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Hydraulic characterization of a karstic limestone vadose zone based on multi-methods geophysical measurements and lab testing

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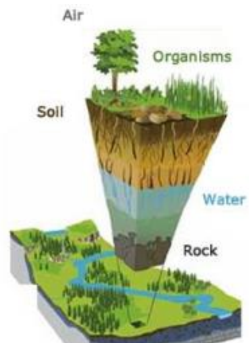

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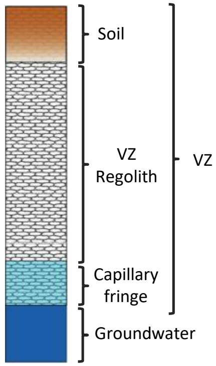


The Vadose Zone A highly heterogeneous & dynamic system

Challenges :

- Preservation of freshwater resources
- Addressing climatic and anthropogenic pressures

How to characterize flow patterns within the vadose zone ?

Geophysics = various physical parameters & image the subsoil.

But it needs calibration !

OZNS: Observatory of transferts in the Vadose Zone

- understand & quantify mass and heat transfers with an **instrumented well &** several associated **boreholes**
- Agricultural field and limestone aquifer (Beauce, Frce)

Developing high-resolution investigations and, focused monitoring techniques and sensors for the vadose zone.

OZNS: Observatory of transferts in the Vadose Zone

Unique to **study & convert physical responses into hydraulic parameters**, in the VZ of a limestone aquifer.

But prior to digging

Geotechnical and Geophysical characterisation

- Geophysical field investigations:

Electrical Resisitvity Imaging, GPR crosshole, Magnetic Resonance Sounding

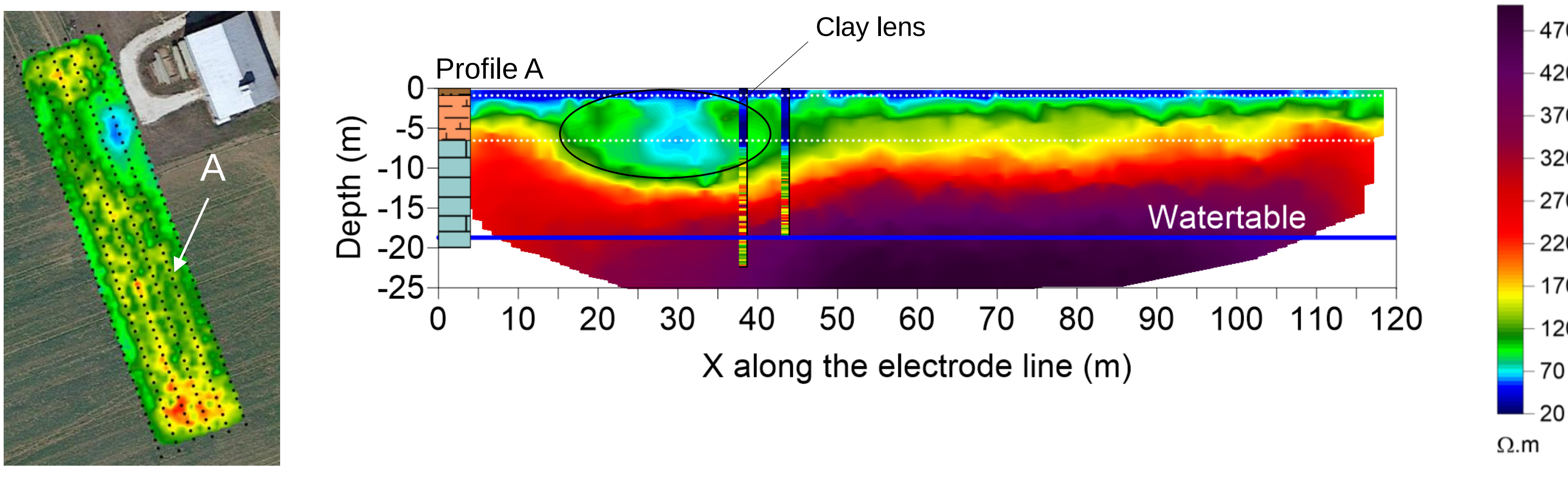
- Three core boreholes to retrieve physical and hydric properties (SC1, SC2 & SC3)
  - Well logging tests
  - Lab testing on core boreholes

