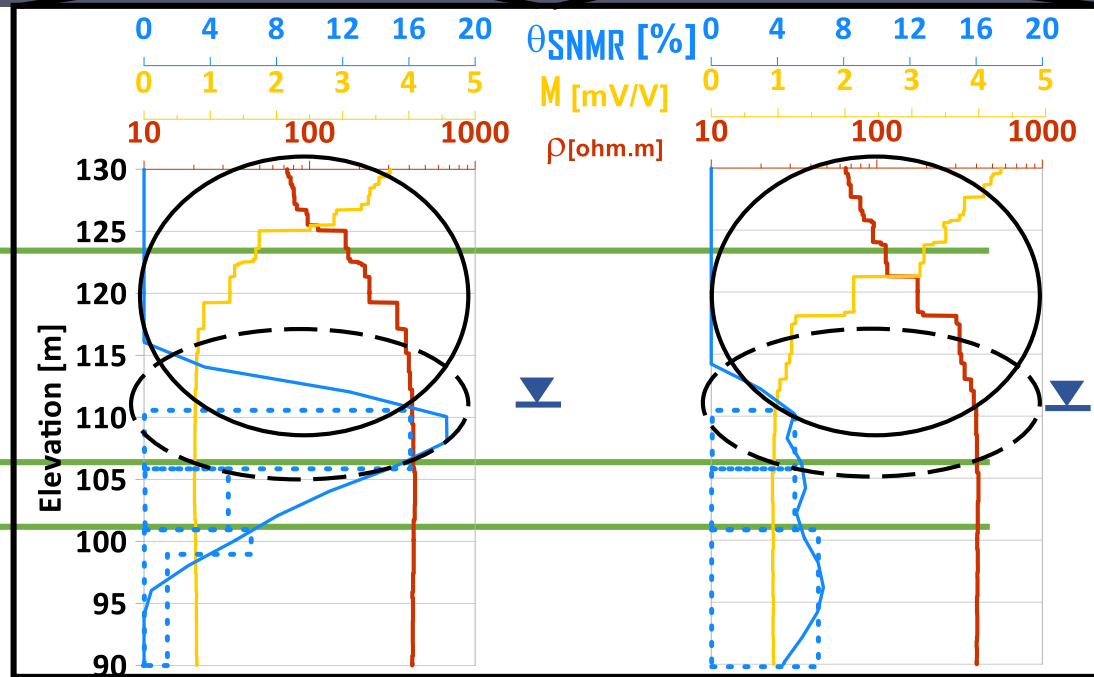
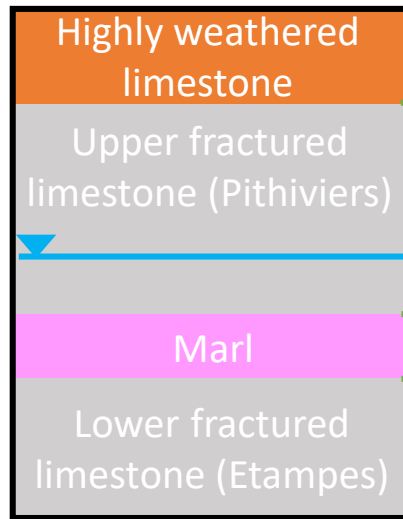
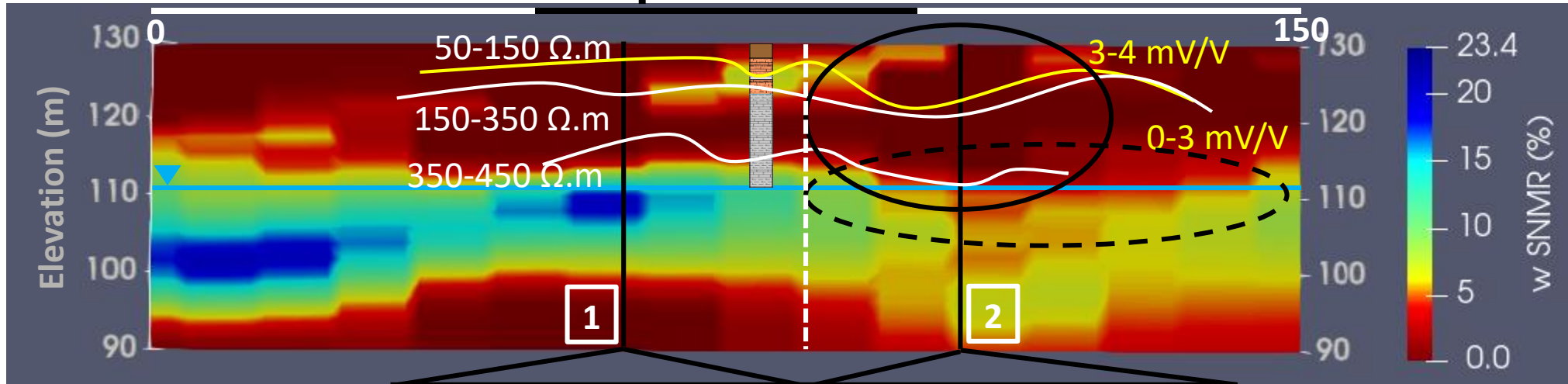
## Legend :

