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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)

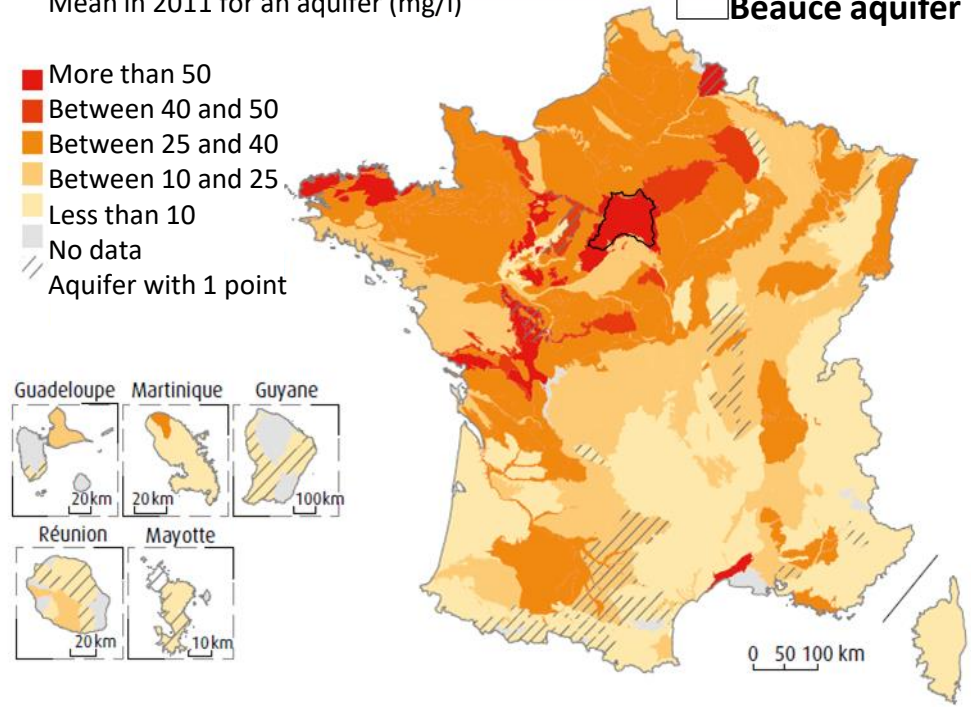
# Context of the study

## 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



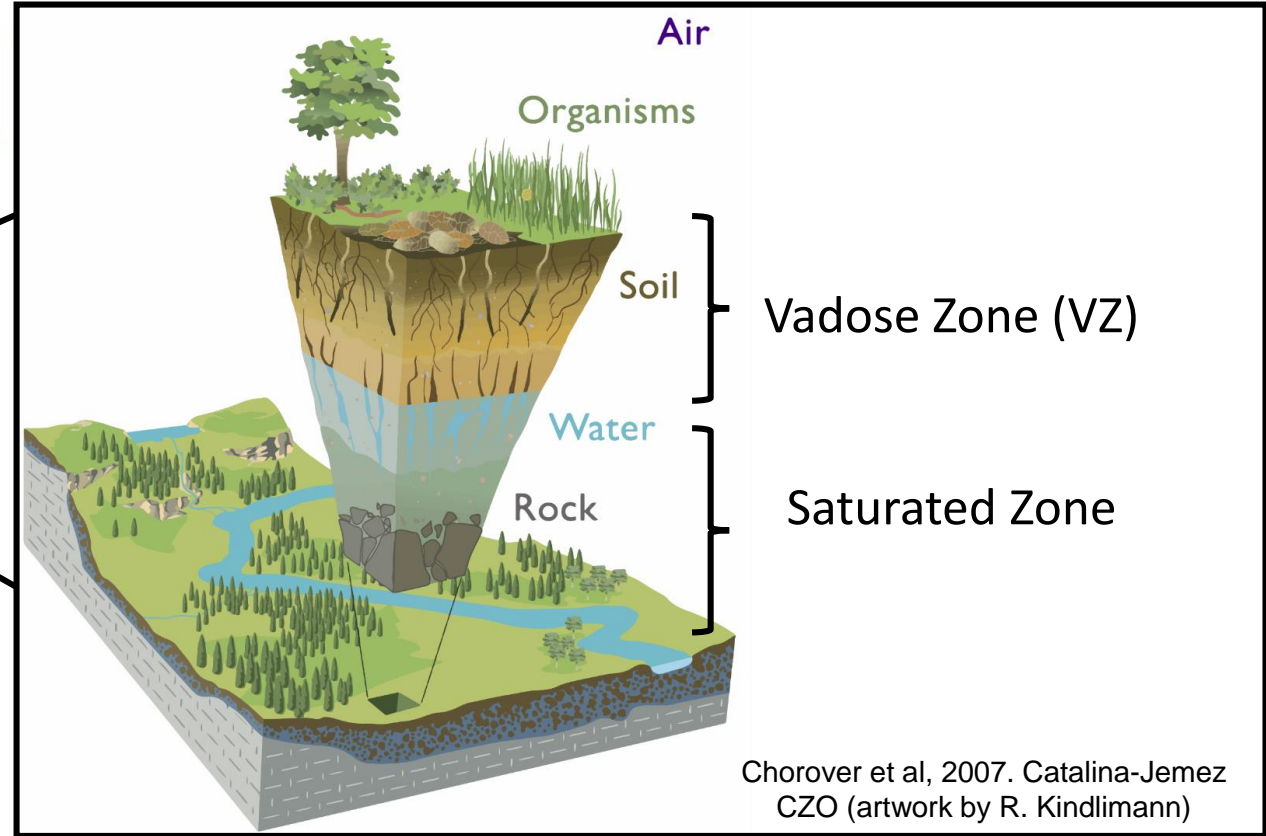
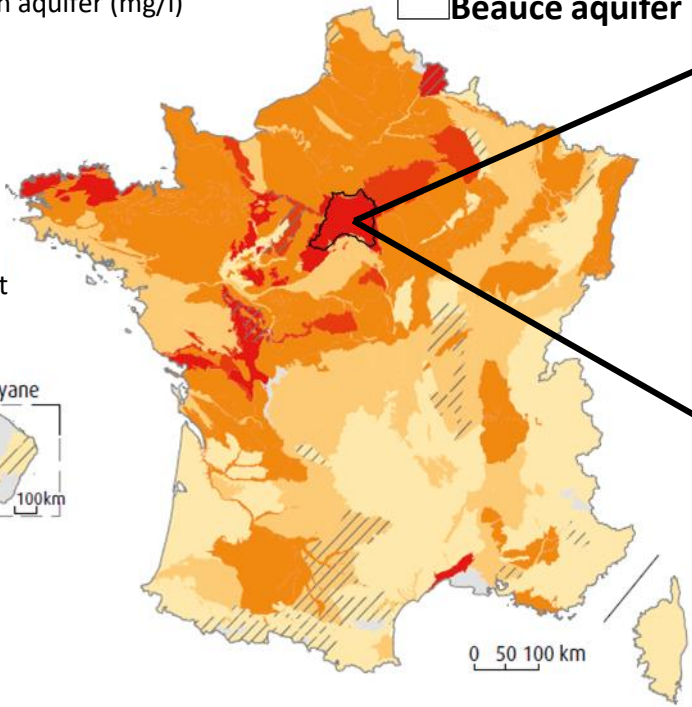
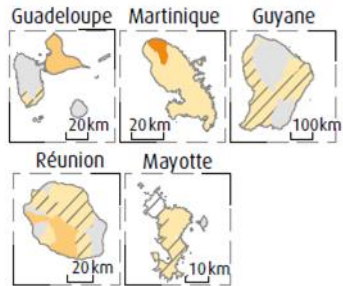
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Chorover et al, 2007. Catalina-Jemez CZO (artwork by R. Kindlimann)

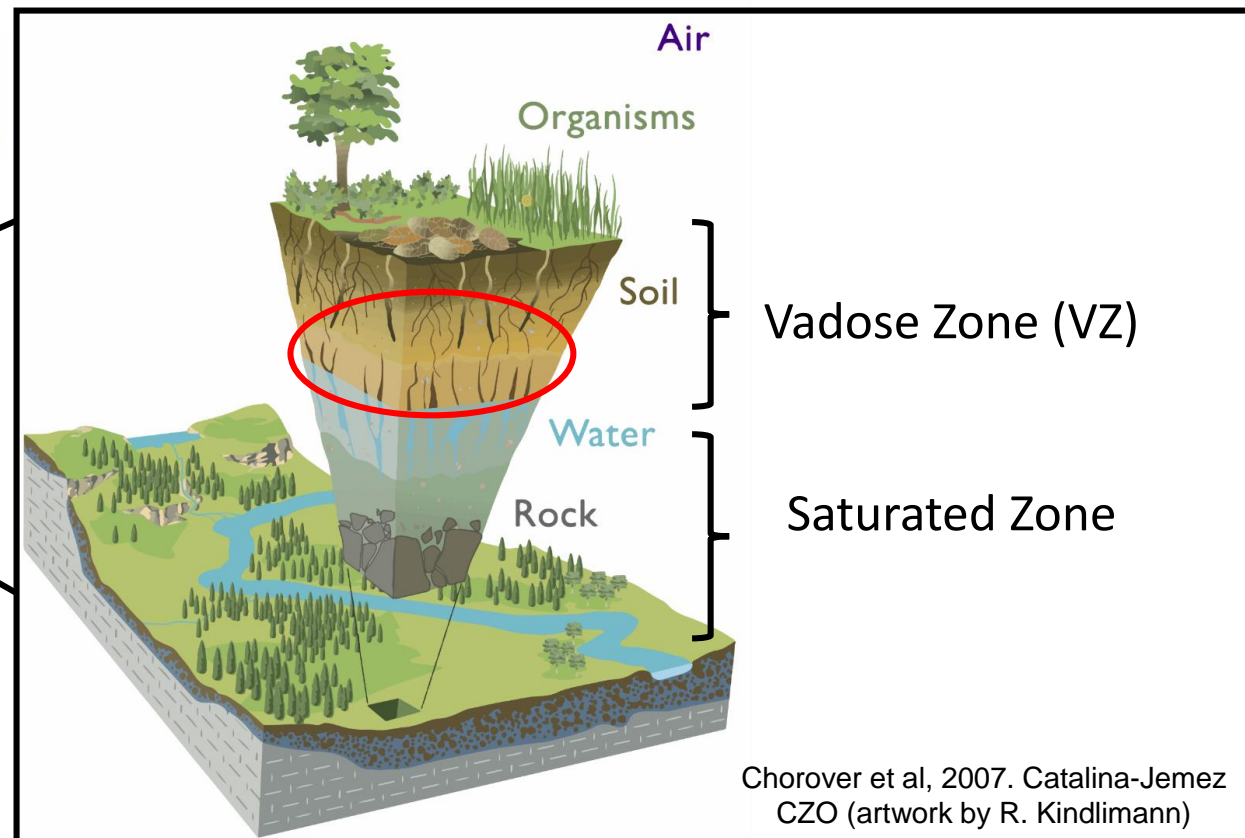
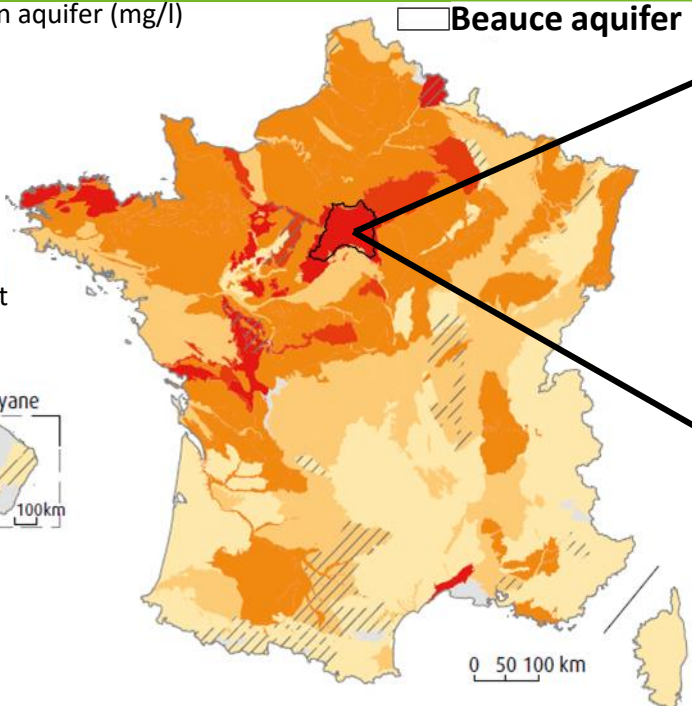
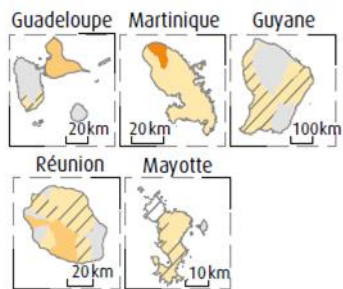
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### Problem