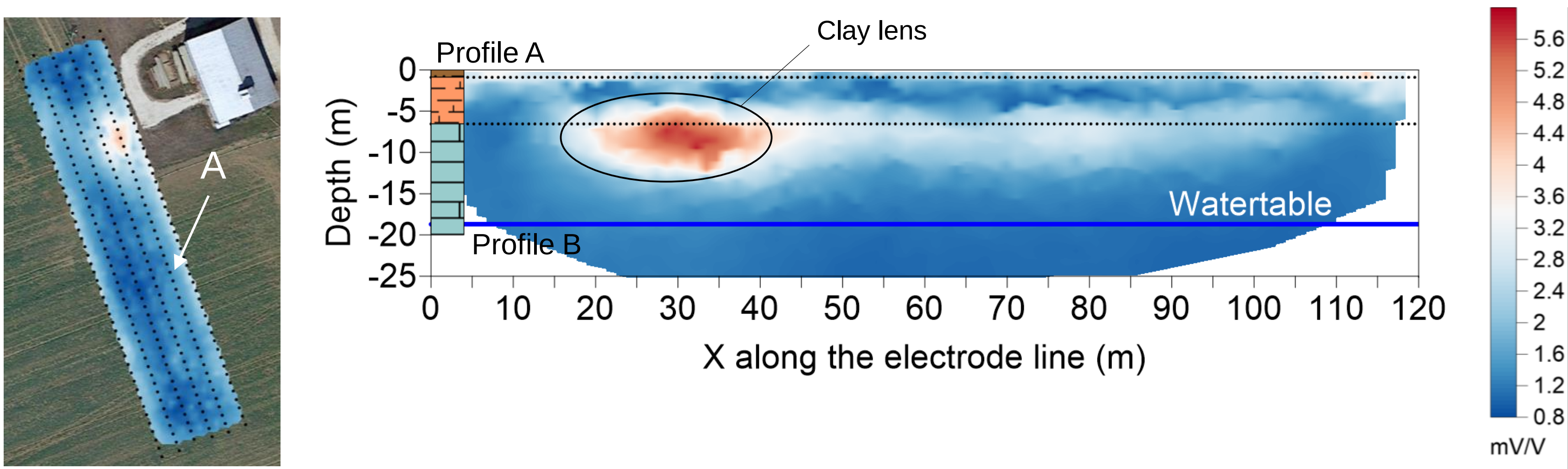
Objectives of the study:

➡ Initial geophysical characterization of the site

➡ Spatial distribution of the medium's properties

Electrical Resistivity Imaging





⇒ Recover the **three main geological groups** as the core boreholes, at a lower resolution but on a greater scale.

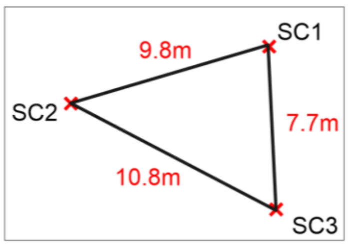
⇒ Highlights the **presence of clay lens** in the karstified limestone level as seen on profile A.

