EXPLORATION OF ELECTROMAGNETIC INDUCTION POTENTIAL TO UNDERSTAND GROUNDWATER INFILTRATION WITHIN THE CHALK CRITICAL ZONE

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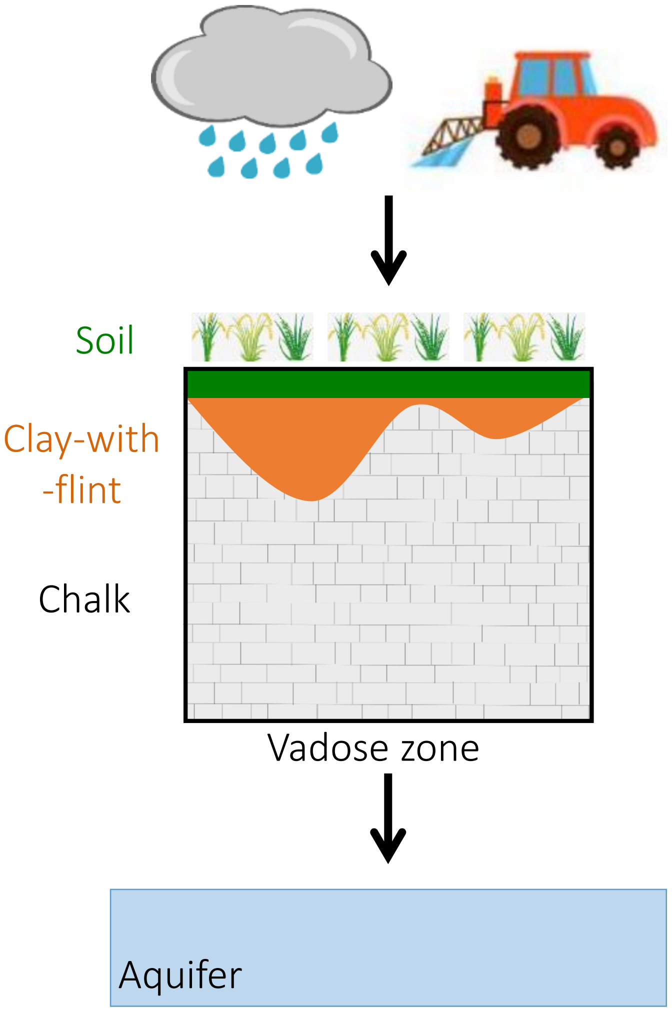
GROUNDWATER ISSUES

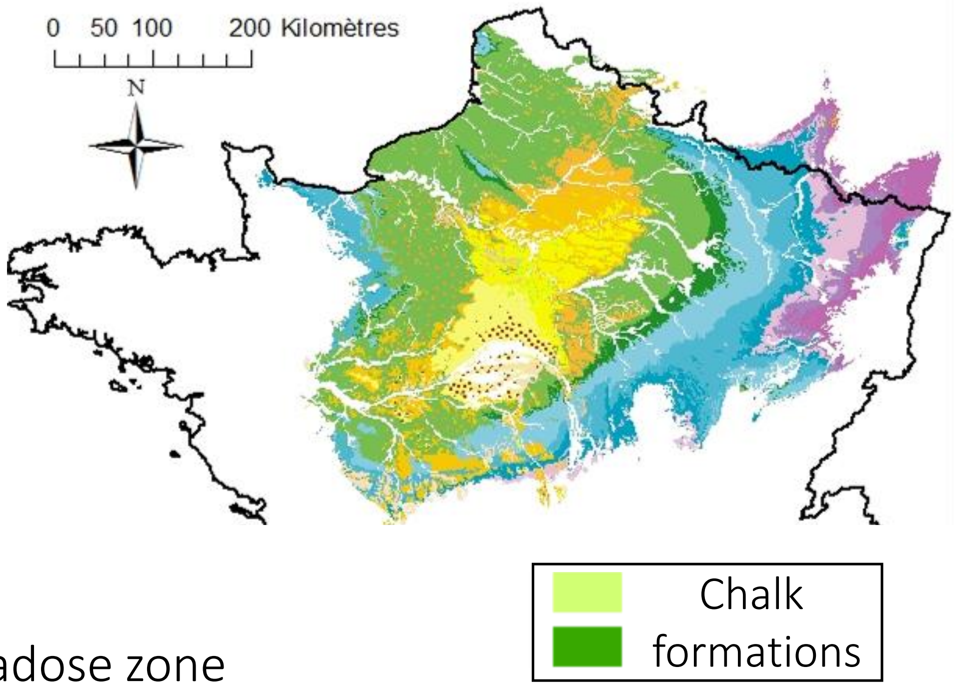
Rainfall and anthropogenic pollution



In the northern part of France,

The **Chalk aquifer** in the Parisian regional aquifer is a **critical resource** for human activities.

GEOLOGICAL MAP OF THE PARISIAN BASIN



In St-Martin underground quarry, groundwater flows through the vadose zone have been studied for about 10 years with two objectives:

- **Understand and quantify groundwater recharge**
- **Estimate aquifer vulnerability to fertilizers and pesticides**

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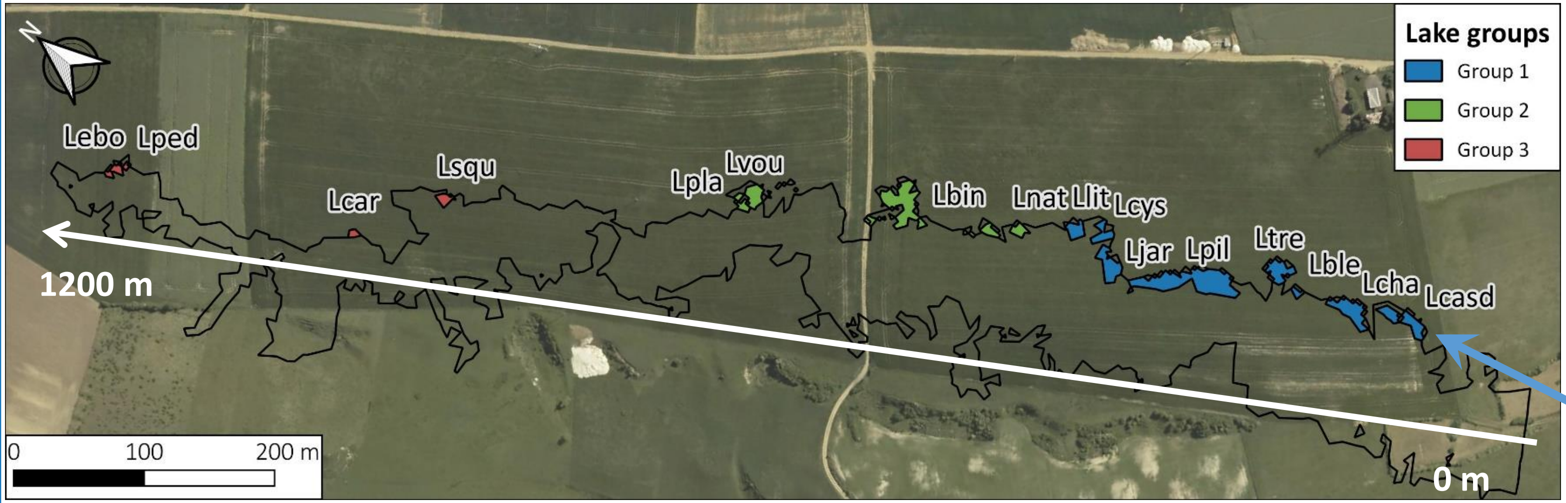
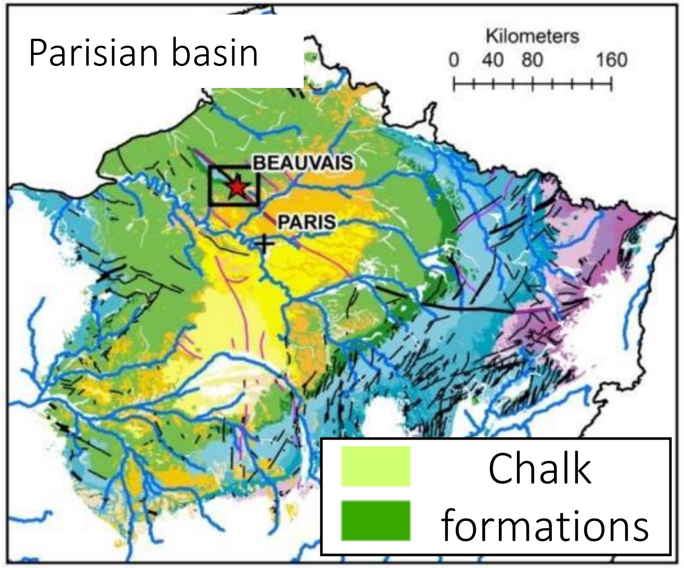
St-Martin underground Chalk quarry