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

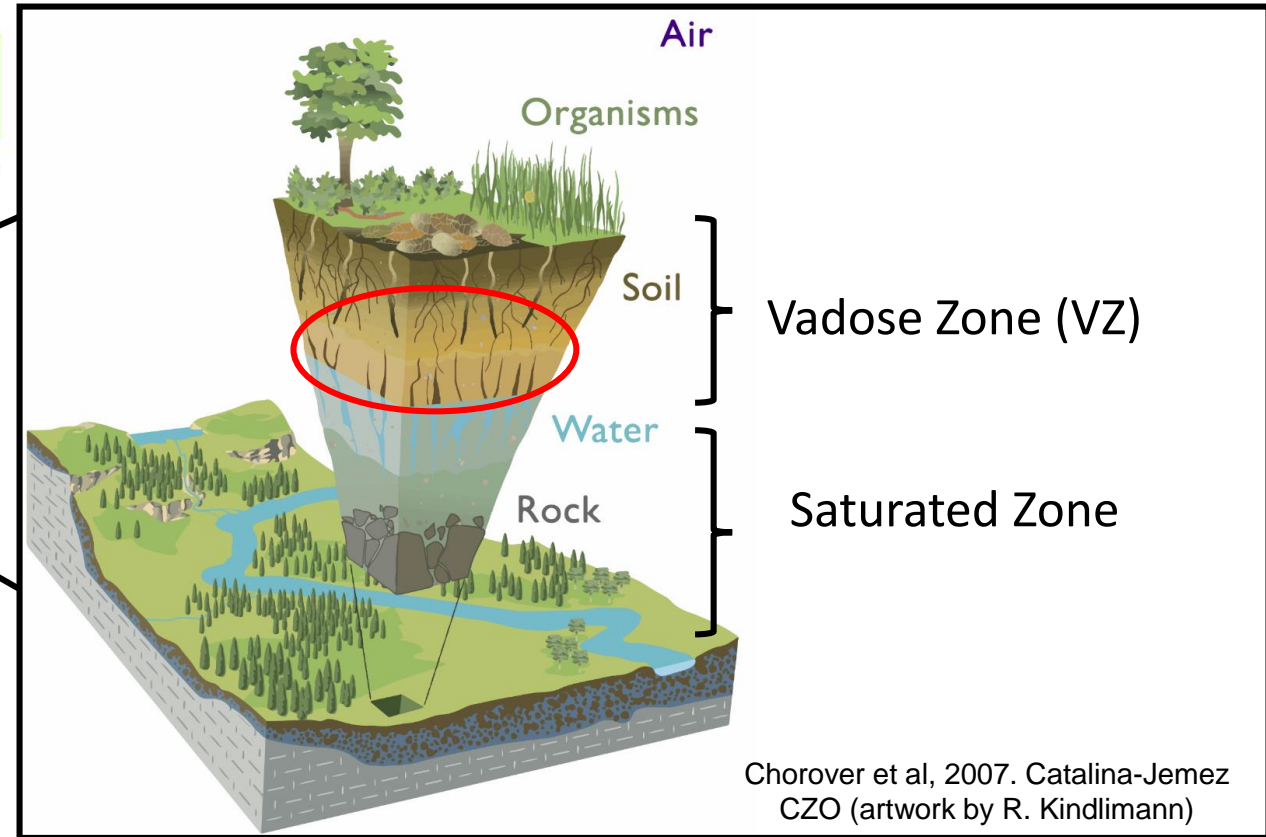
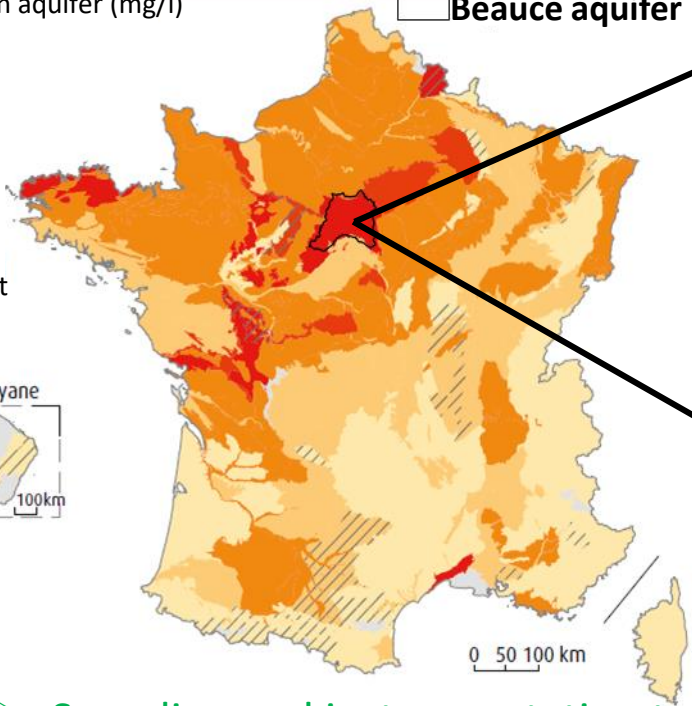
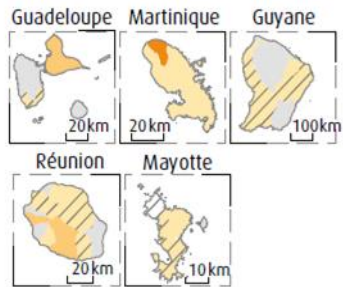
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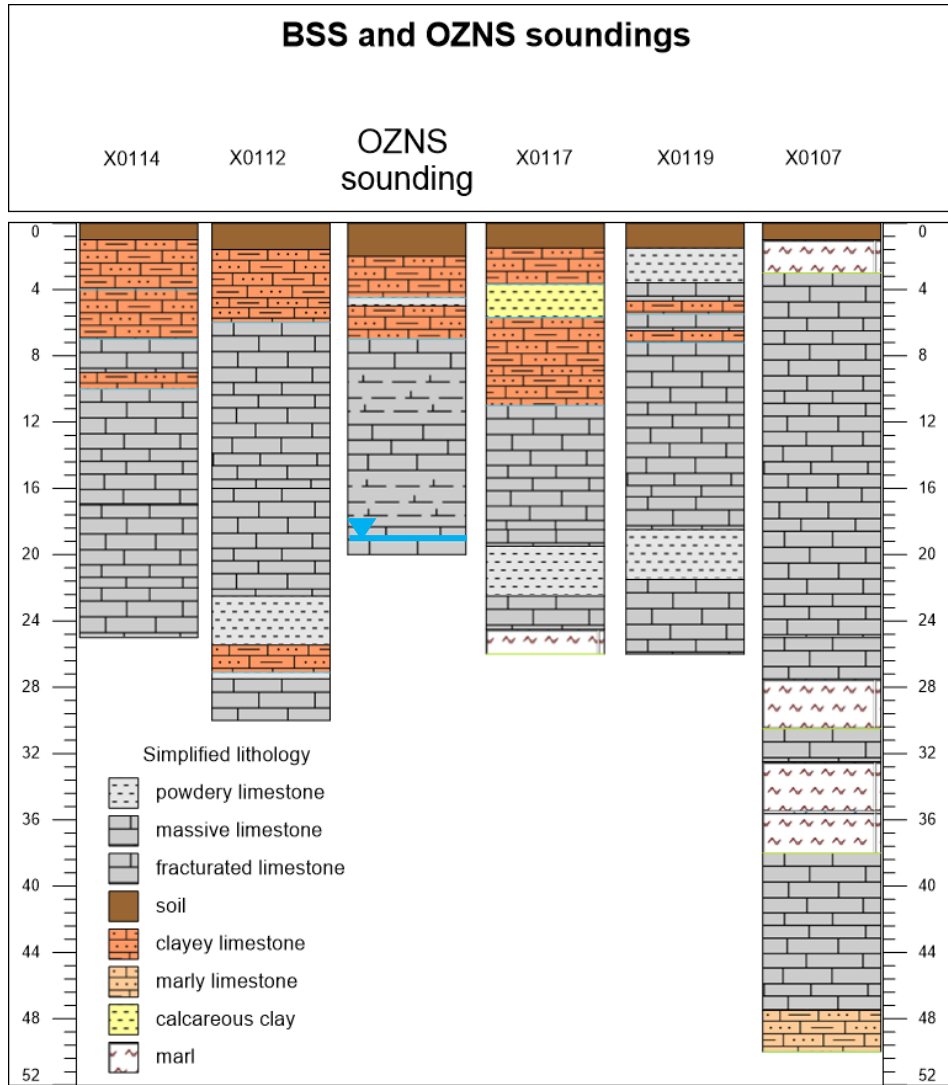
### Problem

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- Heterogeneity and complex behavior in vadose zone