GPR crosshole

Clayed soil : low ER & amplitude, high ε

Marly limestone : low ER & scattered values of ε & amplitude marking the geological variability

Limestone : higher ER & amplitude, lower permittivity



△ SC1-SC3 cross-hole profile

✚ SC1-SC2 cross-hole profile

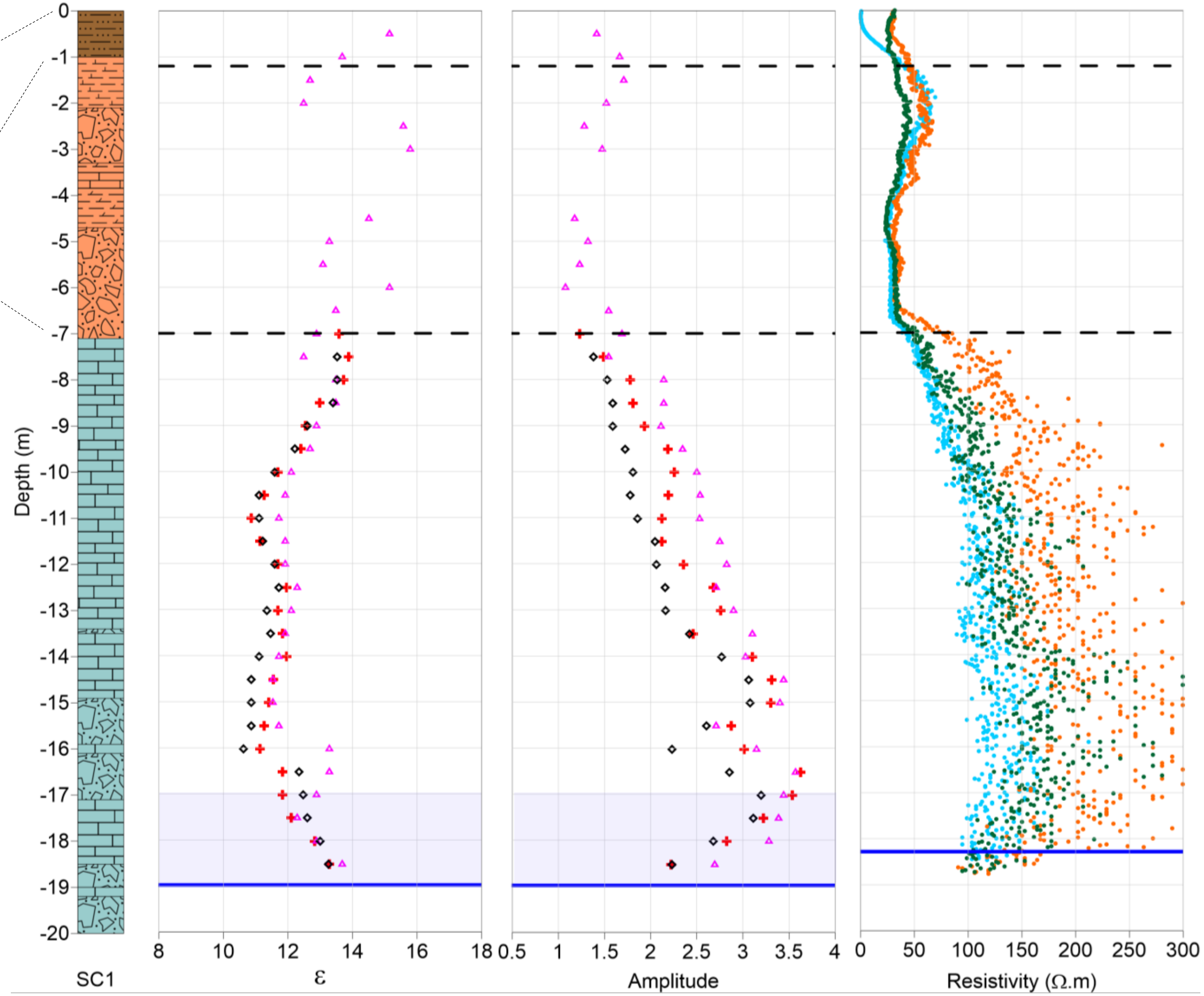
◆ SC2-SC3 cross-hole profile