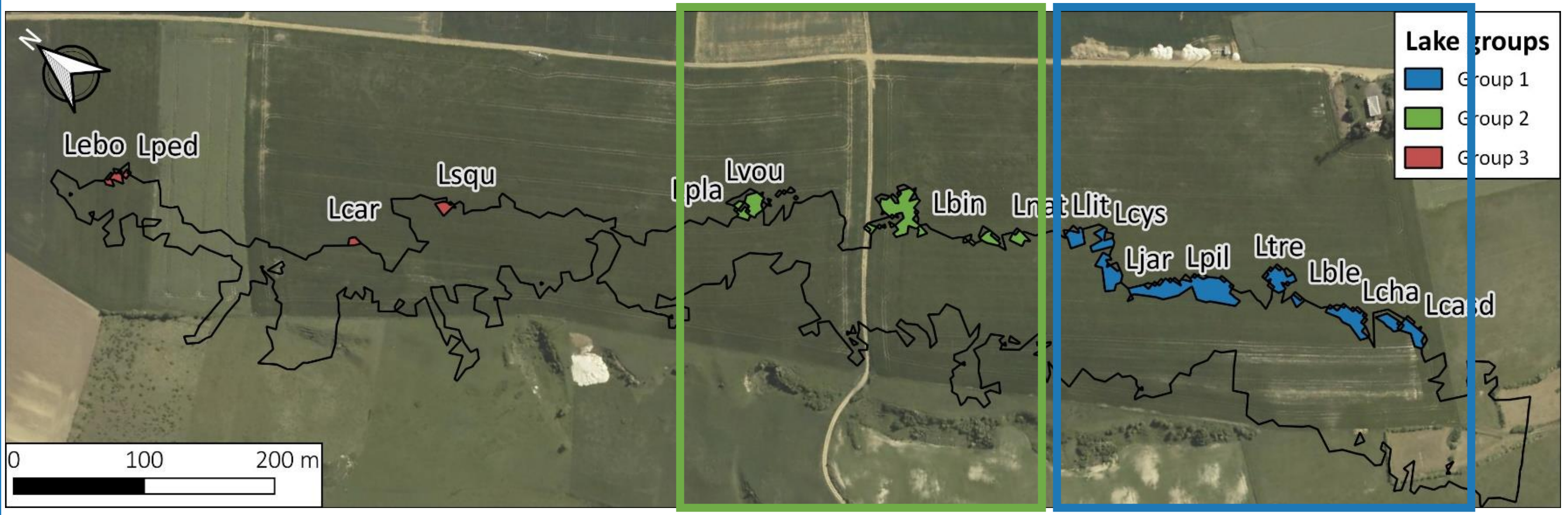


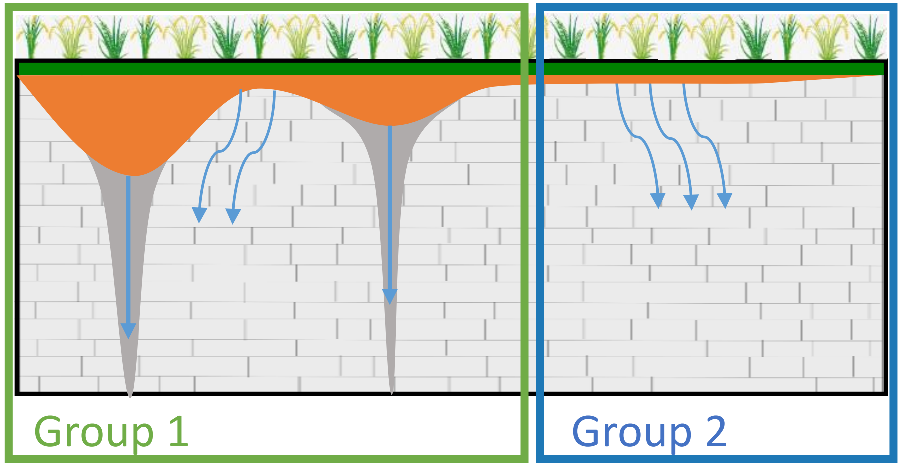


The Chalk underground quarry was dug until it reached the water table
This site have two major characteristics

Provide a direct access to the limit between **Unsaturated Zone / Aquifer**
Located on a **topographic & piezometric ridge**

Groundwater behaviors unraveled in St-Martin





Results of hydrodynamic & geochemical studies

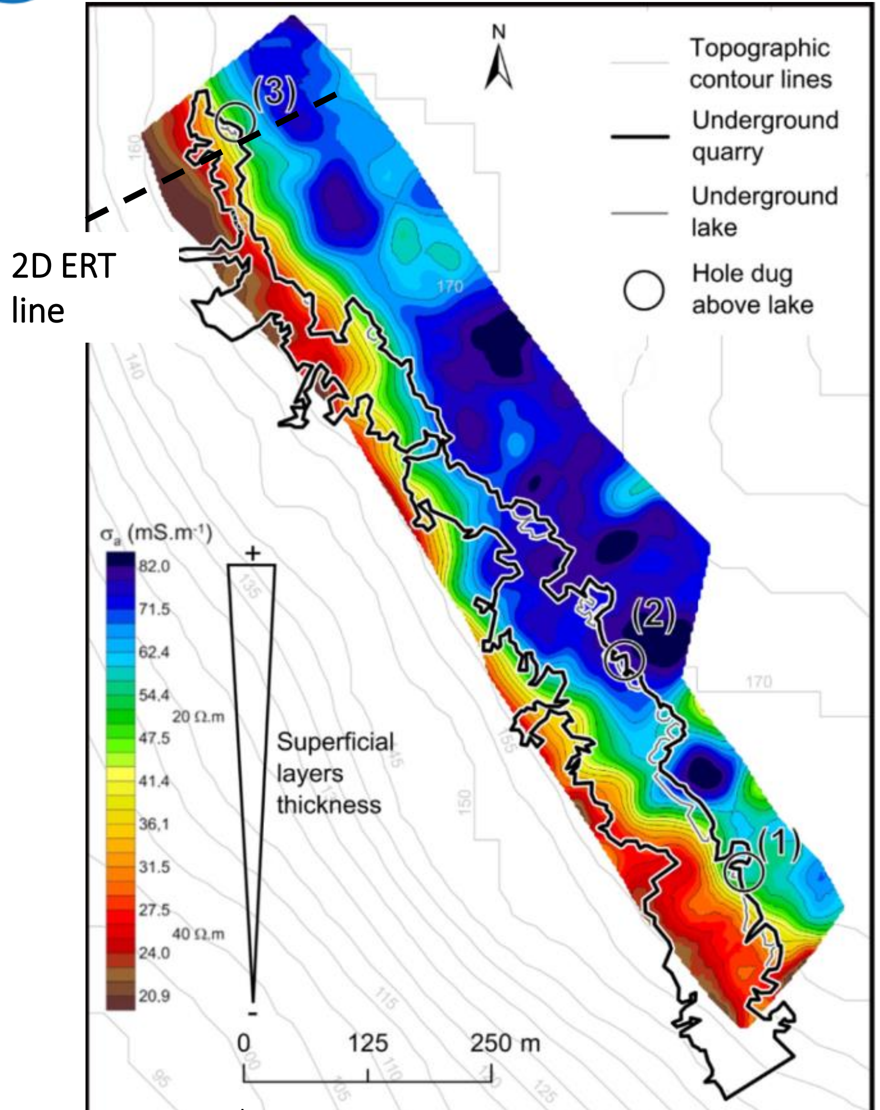
Highlight two different dynamics :

1- diffuse transfers through the chalk matrix (Lake group 1)

2- non-karstified preferential paths related to crypto-sinkholes (Lake group 2)

How geophysics could provide information about this two behaviors ?

PREVIOUS GEOPHYSICAL WORK

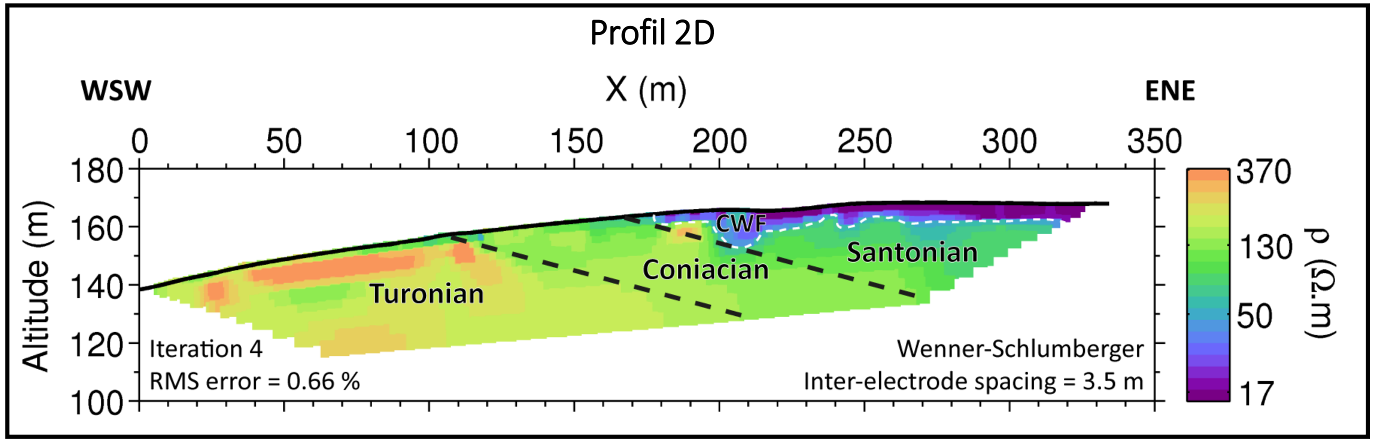


EMI conductivity mapping

In 2013 several acquisitions were made above the quarry:

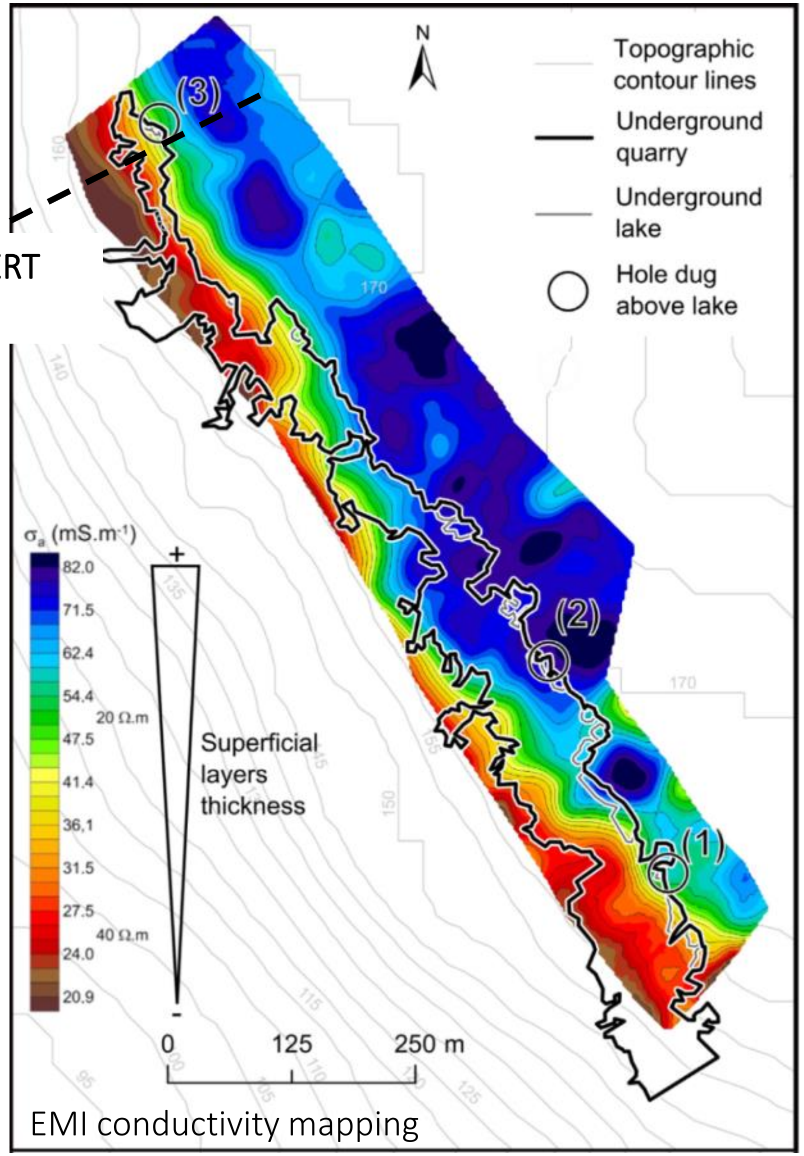
1] **2D ERT lines** with 3.5m electrode spacing along 336m
2] **EMI conductivity mapping** using EM31 integrating the ground signature up to 6m depth

The **2D ERT line** acquired to the north of the zone highlights a conductive horizon at the right of the quarry. Because of the large distance between the electrodes, the geometry of the conductive layer cannot be precisely defined.



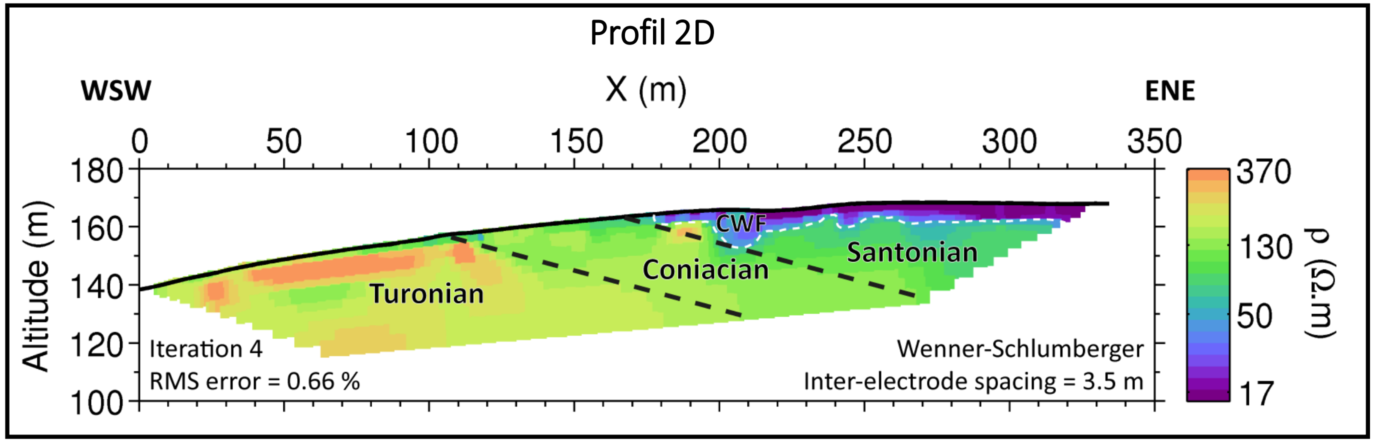
BARHOUM et al., 2014 – Journal of hydrology AND PASQUET et al., 2016 – SAGEEP

PREVIOUS GEOPHYSICAL WORK



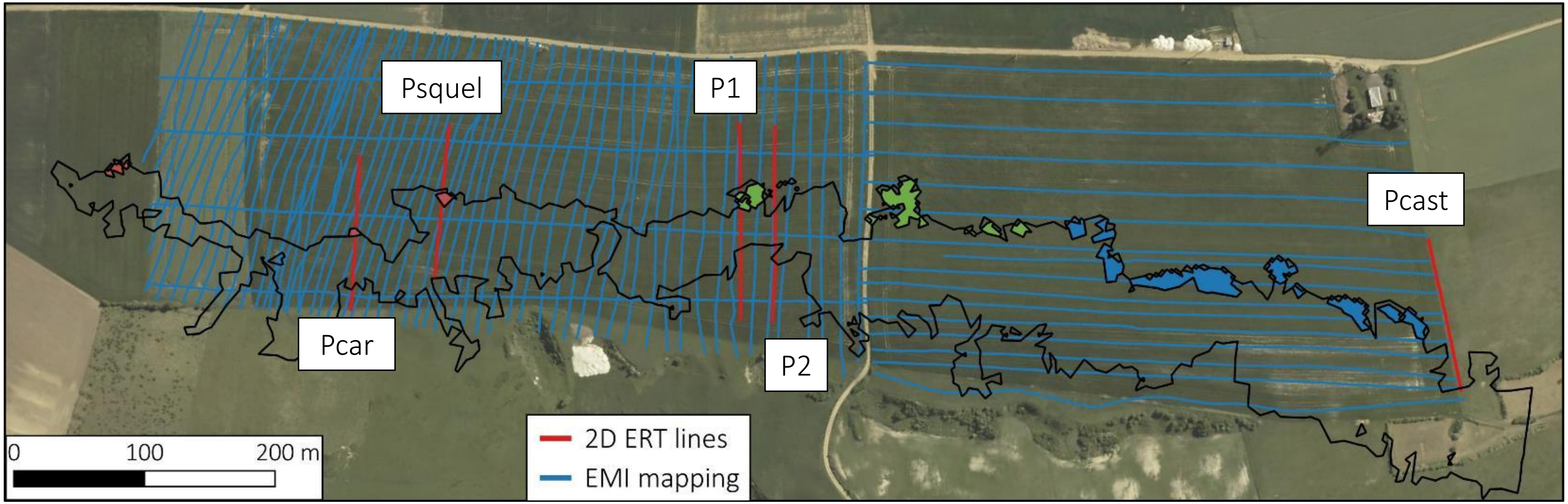
EMI mapping shows a dichotomy between the south-east resistant part and the conductive north-west one. In the latter, circular shapes are more conductive and seem to indicate the presence of the crypto-sinkholes we are looking for. However, it is difficult to specify the structures with a single conductivity map.