### 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

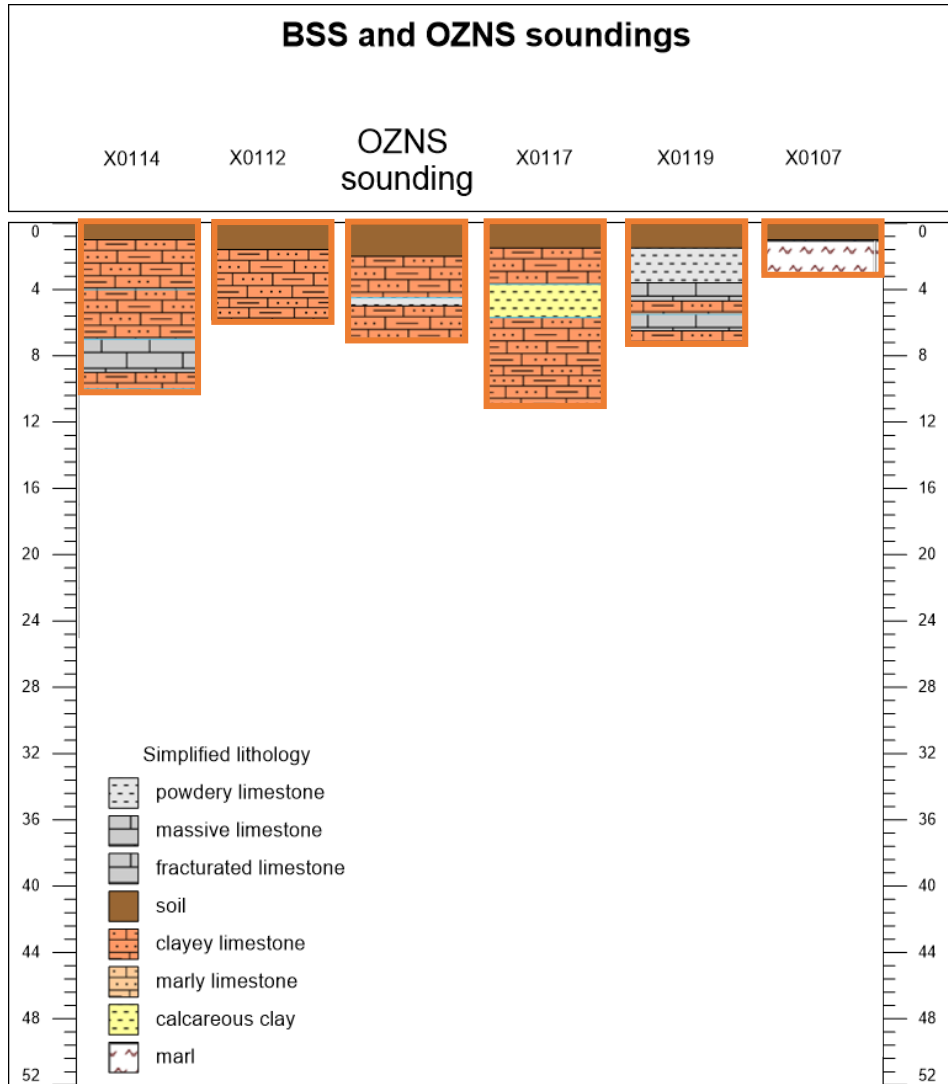
# Study site



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



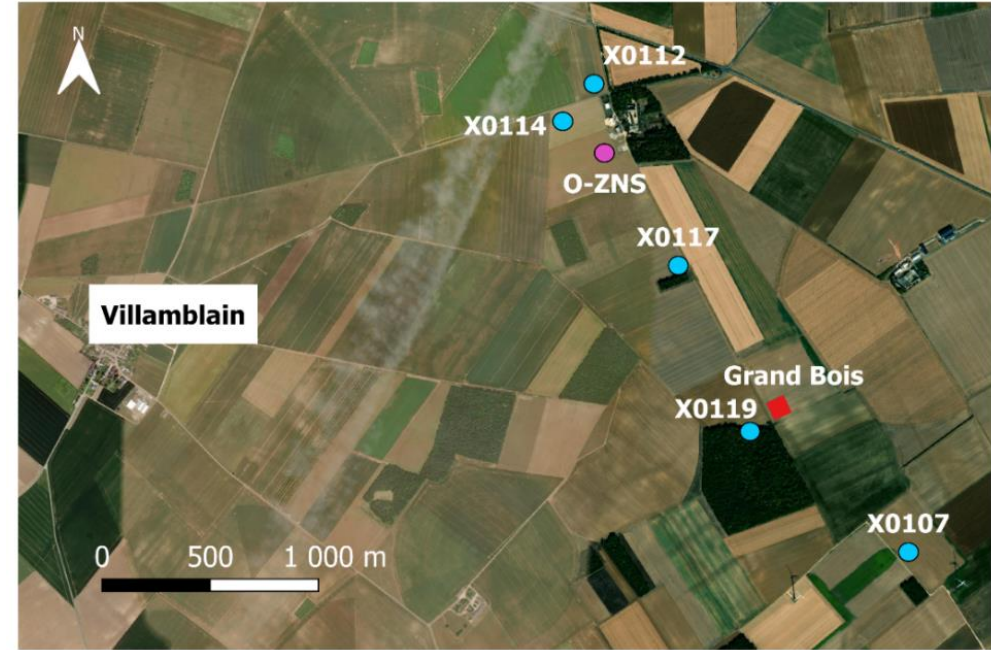
# Study site



Simplified  
geology

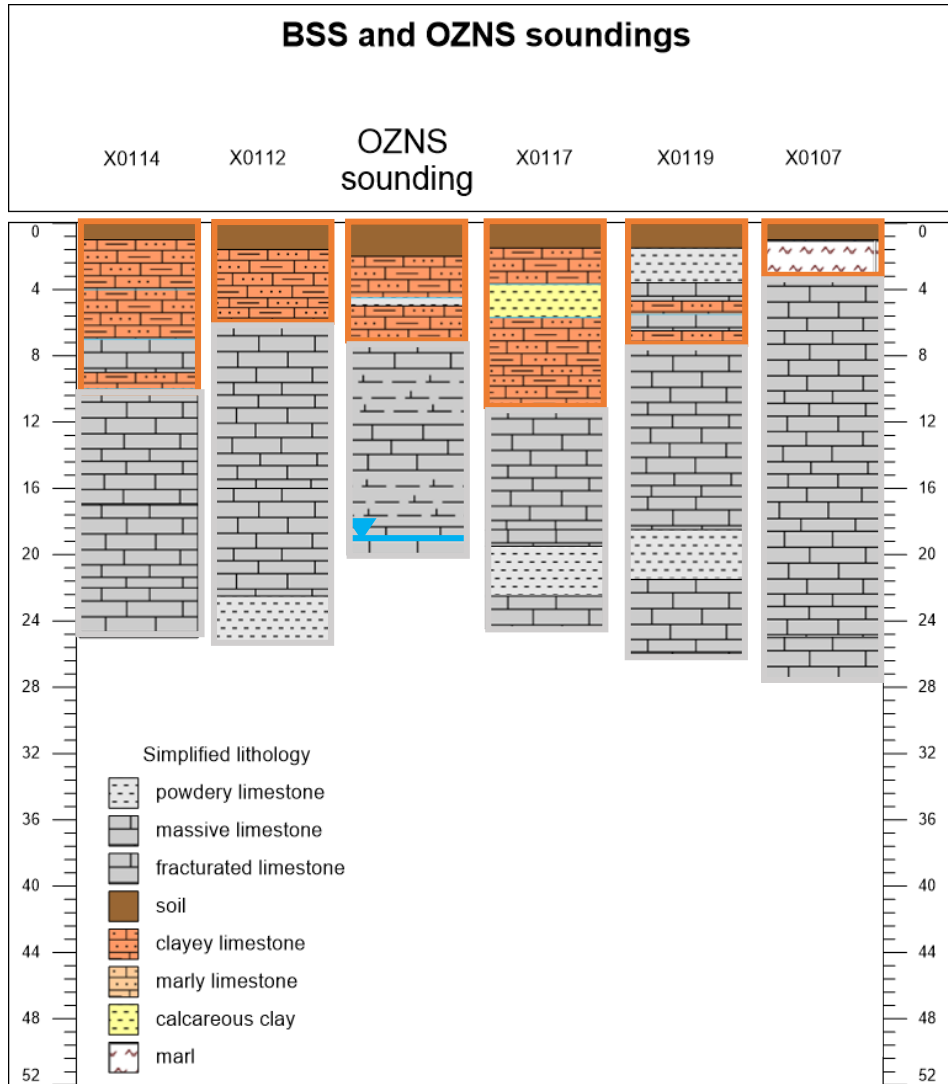
Highly weathered  
limestone

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

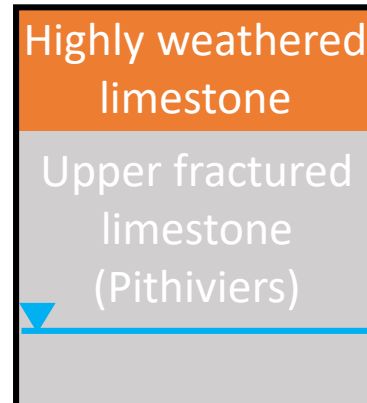




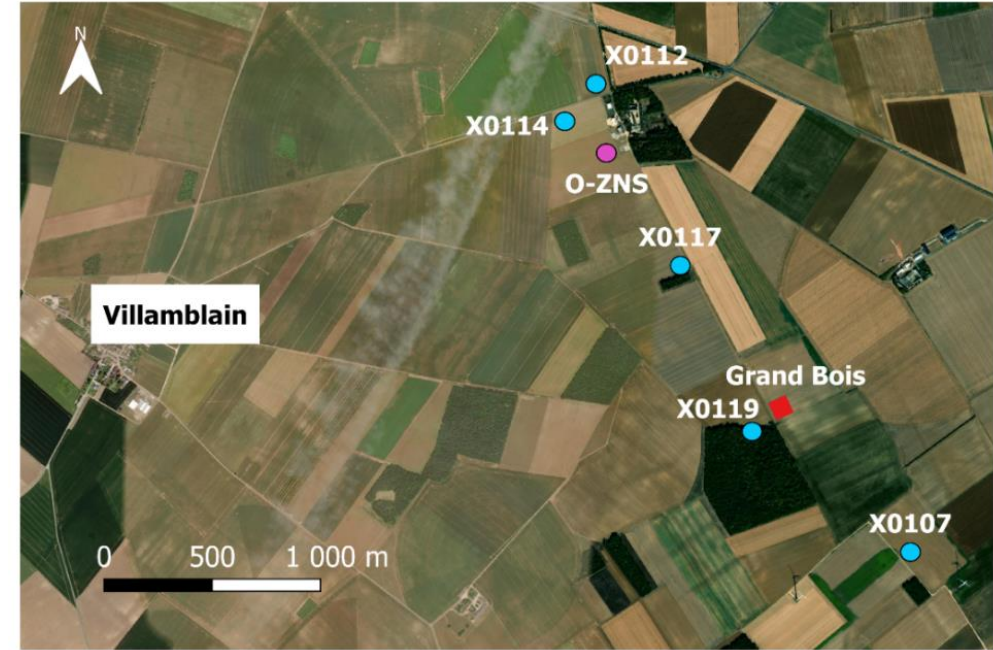
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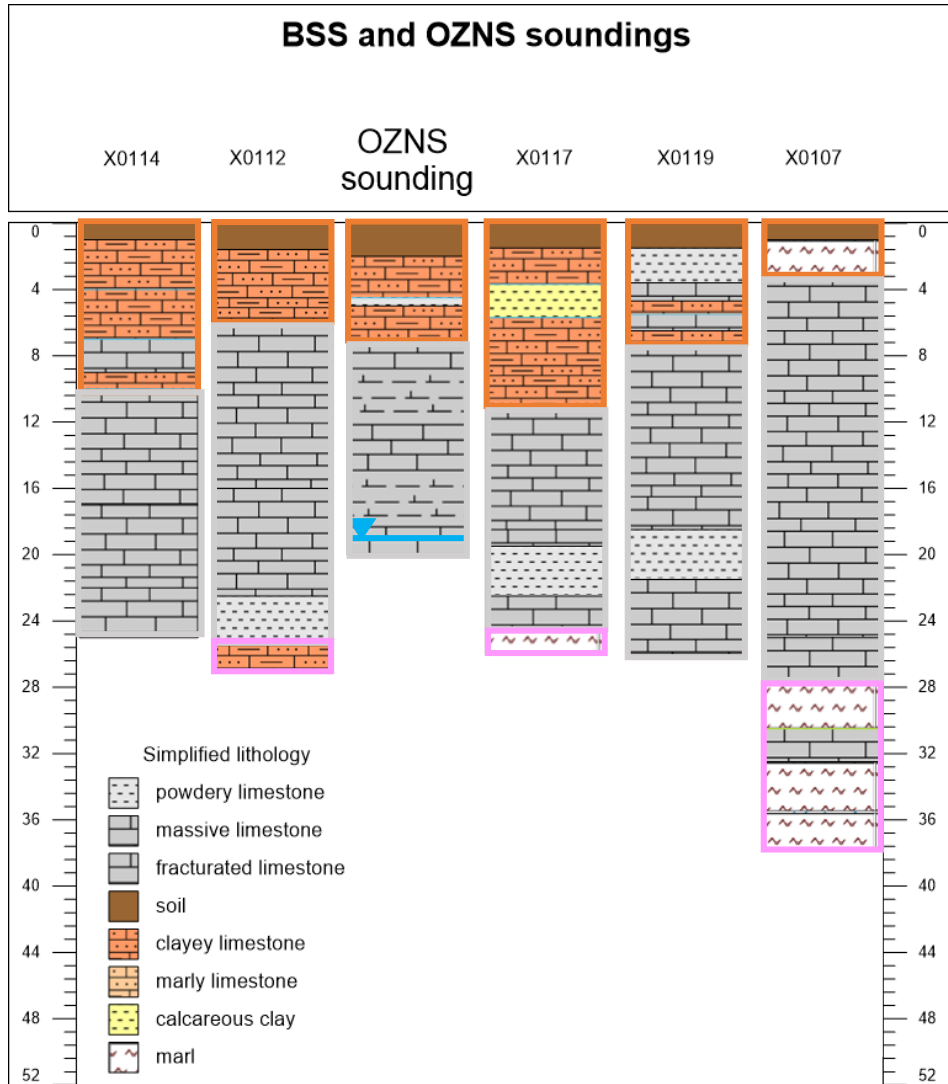
## Simplified geology



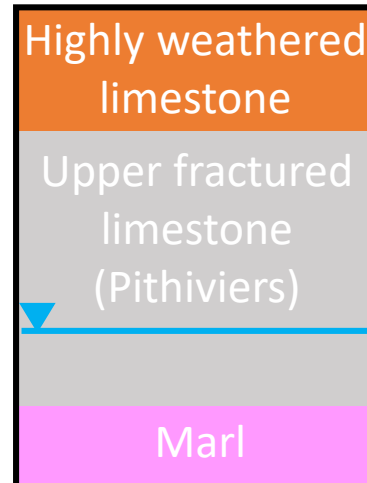
## Villamblain study sites and BSS soundings (ID X01--)



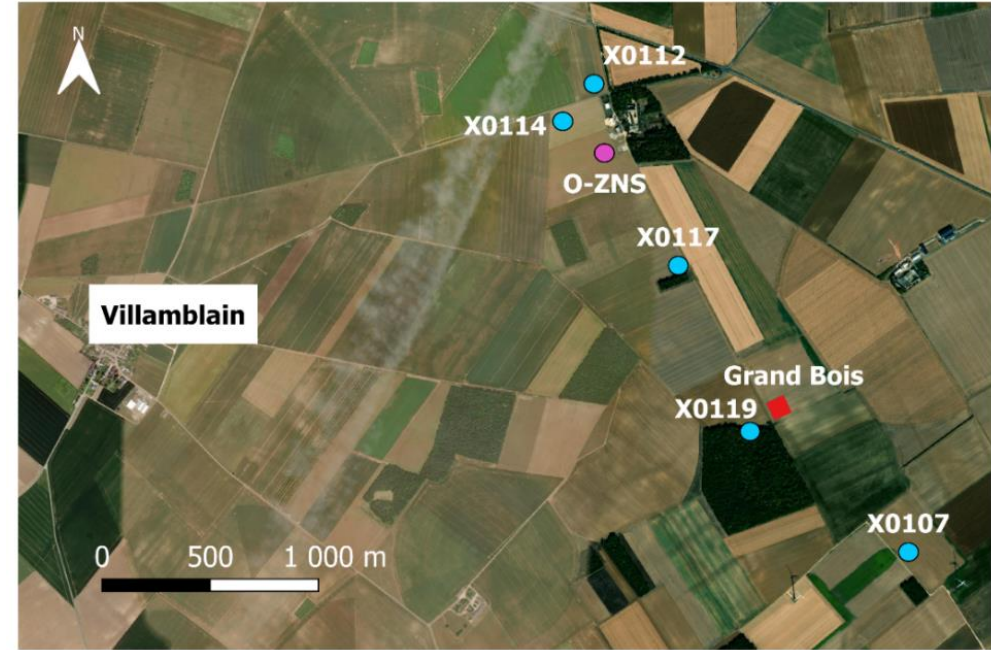
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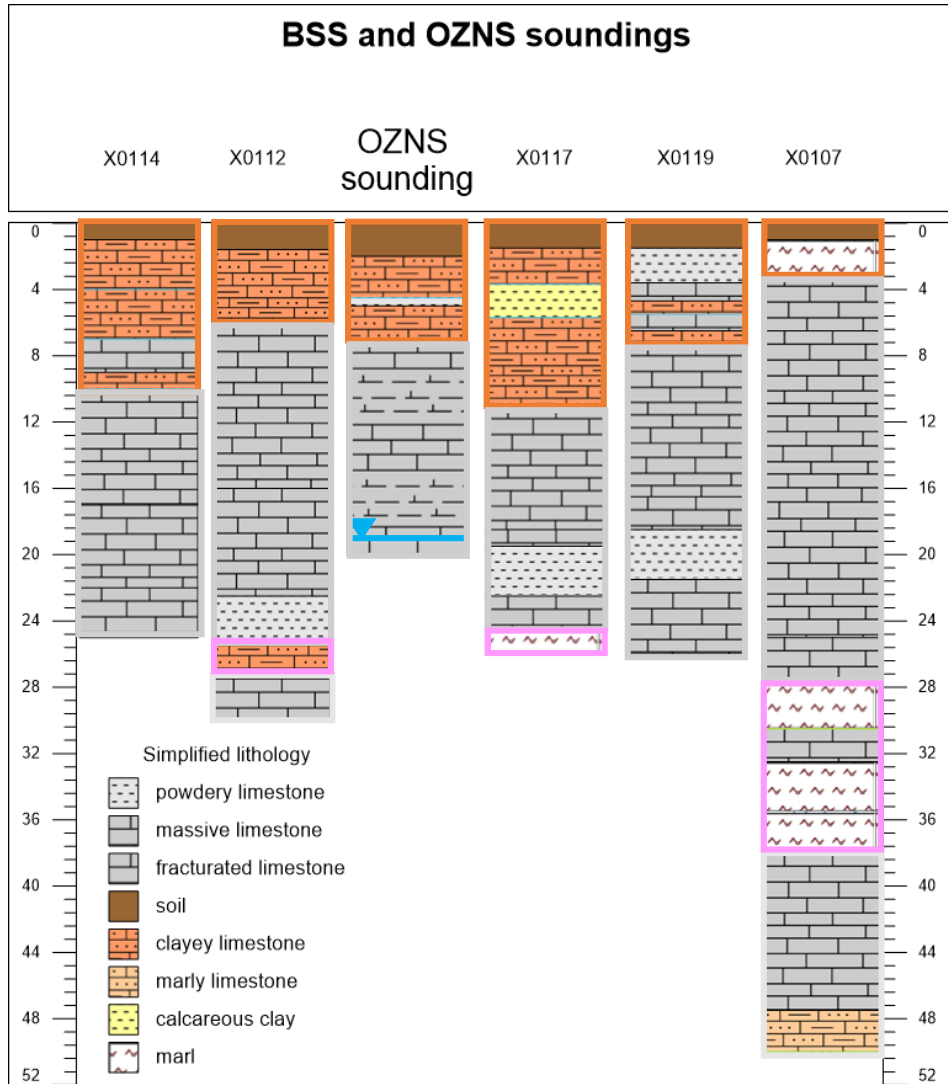
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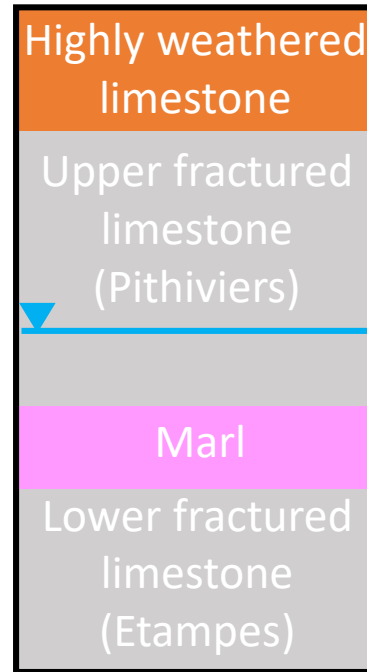
## Villamblain study sites and BSS soundings (ID X01--)