● SC1 borehole

● SC2 borehole

● SC3 borehole

— Watertable

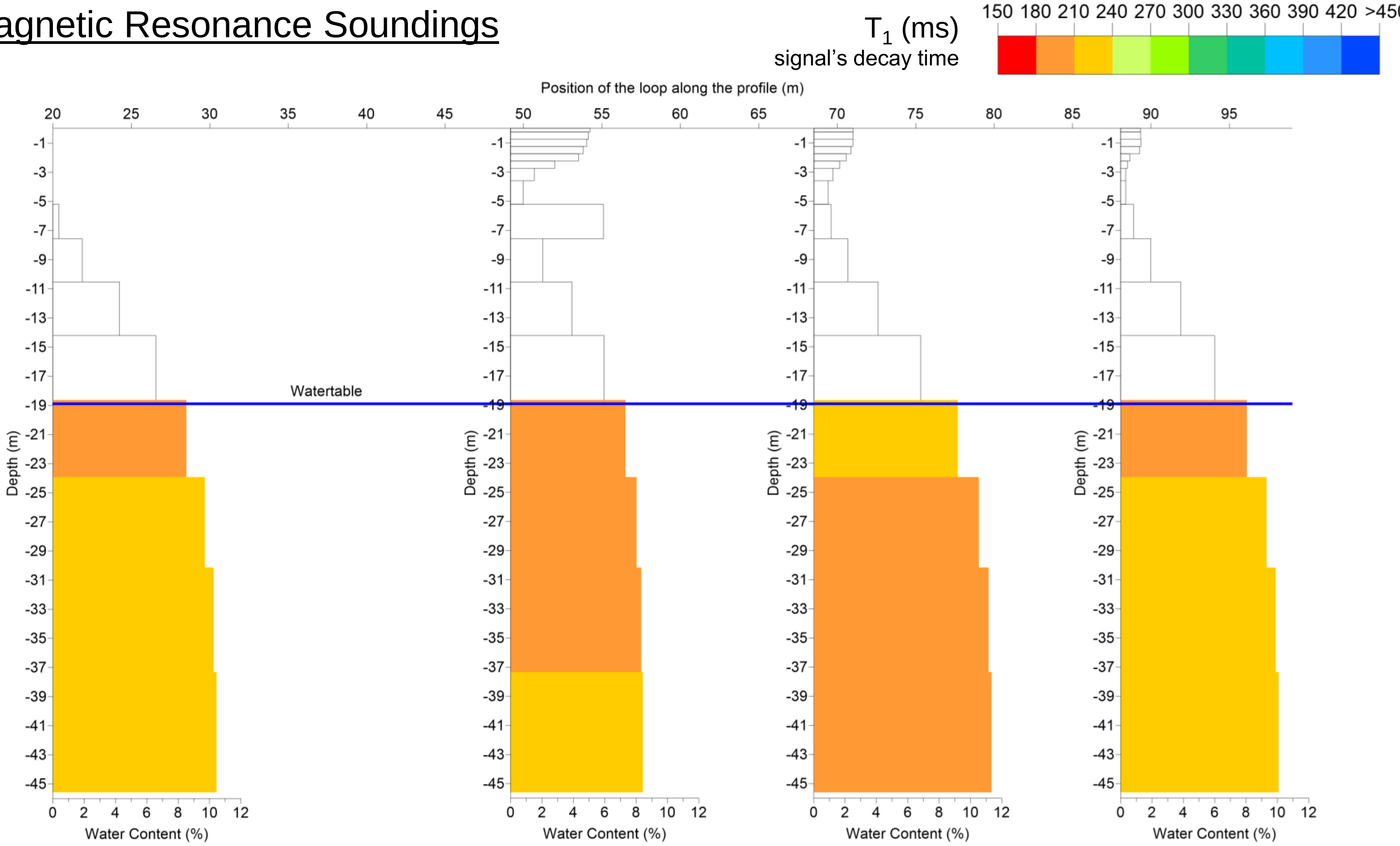


⇒ **High conductive soil** limits GPR signal **penetration depth.**

⇒ **Correspondence between permittivity, ER and lithology.**

⇒ Influence of the water table on permittivity & amplitude **revealing a capillary fringe** ~ 2 m thick.