These results underline the need for **imaged the vertical resistivity variations as densely as possible above the quarry.**



BARHOUM et al., 2014 – Journal of hydrology AND PASQUET et al., 2016 – SAGEEP

GEOPHYSICAL SURVEY



the EMI and ERT surveys were acquired in two consecutives days to minimize changes of the hydrological state

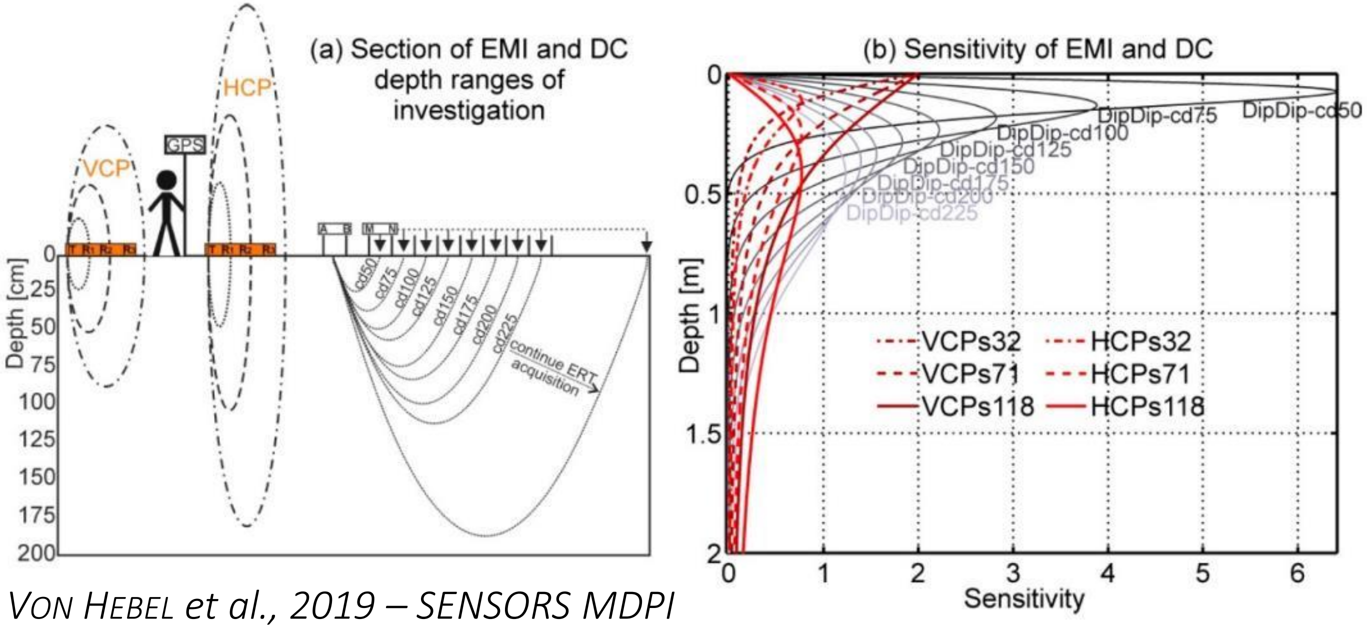
2020/05/06 – **Five 2D ERT lines** have been acquired above lakes characterized by different groundwater behaviors. After ERT acquisition, each 2D lines have been covered by and EMI acquisition to proceed the calibration.

2020/06/07 – An extensive **EMI survey** have been acquired above the quarry with the CMD explorer instrument. Thanks to its three receiver coils, we investigate three depths: 2.2m, 4.2m, 6.7m

EMI CALIBRATION

The aim of this survey is to create a 3D conductivity model above the quarry with EMI mapping. The ERT 2D lines will be used for two purposes, (i) to validate vertical geometry in depth, (ii) to calibrate EMI dataset.

In order to correctly calibrate EMI data, ERT 2D lines must be acquired in homogeneous sectors so that the calibration is not disturbed by resolution differences between the two methods. In our study, ERT is used to validate the structures at depth, so they were intentionally acquired in heterogeneous sectors.



VON HEBEL et al., 2019 – SENSORS MDPI

EMI CALIBRATION

Here we use the three steps of ERT calibration developed by Lavoué et al. (2010, Near Surface Geophysics):

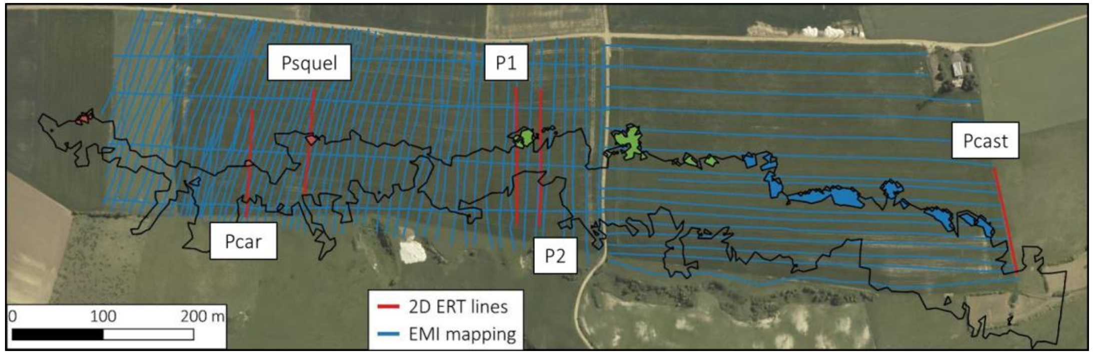
(1) extraction of 1-D layered-earth models from a reference ERT along the profile,
(2) simulation of the equivalent ECa responses for a CMD-Explorer instrument configuration,
(3) comparison of the results with the field-measured ECa to establish shift and scale calibration factors.

After a standard inversion of ERT 2D lines with Res2Dinv, and the analysis of instrumental drift, two kinds of calibration are tested here:

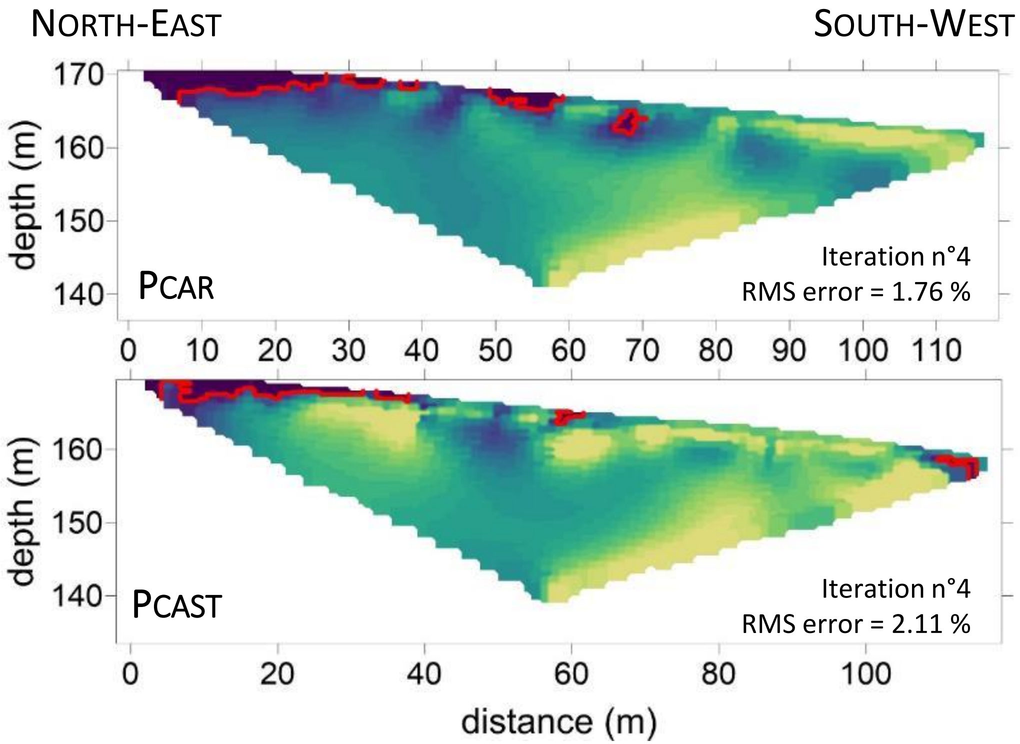
Calibration 1- **Raw EMI data are resampled** at ERT electrodes location