# Study site



## Simplified geology



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

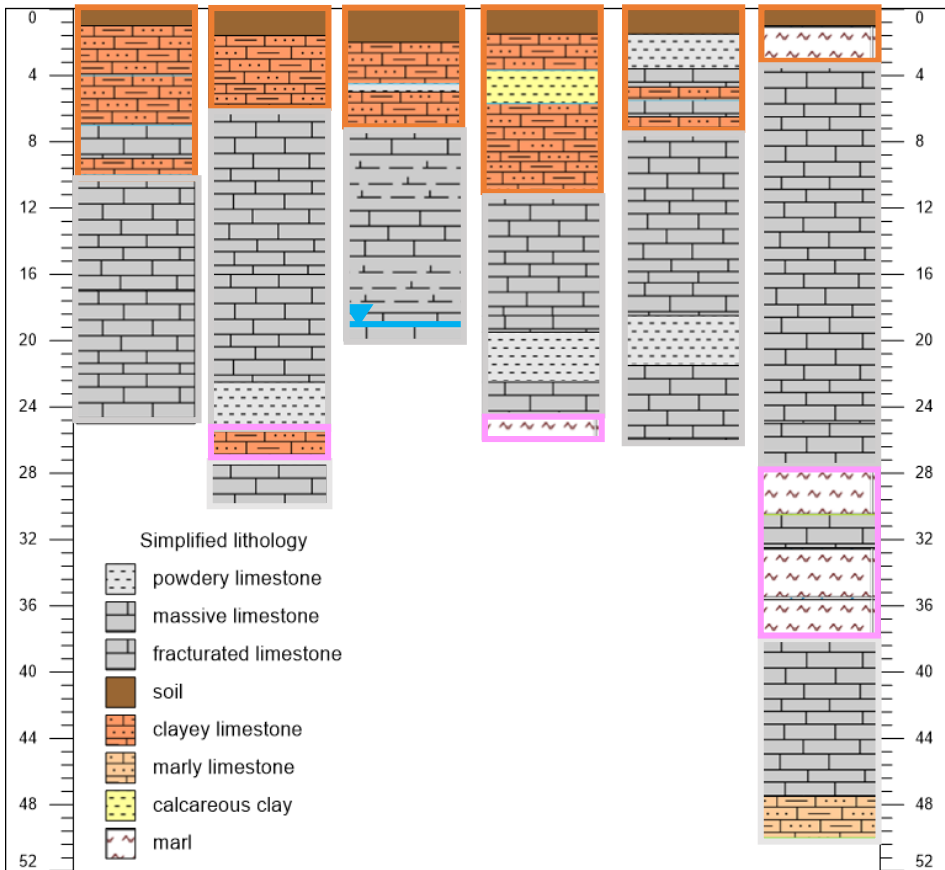


➤ Weathered and highly heterogeneous limestone in VZ

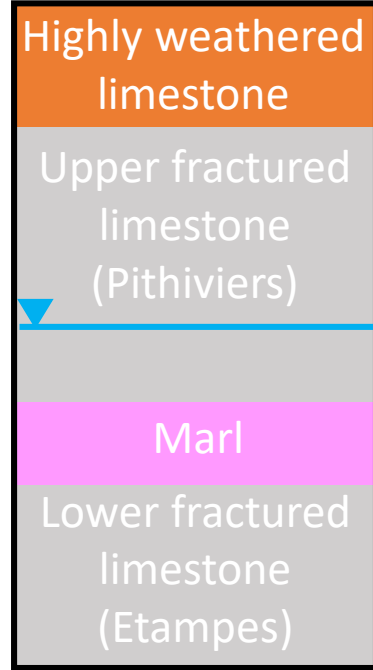
# Study site

## BSS and OZNS soundings

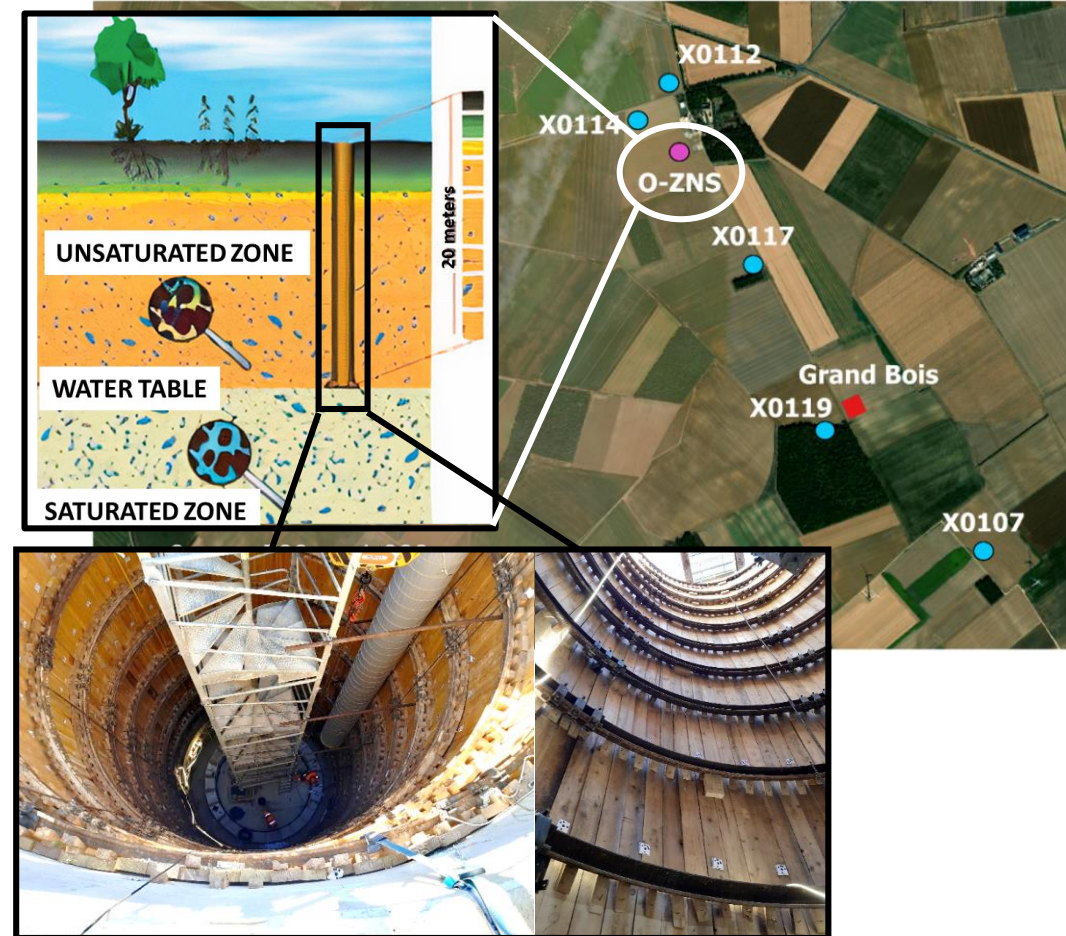
X0114    X0112    OZNS sounding    X0117    X0119    X0107



## Simplified geology



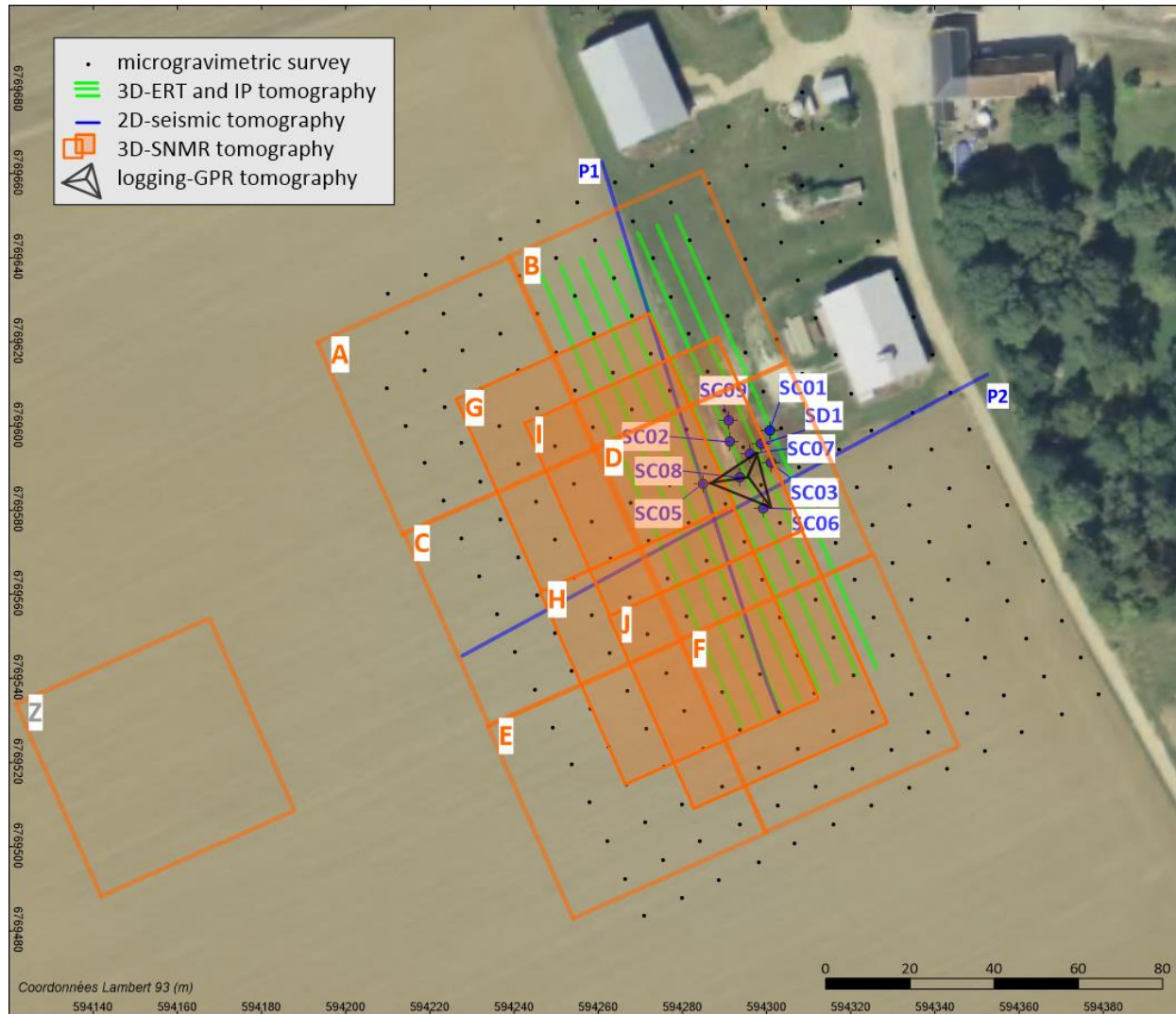
## Villamblain study sites and BSS soundings (ID X01--)