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- Inverted water content
- - - Schematic water content
- Inverted resistivity

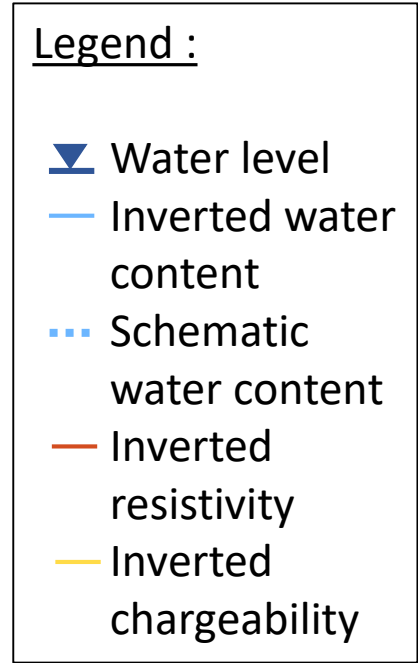
# Identification of lithological heterogeneities from electrical 3D inversion results



# SNMR water content and geoelectrical model of an anomalous area in weathered Beauce Limestone aquifer and ZNS



**FRACTURATED LIMESTONE**      **CLAYEY LIMESTONE**



# Conclusion and perspectives

## Conclusion :

Joint interpretation of SNMR and ERT/IP data in a 3D aquifer and VZ :

- Identify spatial heterogeneities
- Variable hydrogeological properties : Lithology + water content

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Variable hydrogeological properties => variable hydrodynamic and VZ flow properties ?



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- Identify spatial heterogeneities
- Variable hydrogeological properties : Lithology + water content

Variable hydrogeological properties => variable hydrodynamic and VZ flow properties ?

## Future work :

Use these results to characterize the VZ hydrodynamic and flow properties with :