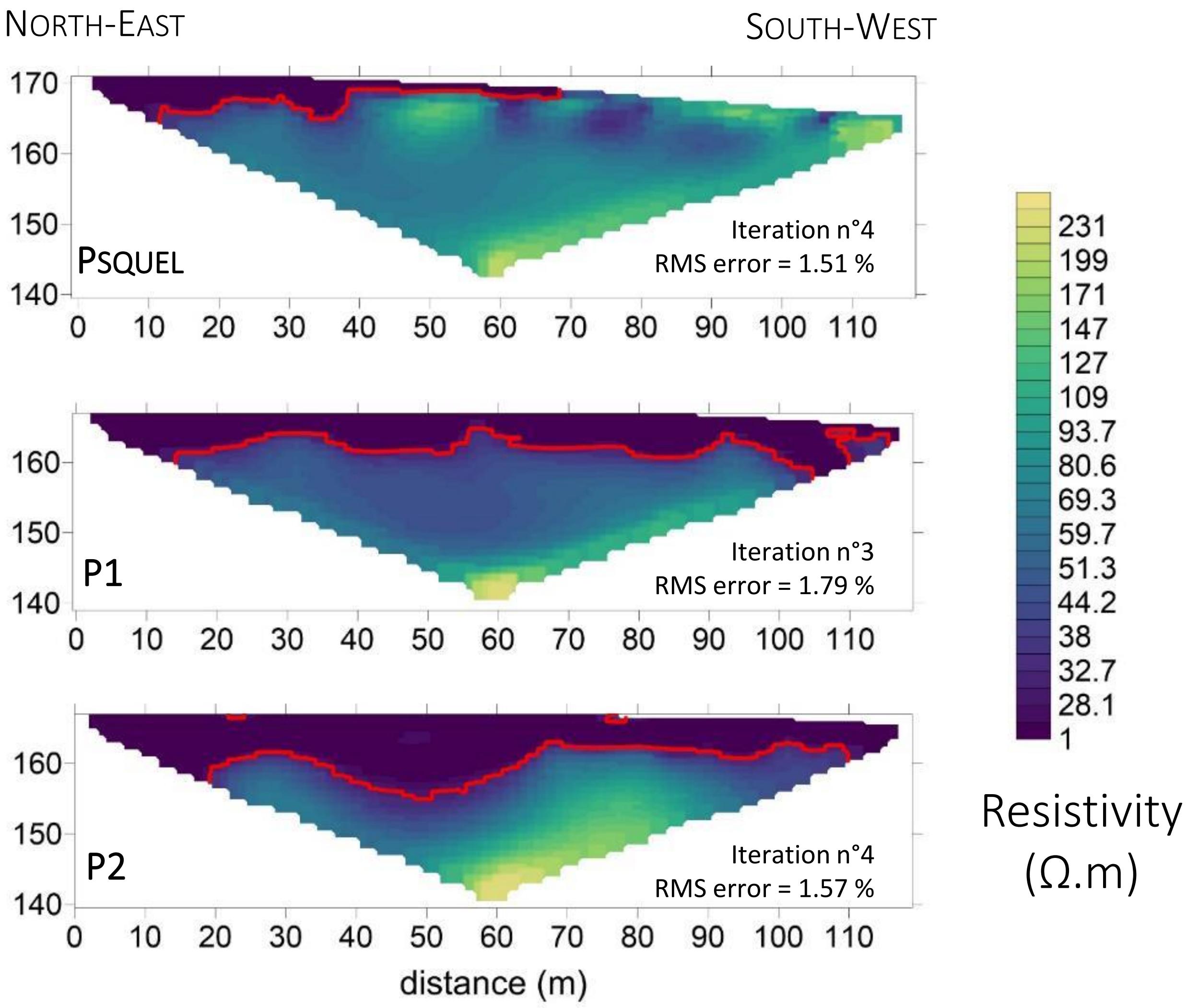
Calibration 2- **EMI data are resampled** and ERT data are filtered to remove local 2D/3D effects

EGU General Assembly 2020 — Results of 2D ERT lines



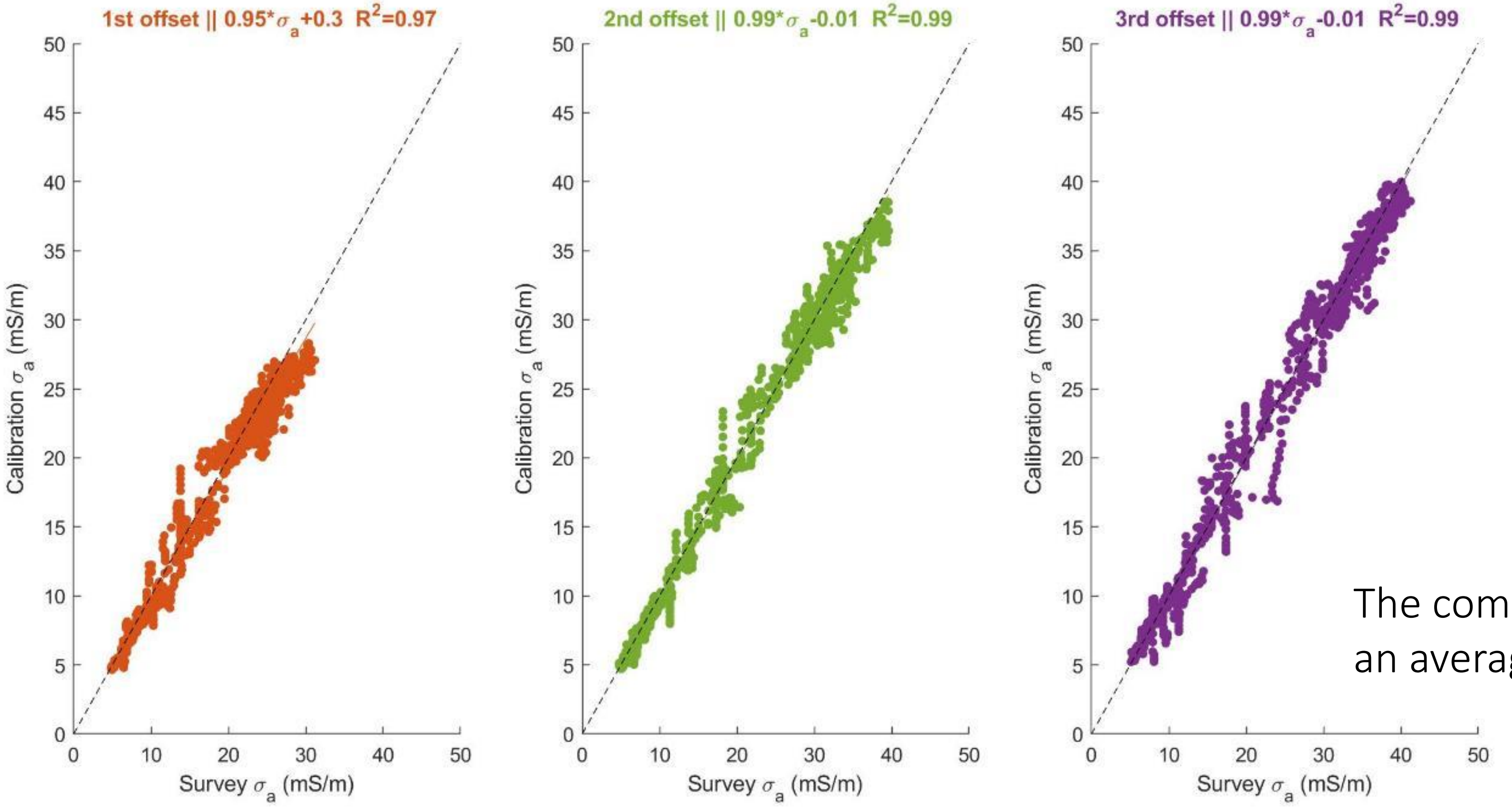
2D ERT lines have been acquired over lakes of different groups in order to image the unsaturated zone in depth





INSTRUMENTAL DRIFT

First, we check instrumental drift during the two days of survey. Each receiver coil offset is represented separately: orange - 1st offset (2.2m depth), green – 2nd offset (4.2m depth), purple – 3rd offset (6.7m depth. This color code will be retained for all subsequent graphics. We obtain a correlation between the two days near by 0.99 for each receiver coils spacing.



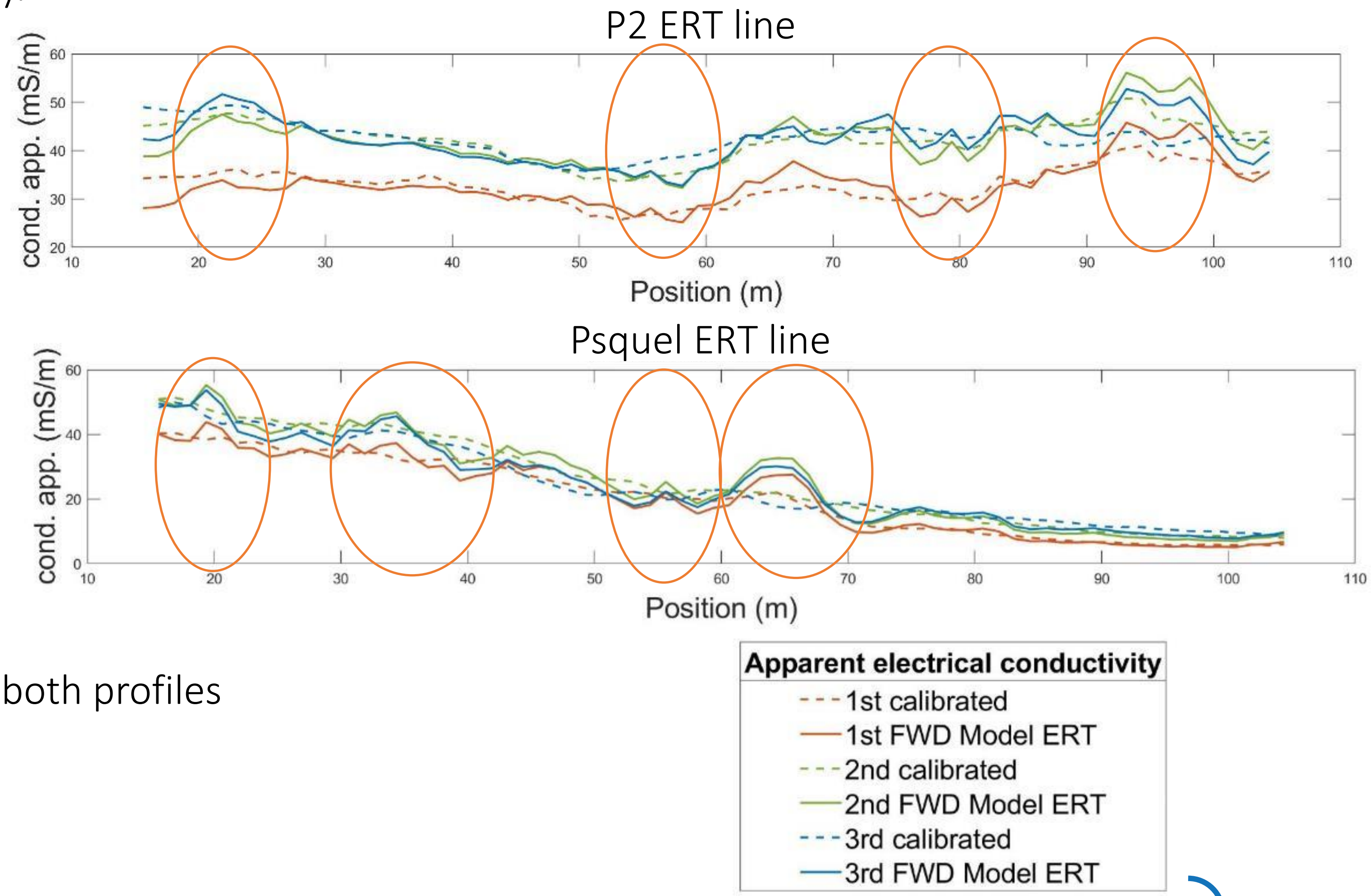
The compared data are spaced an average of 3m apart (±2m).