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

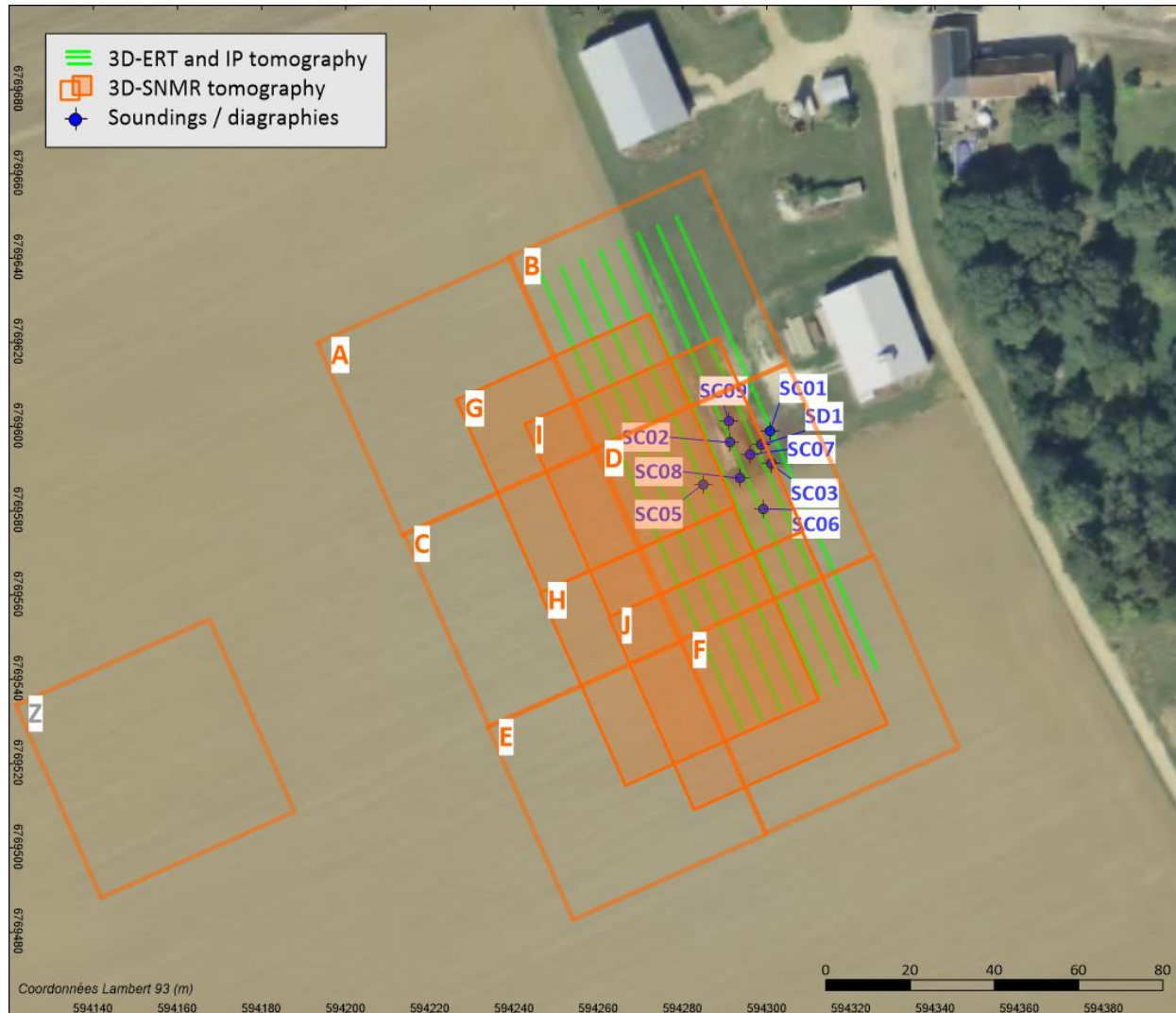
- Weathered and highly heterogeneous limestone in VZ
- O-ZNS study site

# Geophysical investigation and data processing



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

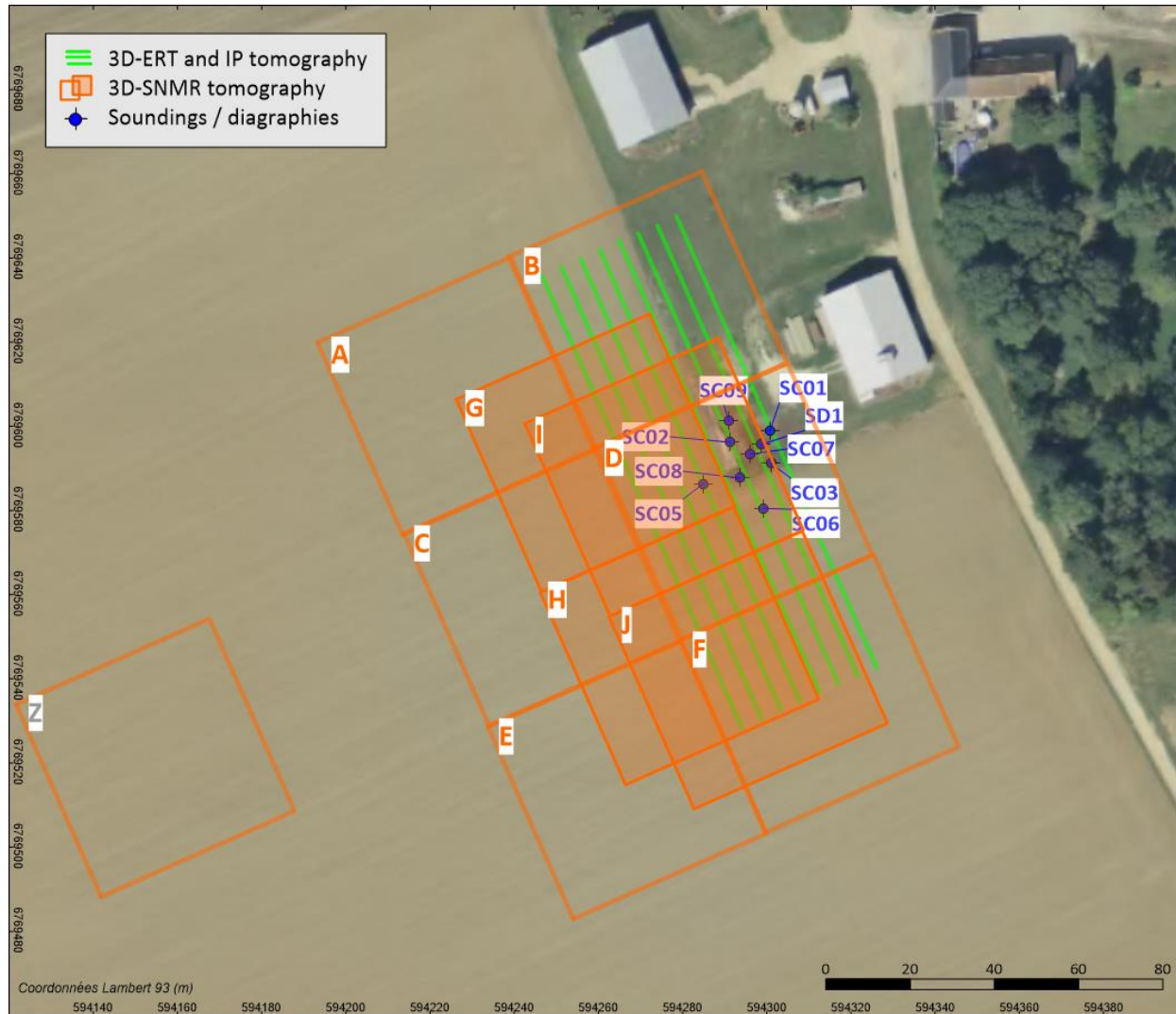
# Geophysical investigation and data processing



	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

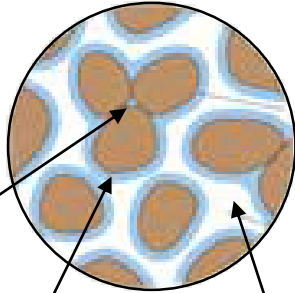
- S/N between 1.5 and 6.6 ; RMSE = 16.2 nV ;  
Noise level = 50 nV

## Electrical data

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

# Data interpretation in the Beauce limestone context

Water in porous media

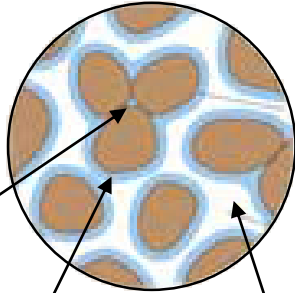


clay water	retention water	gravitational water
Total water content $w$ (%)		



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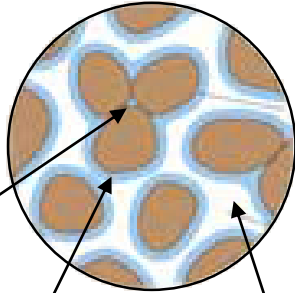
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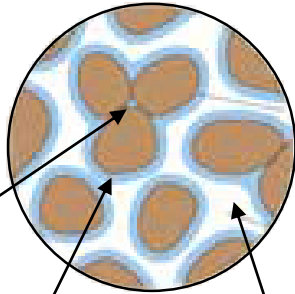
clay	retention	gravitational
water	water	water
	Total water content $w$ (%)	
30	Relaxation time $T_2^*$ (ms)	
		1000

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

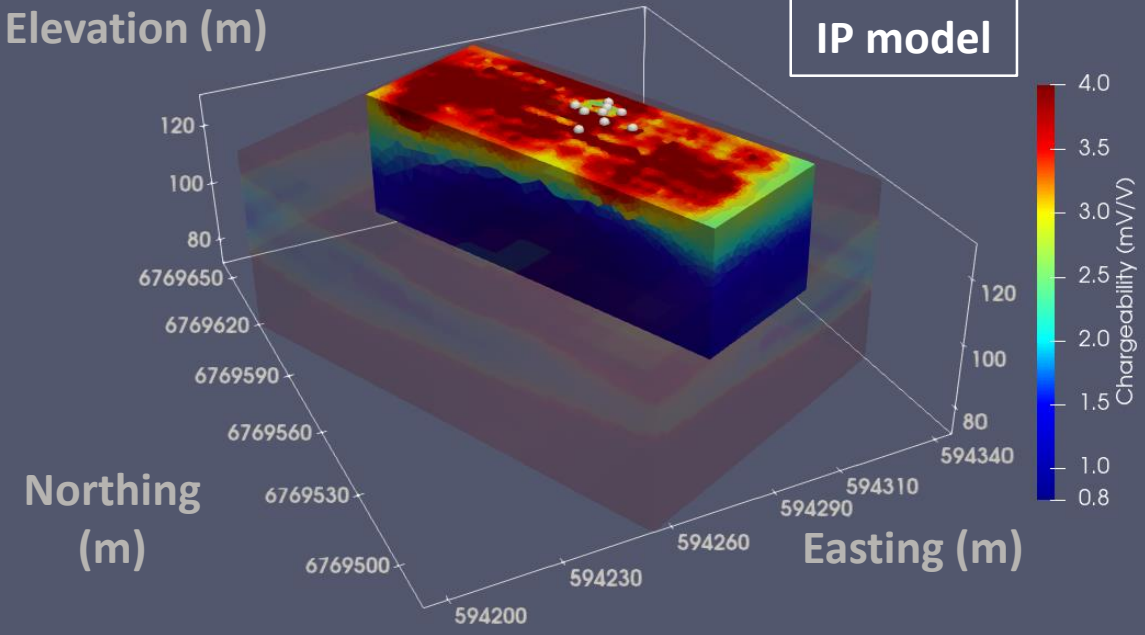
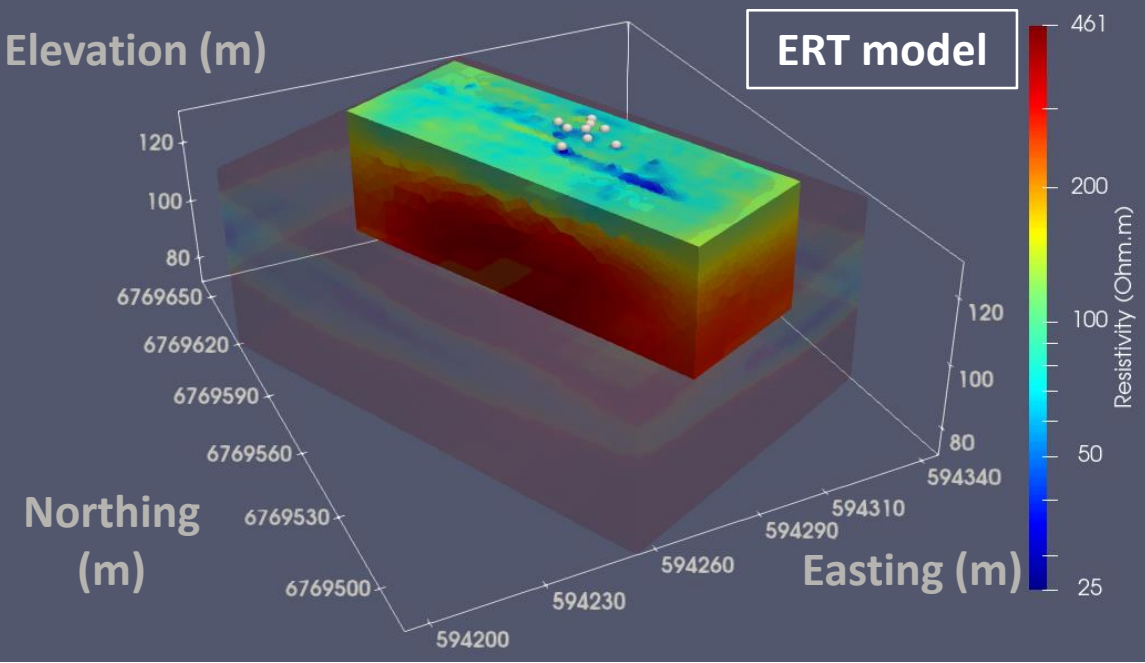
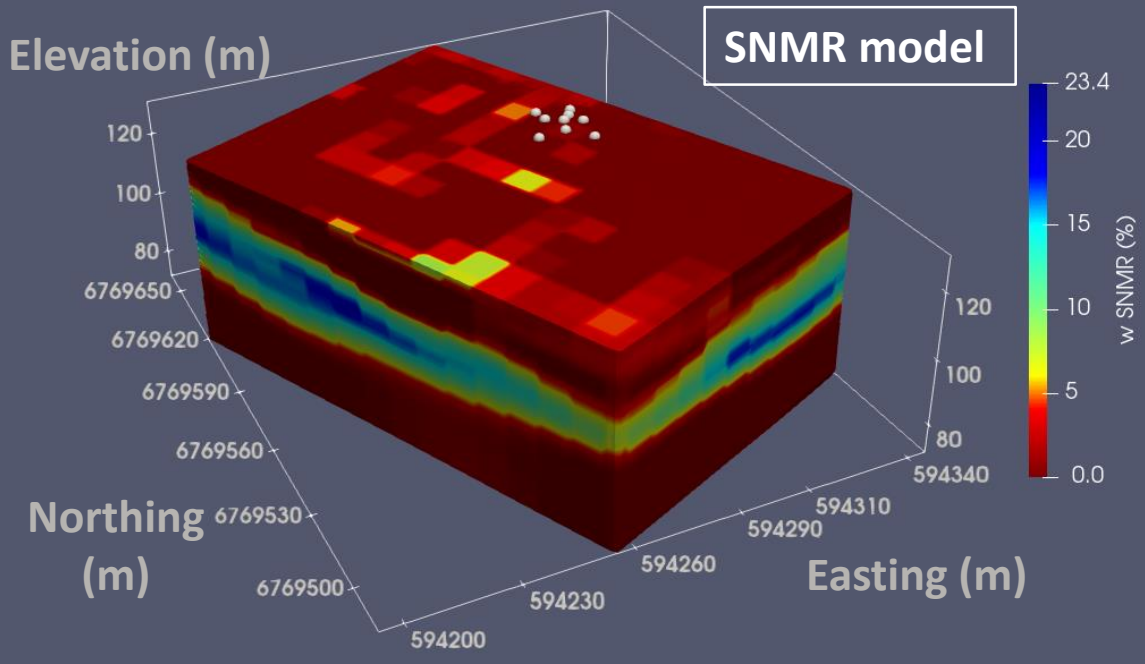


clay	retention	gravitational
water	water	water
	Total water content $w$ (%)	
	Relaxation time $T_2^*$ (ms)	1000
	30	