- Time-lapse SNMR monitoring
- Hydrogeological modeling



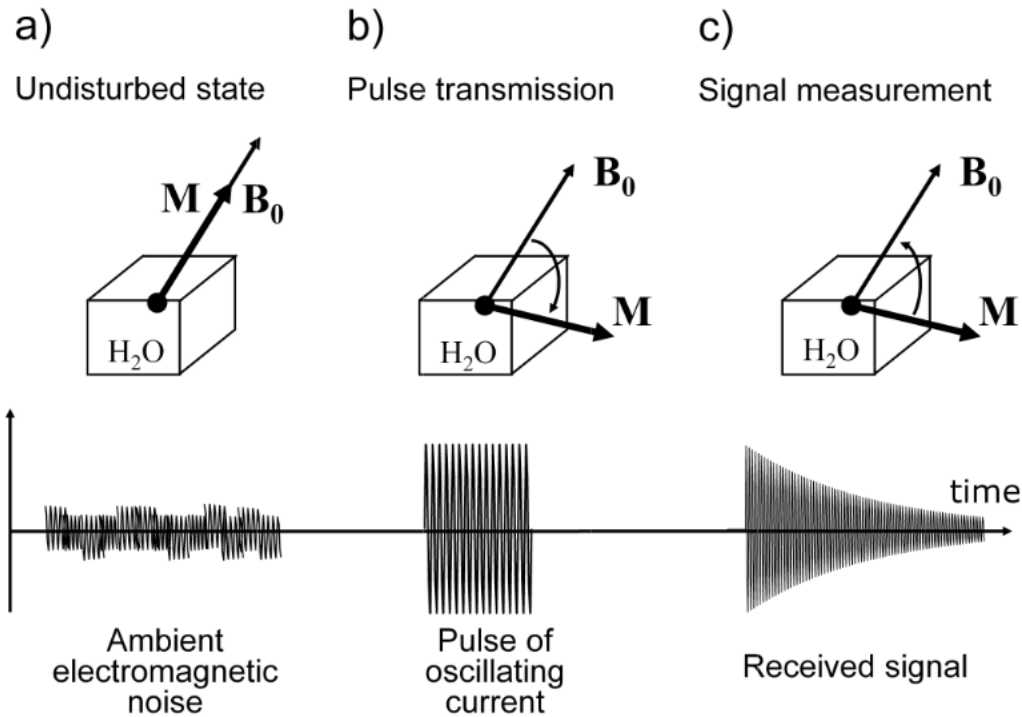
Abstract

# Thank you

Clémence Ryckebusch, J-M. Baltassat, A. Legchenko, P. Kessouri, N. Amraoui, J. Deparis, M. Abbas, M. Azaroual

Contact : [c.ryckebusch@brgm.fr](mailto:c.ryckebusch@brgm.fr)

# SNMR principles



Relaxation time  
 $\propto$  Mean Pore  
 size

Signal amplitude  
 $\propto$  Water content

**Measurement scale :**

Multidecametric (field)

**Data measured :**

Signal amplitude, relaxation time

**Parameters :**

Water content, mean porosity distribution

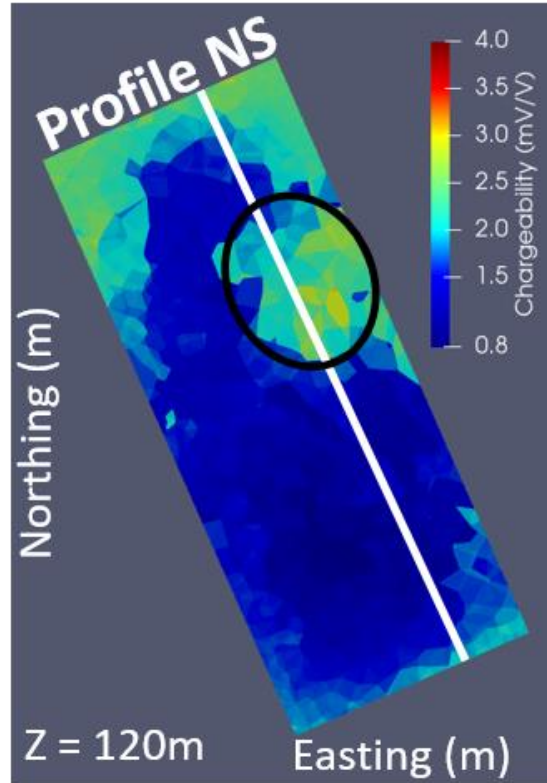
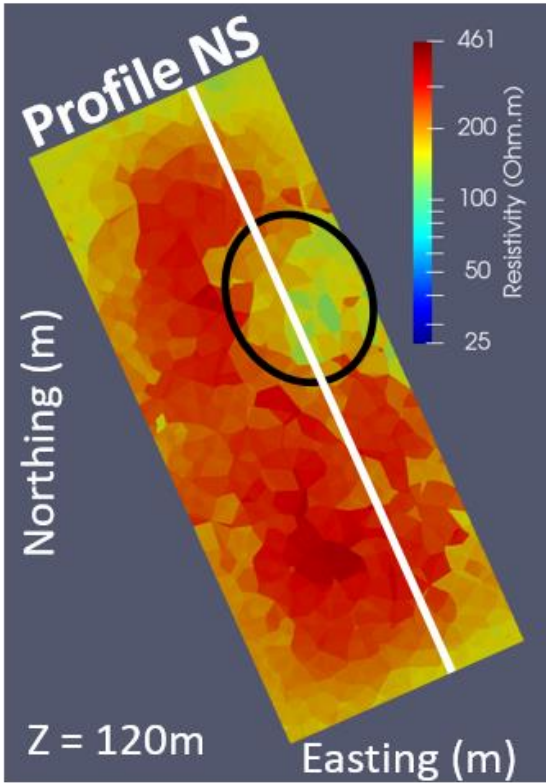
**Particularity of field NMR :**