We can conclude that no instrumental drift distort our dataset.

CALIBRATION 1 – RAW DATA

The first calibration uses Lavoué et al. methodology on raw data without any processing (2010, Near Surface Geophysics). The graphs opposite represent the models from the ERT data (solid line) and the apparent conductivities measured by the calibrated CMD for each profile independently.

For both profiles, the general trend for both methods is consistent. The P2 profile is marked by an area of lower conductivity in the centre, while in Psquel the conductivity is decreasing along the profile.



However, a difference in spatial resolution between the two methods is visible on both profiles. While the EMI data has long wavelength variations, the ERT data has shorter wavelength variations.

In addition, local divergences can be seen on both profiles (surrounded by orange circles).

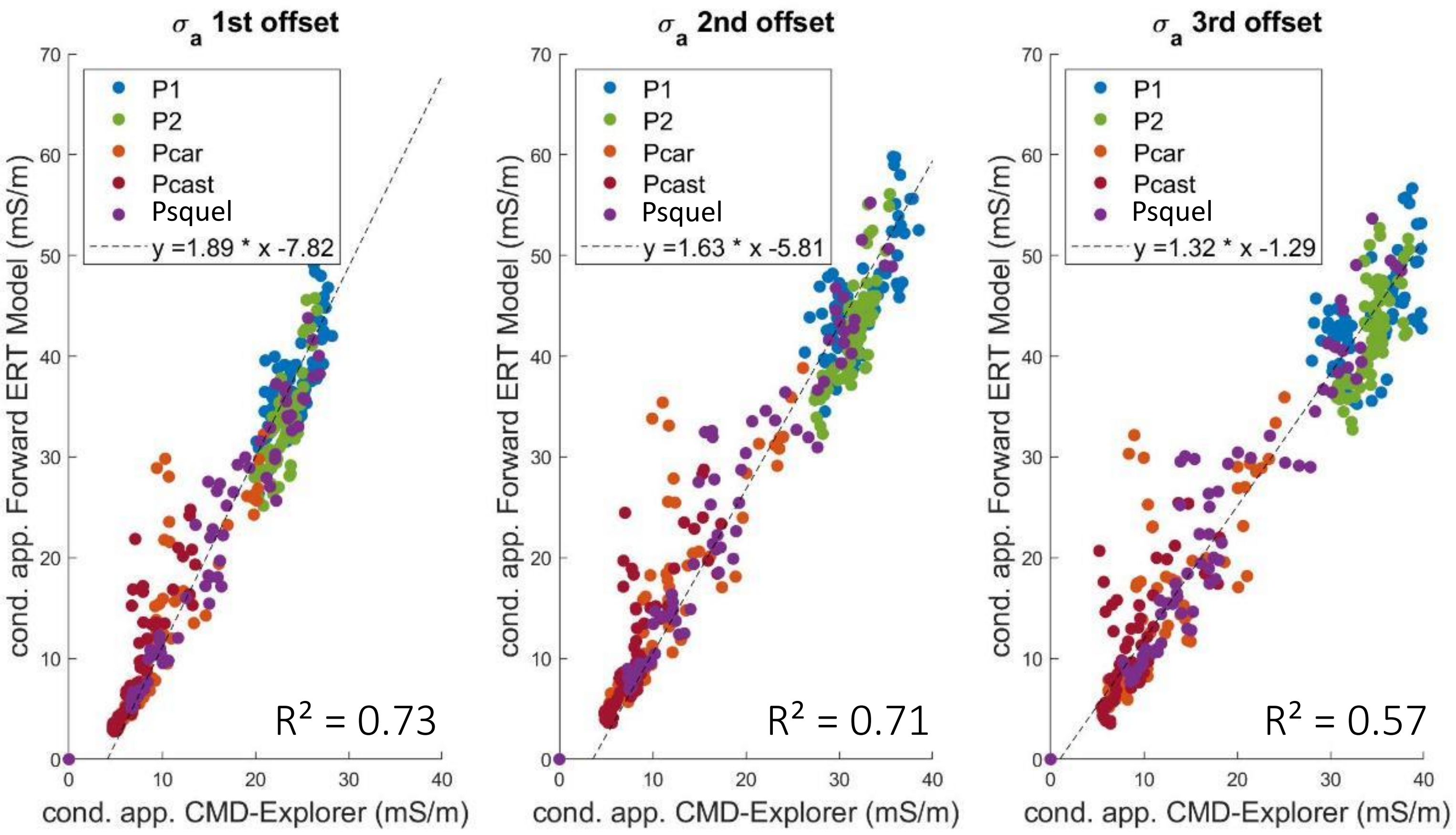
CALIBRATION 1 – RAW DATA

The calibration results are shown in the adjacent figure.

For each offset, shift and scale calibration factors are calculated using the results of all 5 ERT 2D lines.

For the first two offsets, the results are favourable despite some data scatter.

In depth, the influence of more distant structures accentuates the bias decreasing the quality of the calibration.