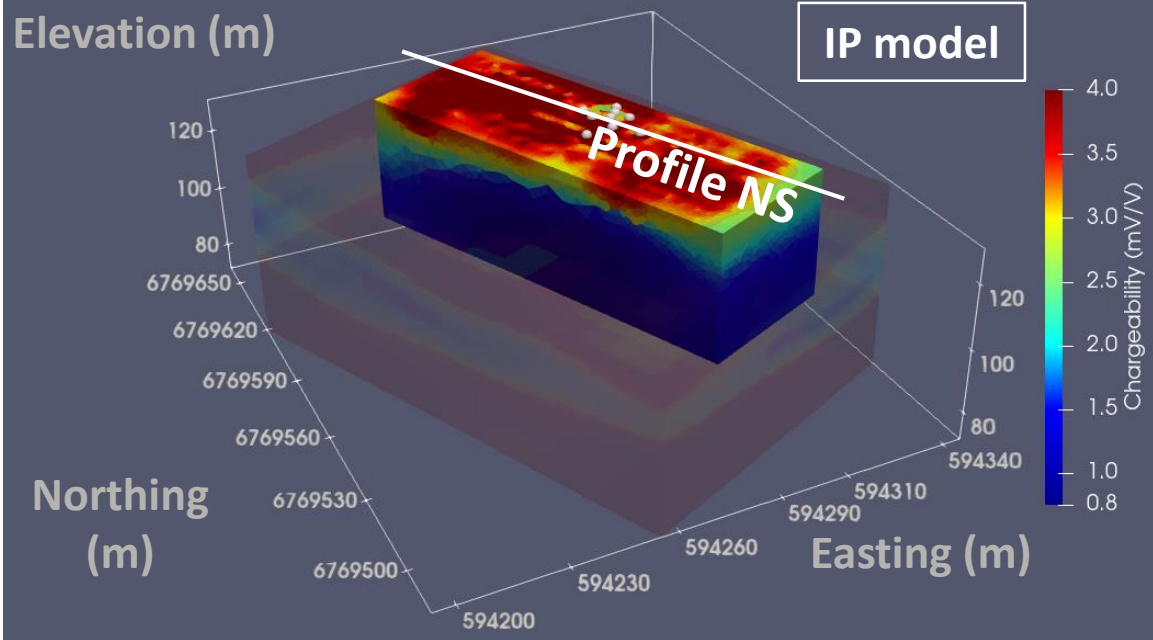
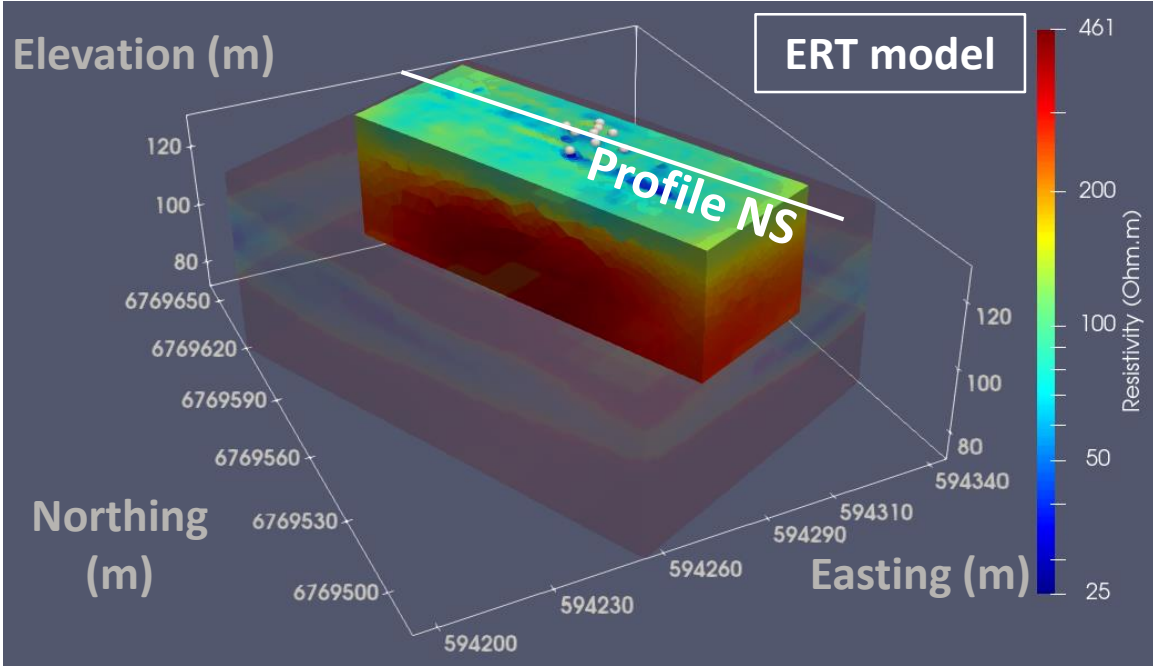
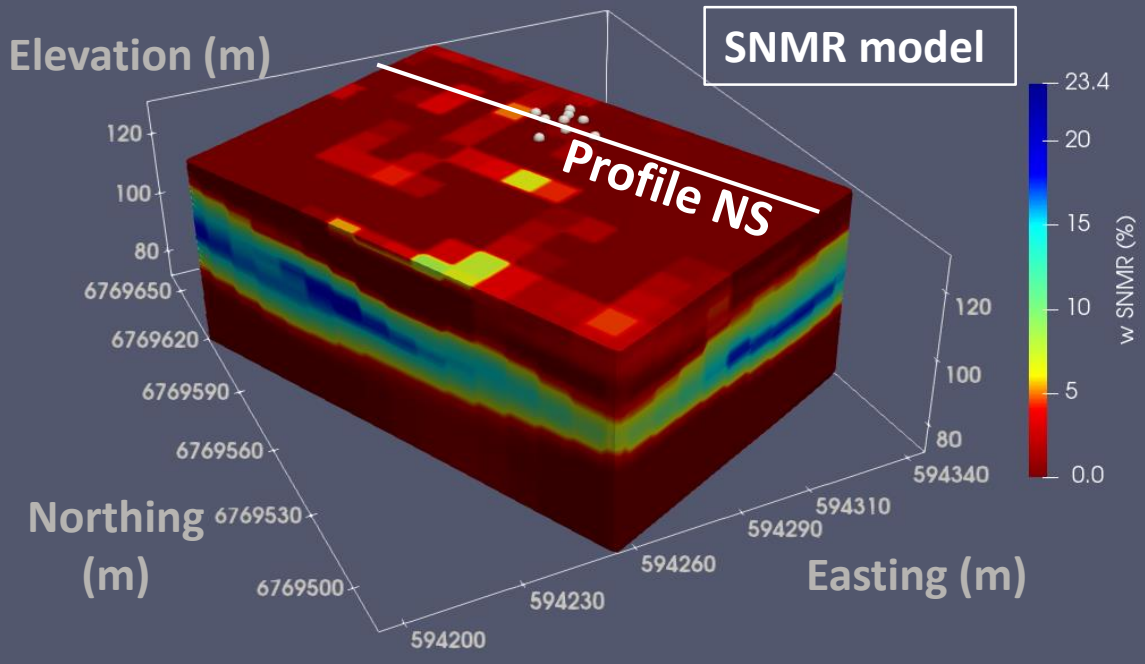
SNMR detection threshold  
in Beauce limestone

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

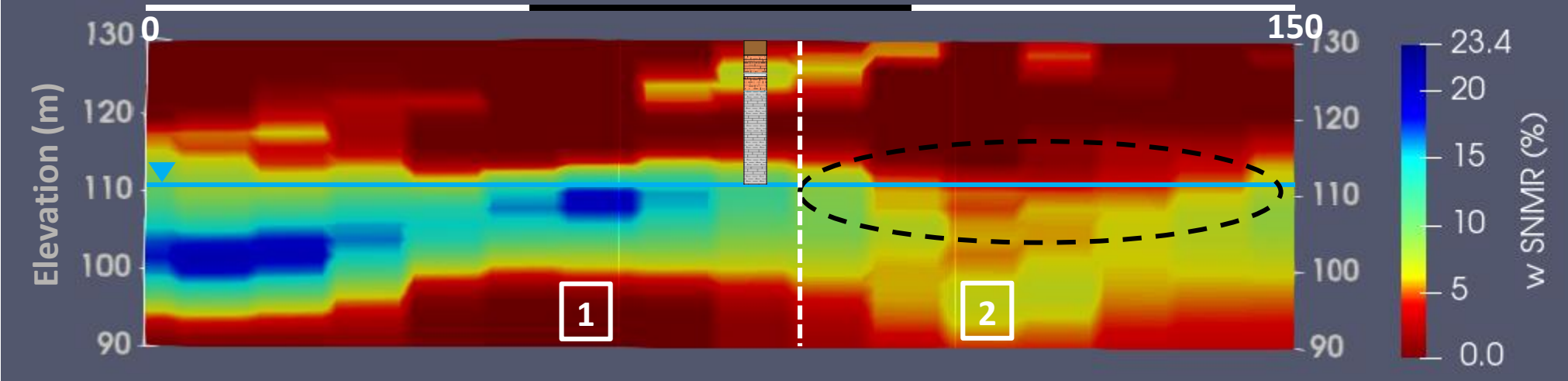
# 3D SNMR and ERT/IP inverse models



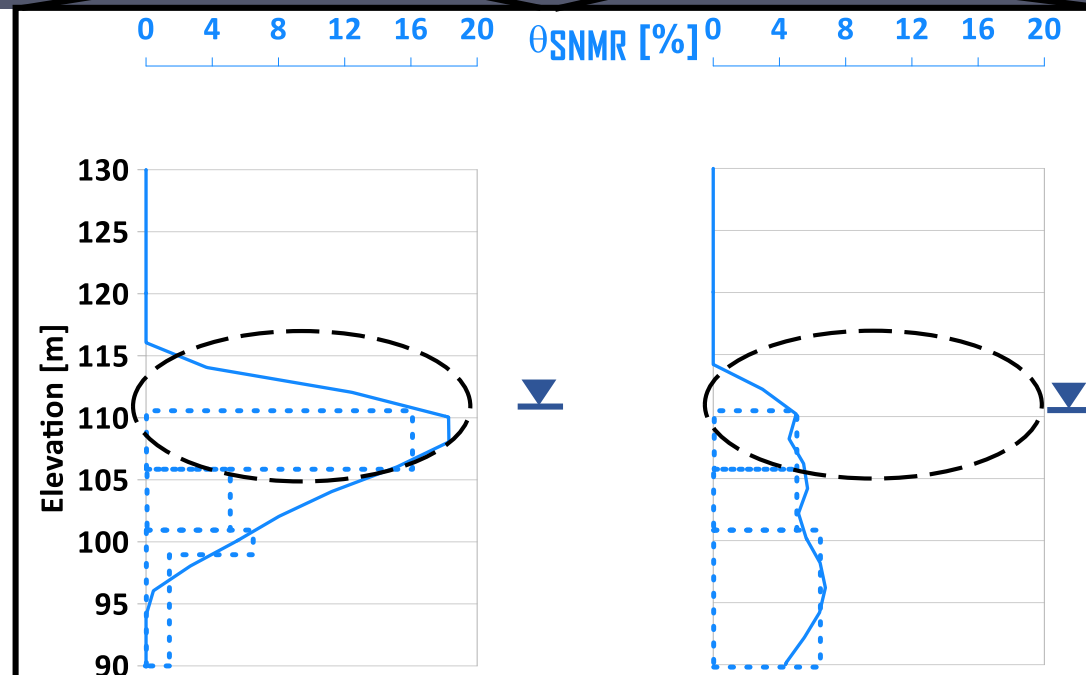
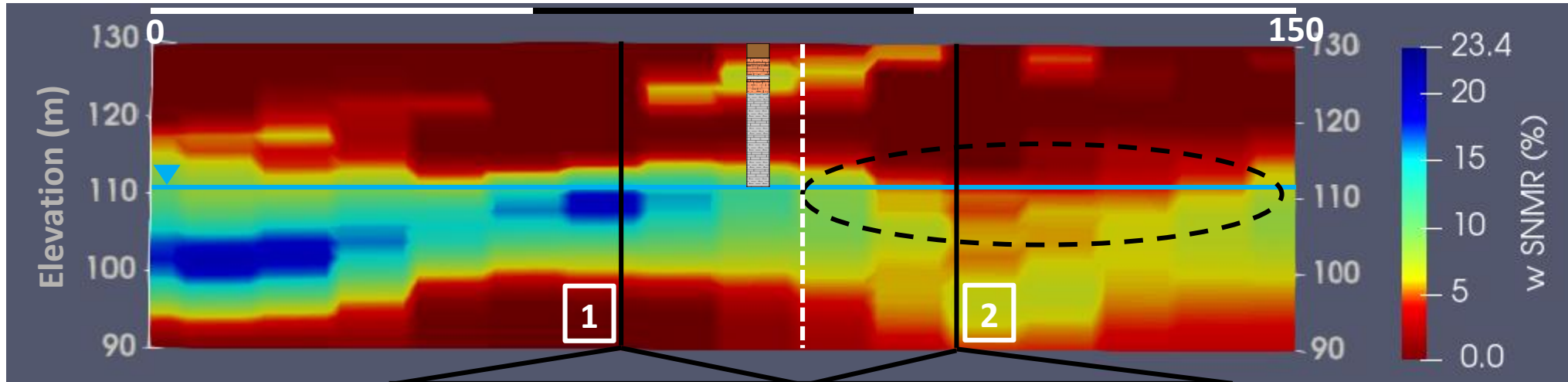
# 3D SNMR and ERT/IP inverse models