Magnetic Resonance Soundings



⇒ MRS water content shows **significant water content variation above the water table**.

⇒ Uniform **water content and T_1 under the water table** confirm the **global tabularity** of the limestone massif.

Well logging & Lab testing to establish petrophysical relationships in VZ

OZNS: Observatory of transferts in the Vadose Zone

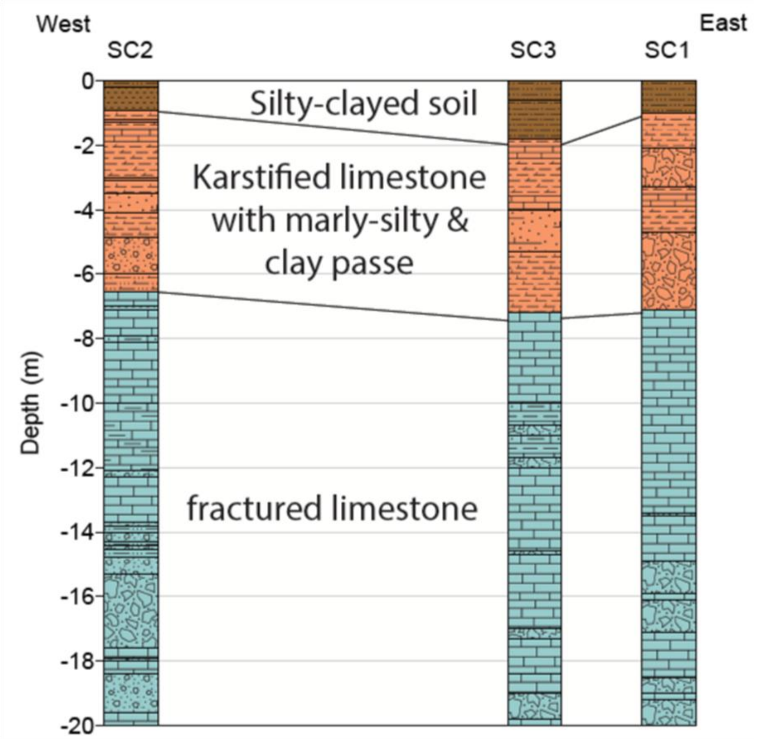
Unique to **study & convert physical responses into hydraulic parameters**, in the VZ of a limestone aquifer.