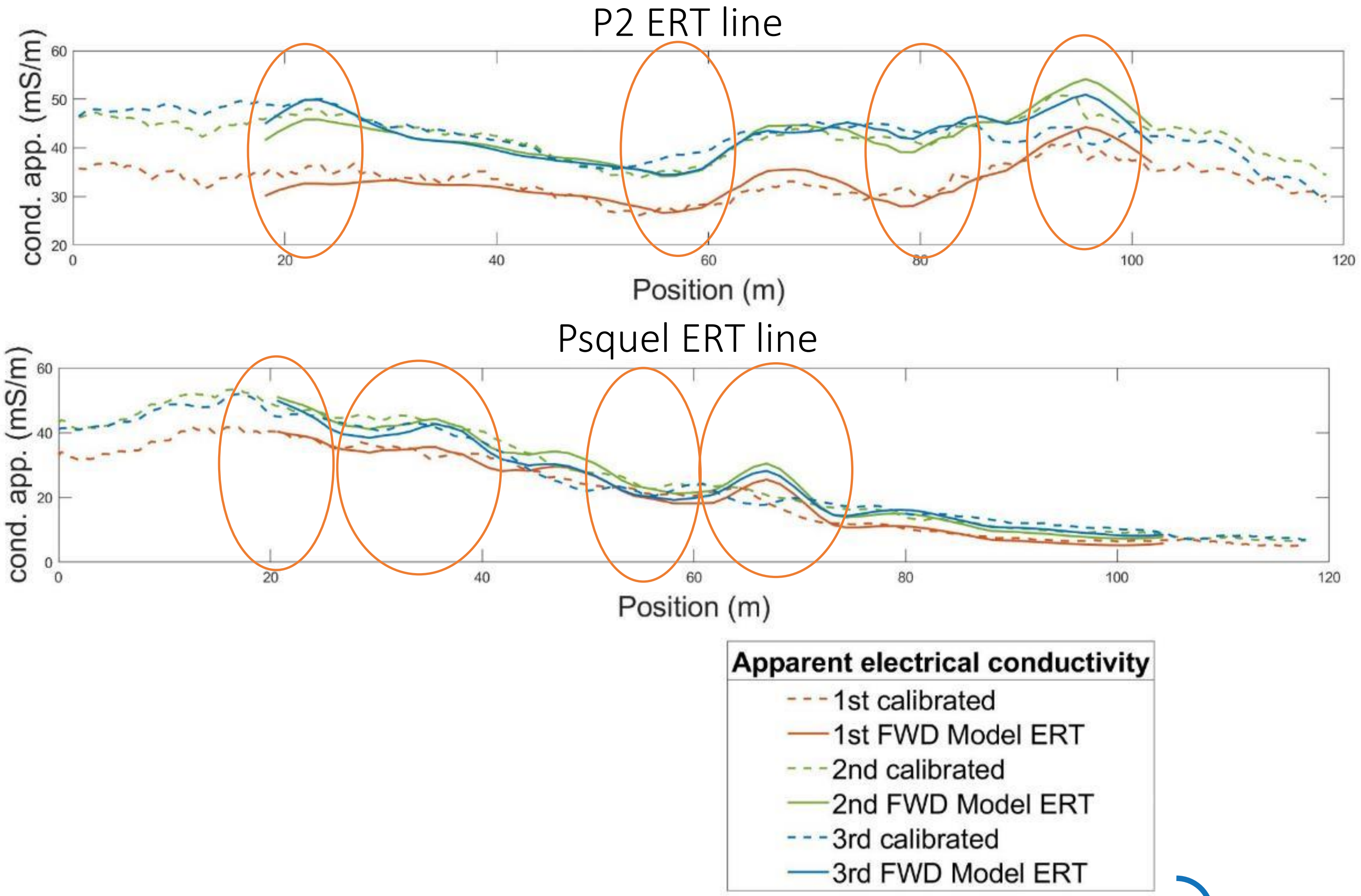
CALIBRATION 2A – DATA FILTERED

For the second calibration, the ERT data is filtered to reduce the resolution difference between the two methods. The ERT electrode spacing was 1.25m while the larger offset energizes the subsurface within a radius of 6.7m. To reduce the difference, the ERT data is filtered over a range of 5 electrodes.

The artificially obtained ERT resolution should be close to 6.25m.

The graphs on the right show a better coherence in the variation frequency of the two methods.

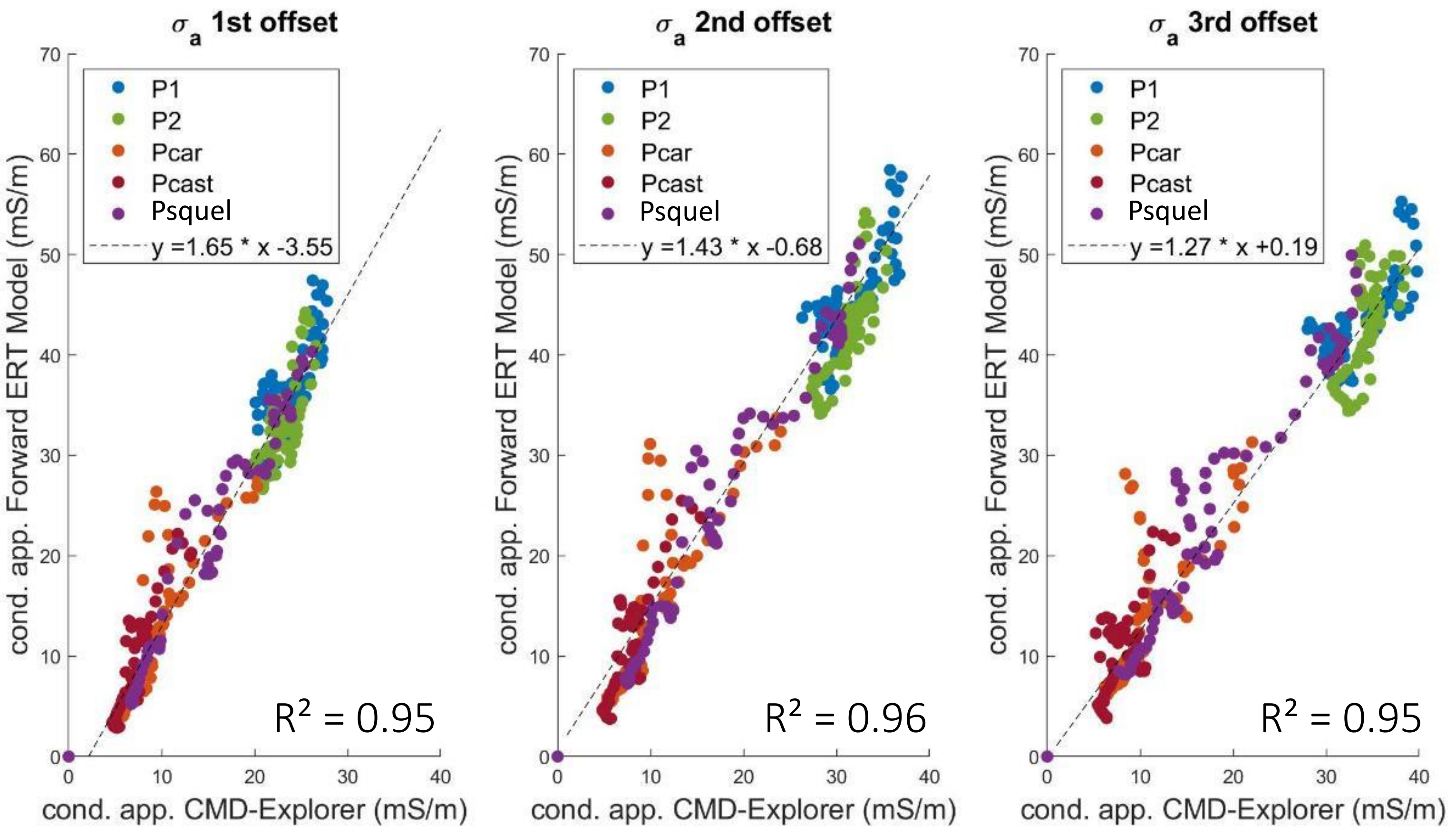
In regards of the major biases highlighted during the first calibration, they are generally reduced despite the presence of significant differences.



CALIBRATION 2A – DATA FILTERED

The results of the second calibration protocol are significantly improved. We obtain R^2 values around 0.95 for all the offsets.

For each of the offsets, a slight scattering of the data persists.

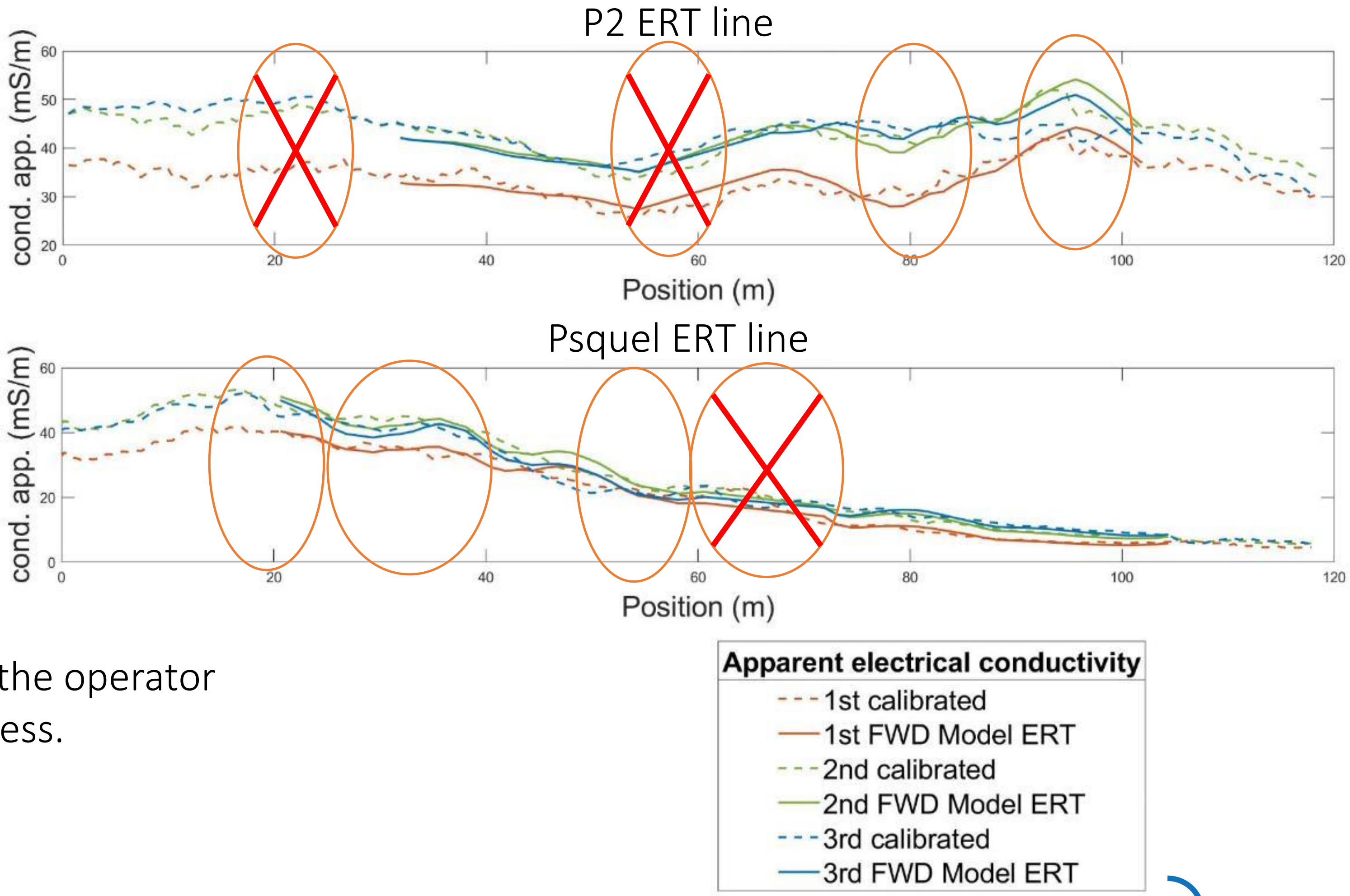


CALIBRATION 2B – DATA FILTERED & SELECTED

In order to improve the second calibration, the data over major biais highlighted above are removed during the calibration process. Indeed, we consider that these data are disturbed by lateral heterogeneities integrated differently by the electrical and electromagnetic method.