# Water content heterogeneities resulting from SNMR 3D inversion



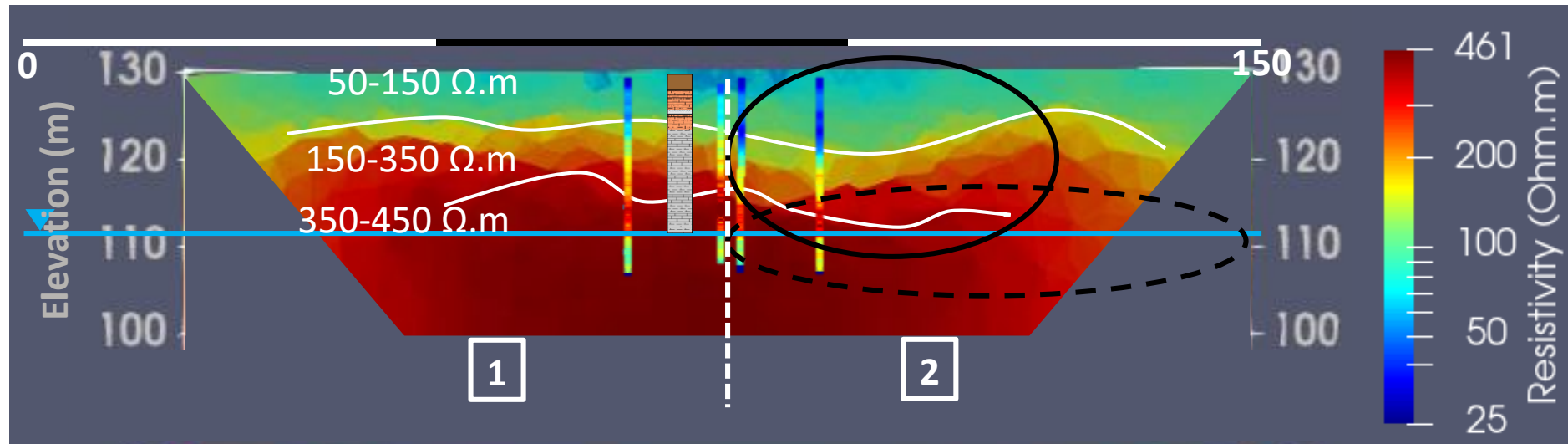
# Water content heterogeneities resulting from SNMR 3D inversion



## Legend :

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

# Identification of lithological heterogeneities from electrical 3D inversion results

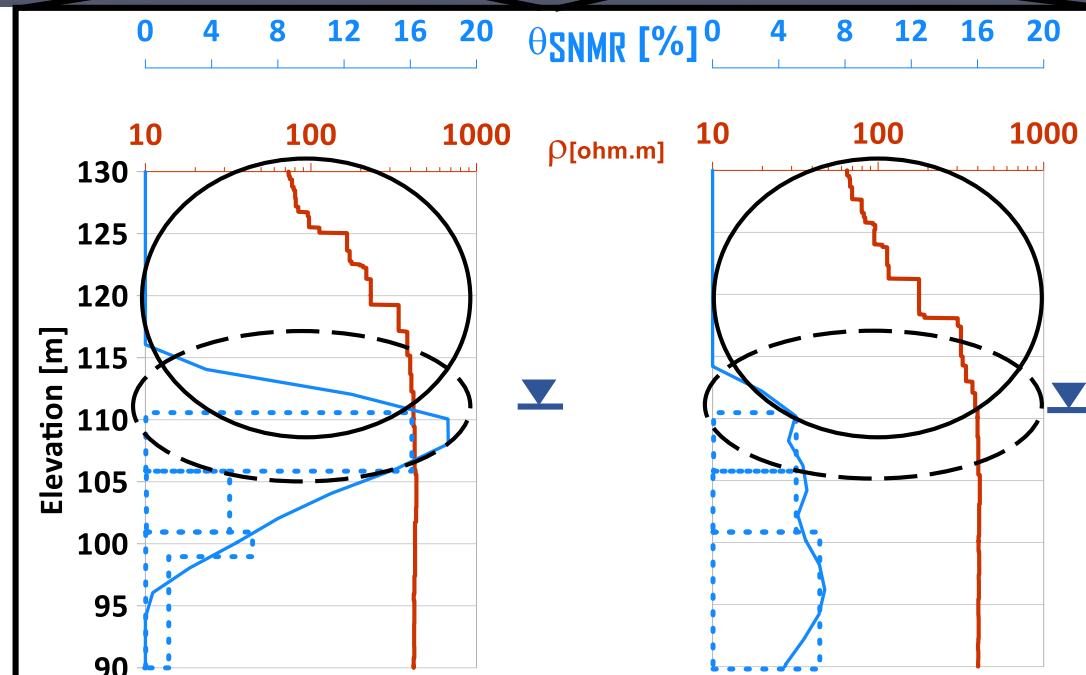
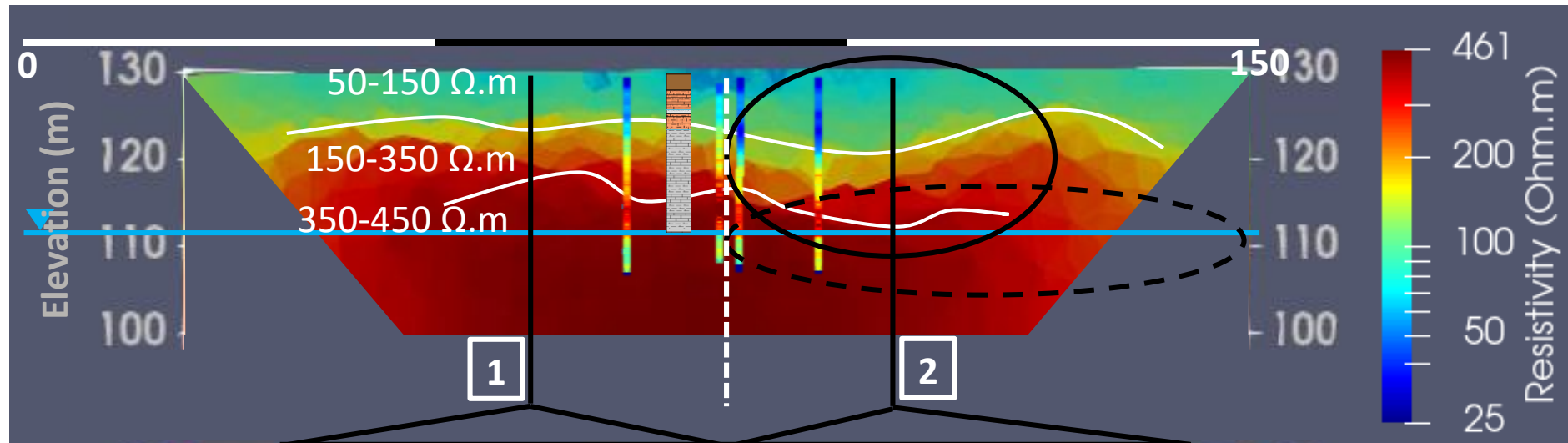


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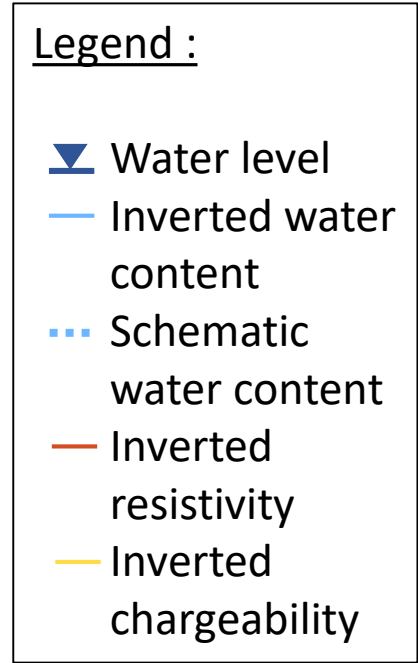
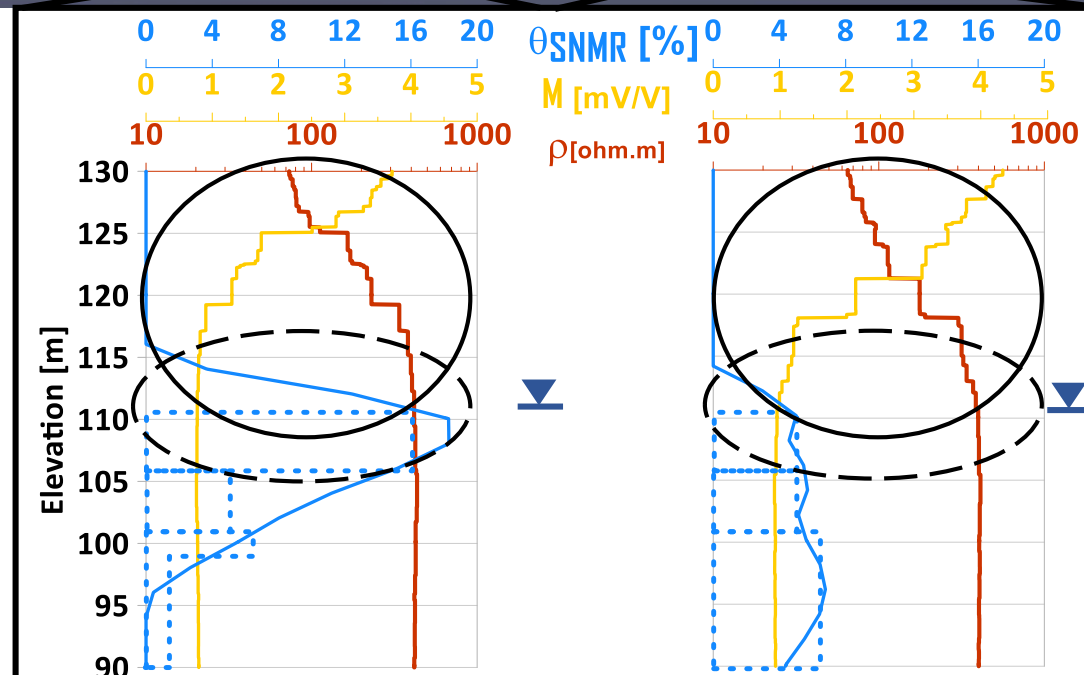
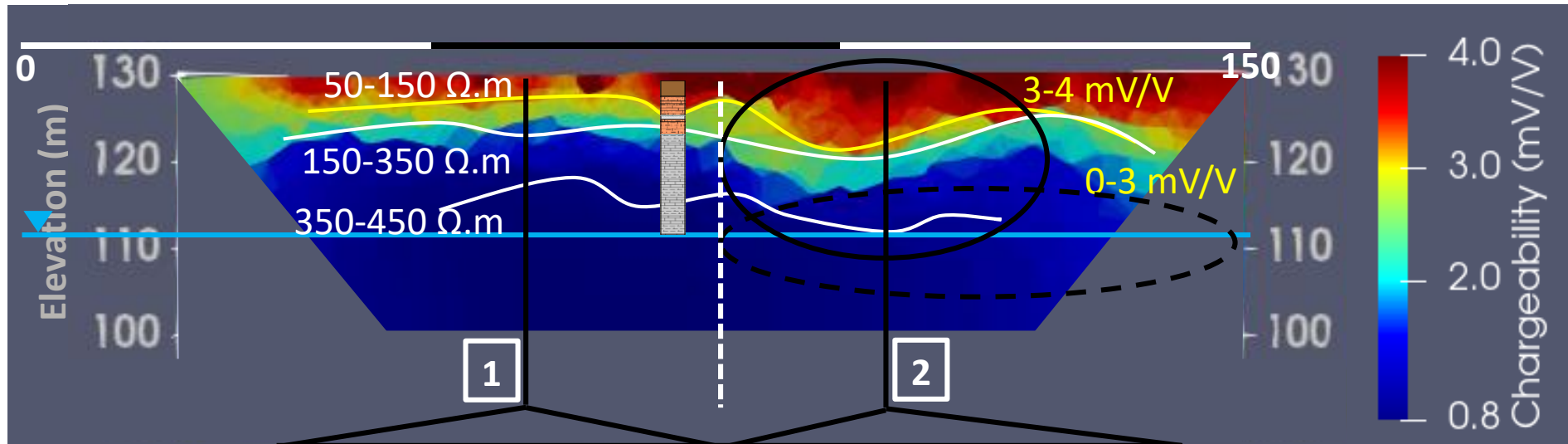
# Identification of lithological heterogeneities from electrical 3D inversion results