But prior to digging

Geotechnical and Geophysical characterisation

- Geophysical field investigations & Core boreholes

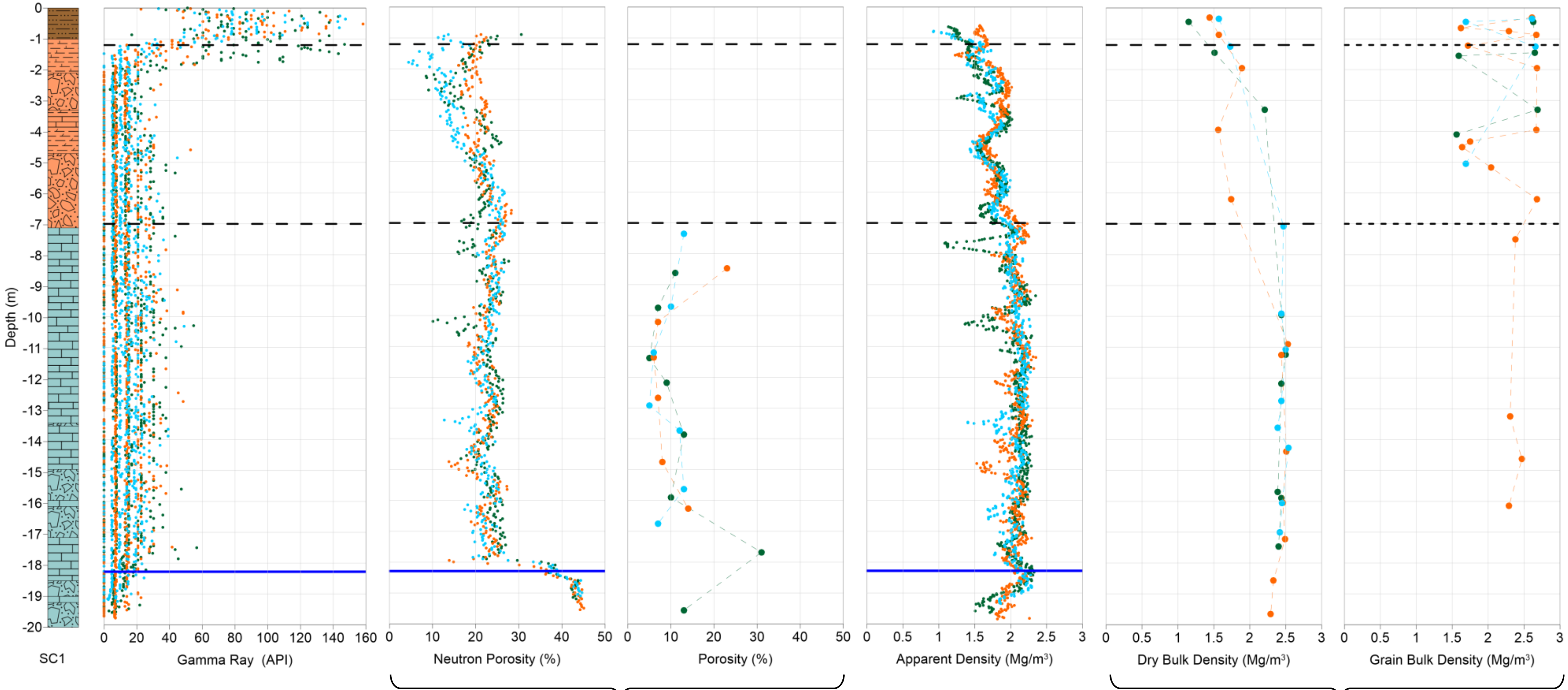
highlighted 3 main lithological groups with high heterogeneity and influences on transfers' behaviour in the VZ



How to link quantitatively geophysical measurements to the medium's parameters ?

Use Model and petrophysical law based on well logging profile and lab testing to get appropriate parameters.

Well logging & Lab testing to establish petrophysical relationships in VZ

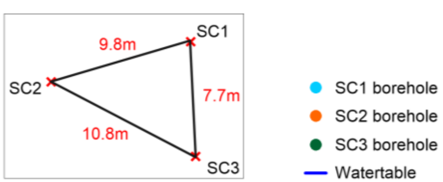


Clayey material

$\phi \approx 0.2$

$\rho_{eff} \approx 2Mg/m^3$

$\rho_s \approx 2Mg/m^3$



Lab testing **and** well **logging allow** to obtain **localised properties** of the subsoil that can be used in petrophysical relations **to converts geophysical** data **into hydrogeological properties**

Well logging & Lab testing to establish petrophysical relationships in VZ

Example with the GPR ⇒ Refractive Index Mixing model (CRIM) to estimate water saturation

$$S_w^n = \frac{\varepsilon_{eff}^{\alpha} - \phi\varepsilon_a^{\alpha} + (\phi - 1)\varepsilon_s^{\alpha}}{\phi(\varepsilon_s^{\alpha} - \varepsilon_a^{\alpha})}$$