No detection of water content for smaller  
 pore sizes

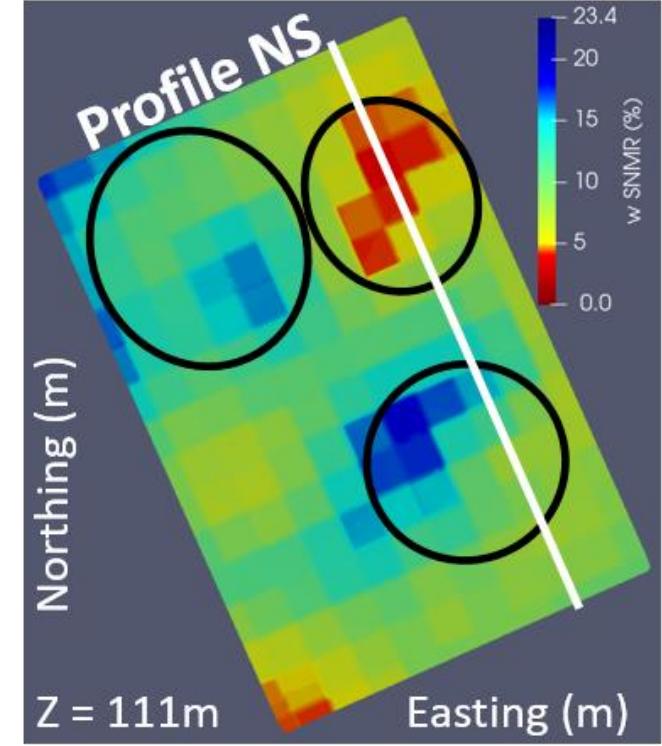
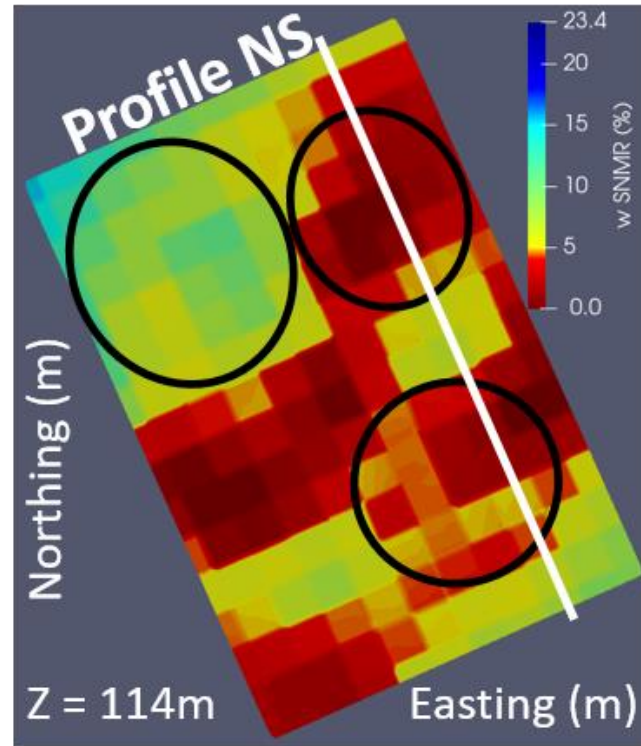
**Figure 1.1.** Typical phases of a magnetic resonance experiment (top) and corresponding magnetic resonance measurements (bottom)

Source : LEGTCHENKO, Anatoly, 2013. *Magnetic Resonance Imaging for Groundwater*. John Wiley & Sons. ISBN 978-1-118-64947-3

# 3D water content and lithological spatial heterogeneities



Maps of electrical resistivity (left) and chargeability (right) at an elevation of 120 m (vadose zone)



SNMR Water content maps at an elevation of 114 m (vadose zone) and 111 m (aquifer)