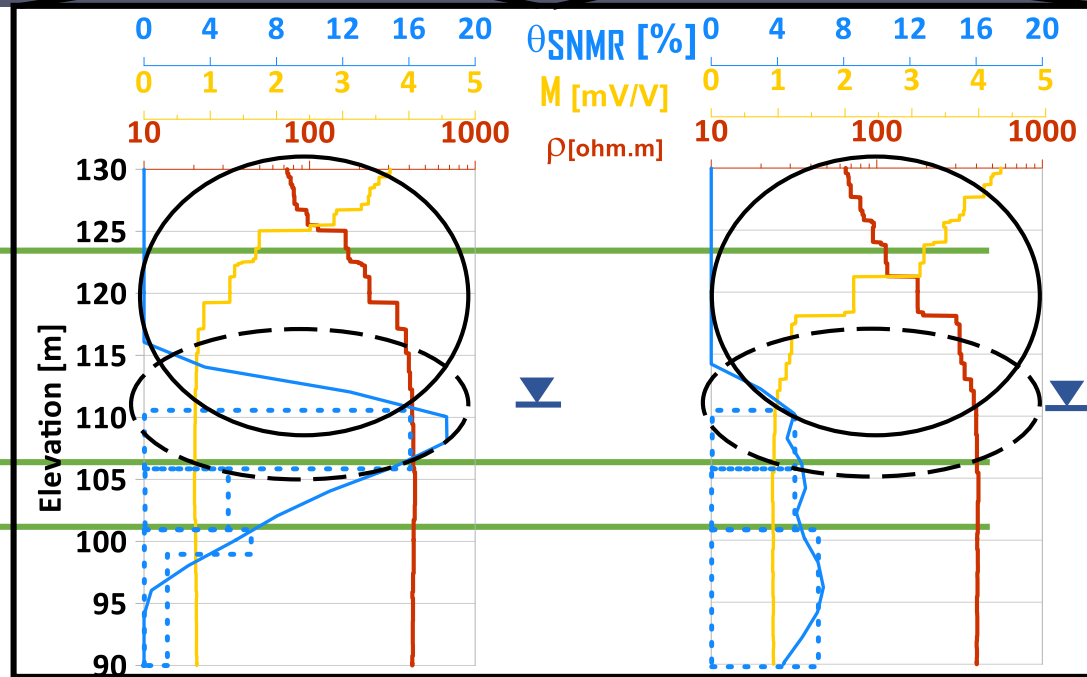
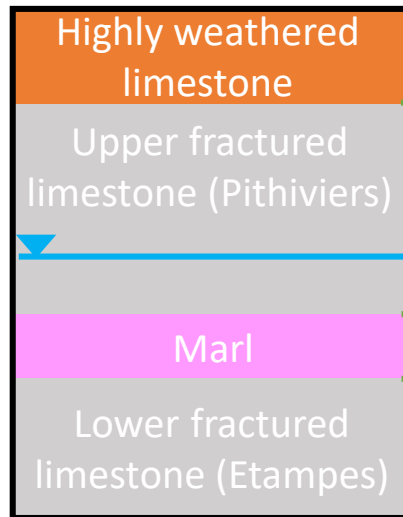
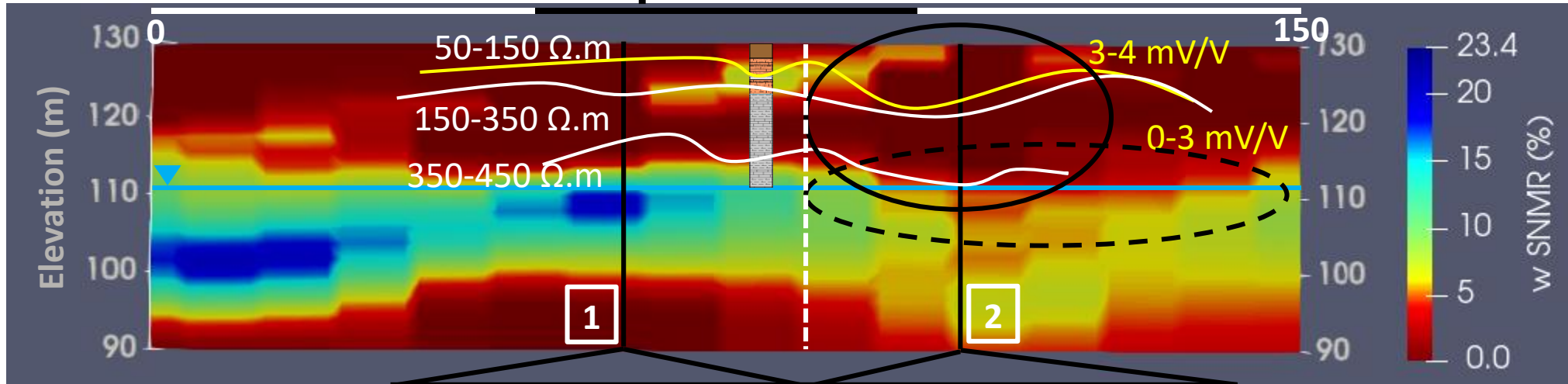
## Legend :

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

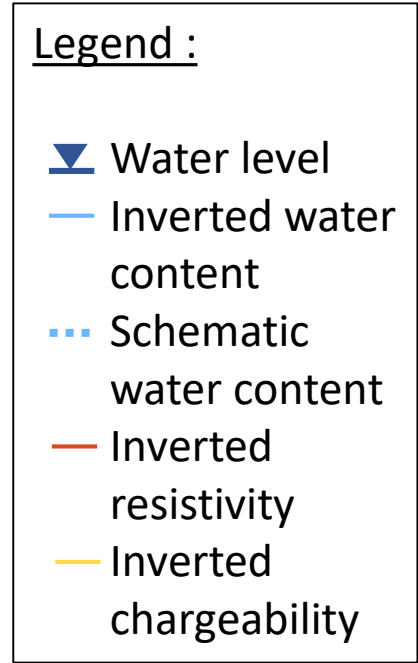
# Identification of lithological heterogeneities from electrical 3D inversion results



# 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



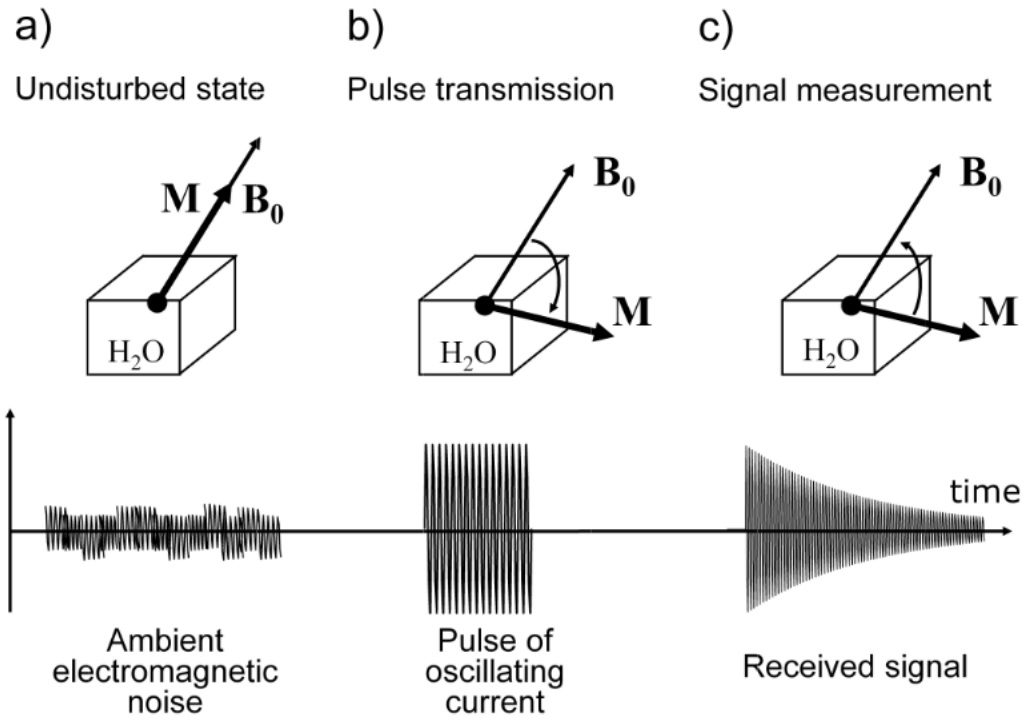
Abstract

# 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 :**

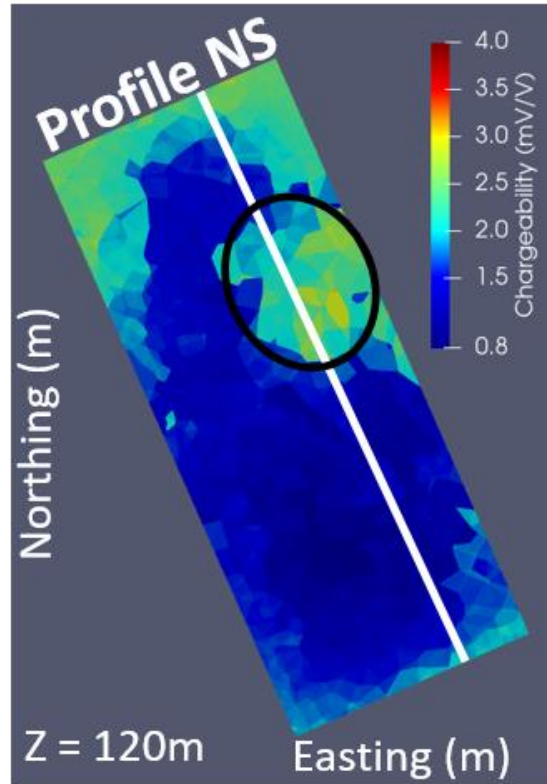
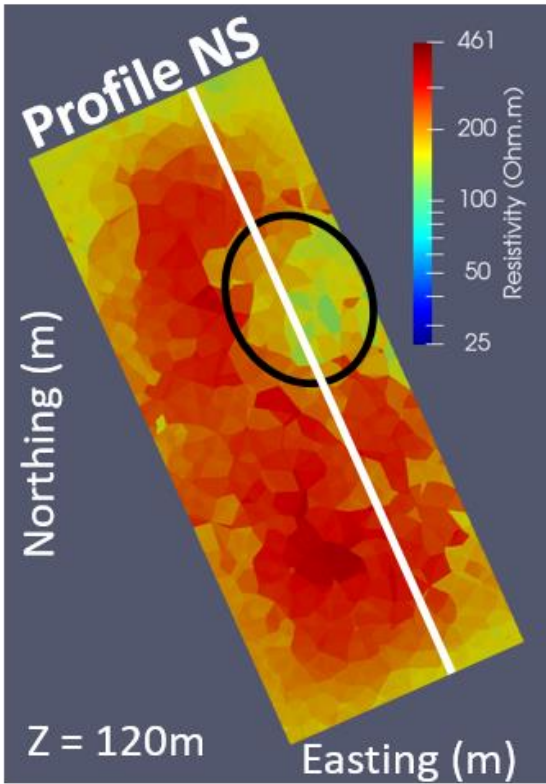
No detection of water content for smaller  
 pore sizes

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

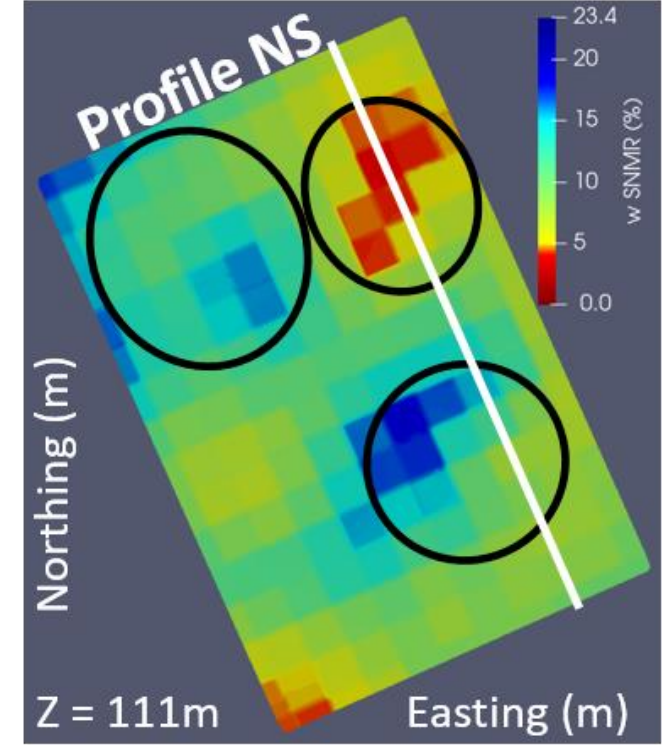
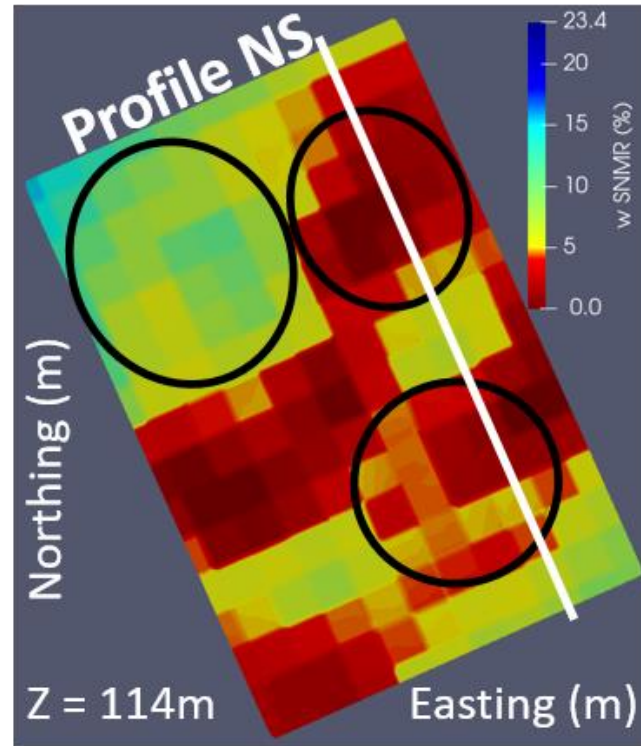
Source : LEGTCHENKO, Anatoly, 2013. *Magnetic Resonance Imaging for Groundwater*. John Wiley & Sons. ISBN 978-1-118-64947-3



# 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)