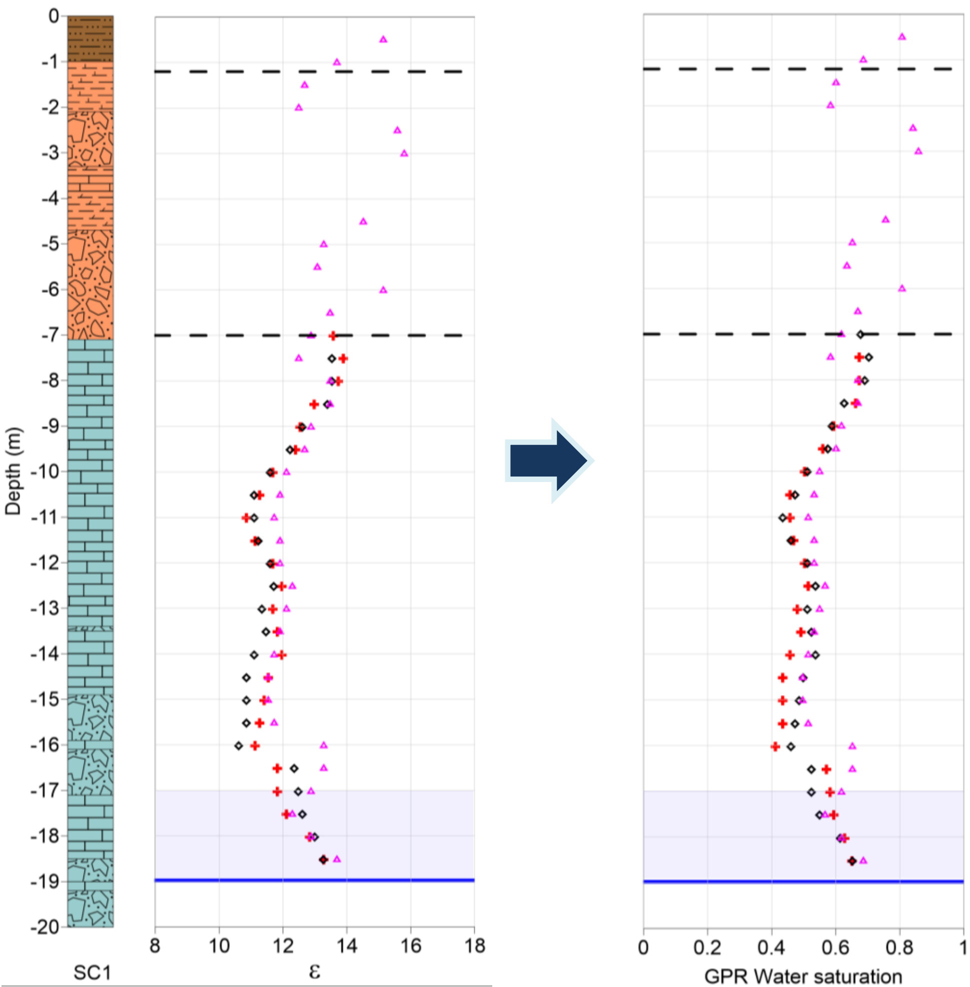
[Huisman et al., 2002]

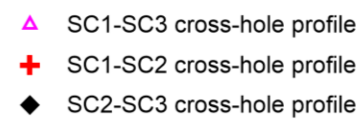
$\varepsilon_{air} = 1.00006;\ \varepsilon_{solid} = 6;\ \varepsilon_{water} = 81;$
$\alpha = 0.5;\ n = 1$

defined from literature

$\phi \approx 0.2$ ⇒ defined from log & lab

$\sqrt{\varepsilon_{eff}}$ *measured (GPR)*





Warnings :

- Uses of mean values not representative of the heterogeneity of the medium
- ε_{solid} is not calibrated to the geology
- ε_{water} value does not take into the temperature of the soil (under 15°C in January 2019)
- Above 7m depth, over estimation of water saturation due to the ε_{solid} that does not take into account clayey material

Well logging & Lab testing to establish petrophysical relationships in VZ

Not so easy

- What is the worth of the values defined from literature ?
- What model to use ?
- Scale effects ?

- Ground Penetrating Radar : Refractive Index Mixing model (CRIM)

defined from literature or lab

$$S_w^n = \frac{\varepsilon_{eff}^{\alpha} - \phi\varepsilon_a^{\alpha} + (\phi - 1)\varepsilon_s^{\alpha}}{\phi(\varepsilon_s^{\alpha} - \varepsilon_a^{\alpha})}$$

$\varepsilon_{air} = 1.00006; \varepsilon_{solid} = ?; \varepsilon_{water} = ?;$
$\alpha = ?;$ n $= ?$
$\phi \Rightarrow$ defined from log & lab
$\sqrt{\varepsilon_{eff}}$ *measured (GPR)*

- Electrical Resistivity

$$S_w^n = \frac{\sigma_{eff} - (1 - \phi^m)^p \sigma_r - \sigma_{arg}}{a\phi^m \sigma_w}$$

$$p = \frac{\log(1 - \phi^m)}{\log(1 - \phi)}$$

$\sigma_r = ?\ S.m^{-1}; \sigma_{arg} = ?\ S.m^{-1}$
$a = ?;$ m $= ?;$ n $= ?$
$\phi \Rightarrow$ defined from log & lab
$\sigma_w = 0{,}47.10^{-3} S.m^{-1}$ *at* $9.16°C$
σ_{eff} *measured (ERT)*

- Magnetic Resonance Sounding

$$k_{MRS} = C_p \theta_{w_{MRS}} T_1 \Delta z$$

↕ Comparison

$$K_S = \frac{k_S \rho_w g}{\eta_w}$$

$$\rho_{eff} = (1 - \phi)\rho_s + \phi\rho_w$$

$C_p = ?$
$\theta_{w_{MRS}} T_1 \Delta z$ *measured (MRS)*

$k_S = ?\ m.s^{-1}; g = 9{,}8\ m.s^{-1}$
$\eta_w = 10^{-3}\ Pa.s$
$\phi, \rho_{eff}, \rho_s \Rightarrow$ defined from log & lab

[Huisman et al., 2002; Legchenko et al., 2002; Cai et al., 2017]

Conclusion and future work

- Initial characterization of the Observatory of the transferts in the vadose zone (O-ZNS)
  - Valuable information that enlighten on transfer behaviour in the vadose zone
  - Accordance between methods (geophysics, geology and lab measurements) and scales of observation

⇒ Coupling multi-methods and scales of observation highlights the complexity of the vadose zone

- Calibration of the geophysical measurements and interpretation into water saturation
  - GPR shows that it can be done with a water saturation between 0.4 & 1 for an overall porosity of 20%
  - However there is a wide range of models and the existing relations contains uncertainty

⇒ This first analysis shows a need for in situ calibration and empirical petrophysical relationships

- Next
  - Review of petrophysical parameters used in case of carbonate material
  - Mounting of a geophysical laboratory to establish links between geophysical and hydrogeological parameters under different state of water saturation
  - Comparison of hydrogeological parameters obtain from geophysics to ones obtained by conventional hydro-measurements

⇒ Precise calibration of geophysical parameters will allow us to use complementary scales of observation and to couple methods together to reduce uncertainties and image flow patterns within the vadose zone

⇒ These parameters will then be used as input in hydrogeological models

Thank You

Related work during EGU2020:

- Abbar et al., *Monitoring of the mass and heat transfers in Vadose Zone of an agricultural field at Villamblain (Beauce Aquifer, Orleans, France), ID EGU2020-5294, GI4.4*
- Ammor et al., *Geophysical characterization of a Limestone Heterogeneous Vadose Zone – Beauce Aquifer (France), ID EGU2020-16391, HS8.1.5*
- Isch et al., Material Characteristics, Hydraulic Properties, and Water Travel Time through the Heterogeneous Vadose Zone of a Cenozoic Limestone Aquifer (Beauce, France), ID EGU2020-5862, HS8.3.2
- Mallet et al., *Geophysical estimation of the damage induced by an observatory digging in a limestone heterogeneous vadose zone – Beauce aquifer (France), ID EGU2020-2411, EMRP1.2*

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