This step is challenging due to the need to correctly identify areas of bias between methods while maintaining a sufficient amount of data to be representative of EMI dataset.

Psquel 2D line main artifact, marked by a high amplitude, was clearly identifiable. In contrast, the variations on the P2 profile are less significant and therefore more difficult to identify.

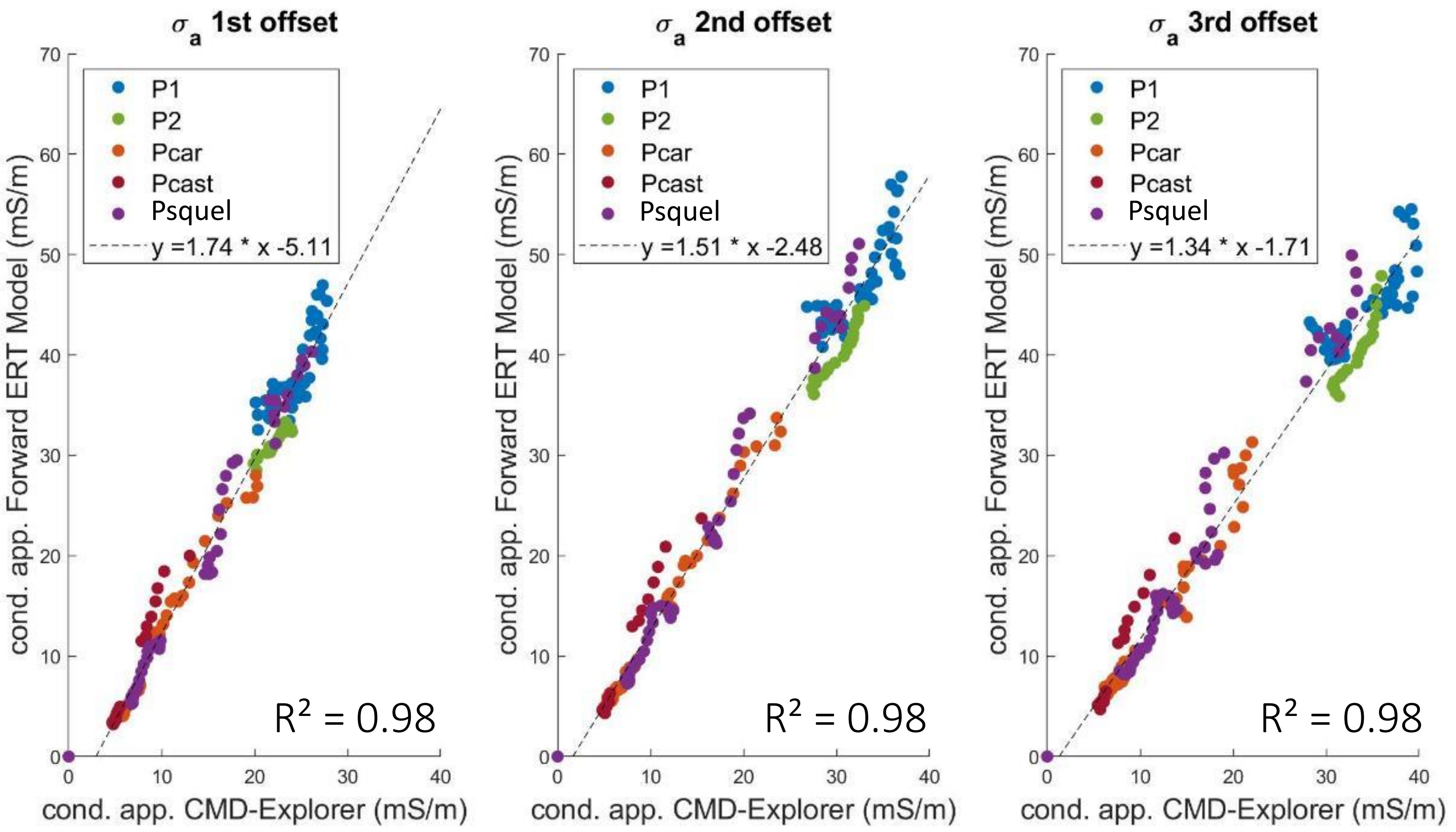


This process is therefore strongly impacted by the operator adding an arbitrary part to the calibration process.

Calibration 2b – Data filtered & selected

The removal of the most important biases allows to further improve the calibration with scores of 0.98 for all offsets.

This calibration is therefore validated and compared with calibration 1 in the following presentation.

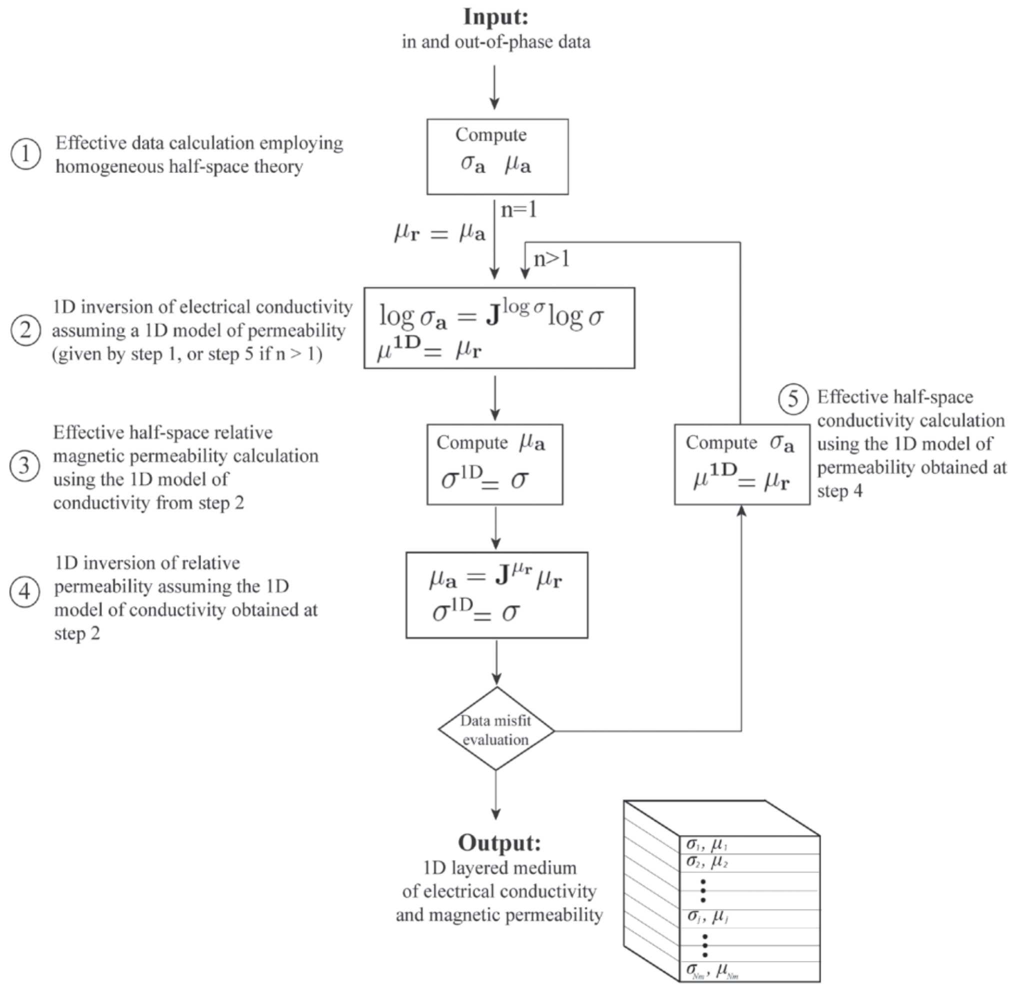


CALIBRATION ANALYSIS – 1D INVERSION

In combination with the correlation score between EMI and ERT data, the accuracy of the calibration process is analyzed on the inverted results.

For this purpose, the data obtained with calibration 1 and 2b described in Guillemoteau et al, 2016 (Near Surface Geophysics), for which the relative permeability has been set to 1 and additional lateral constraints (LCI) were included.

The next slides present preliminary inversion results for ERT lines P2 and Psquel.



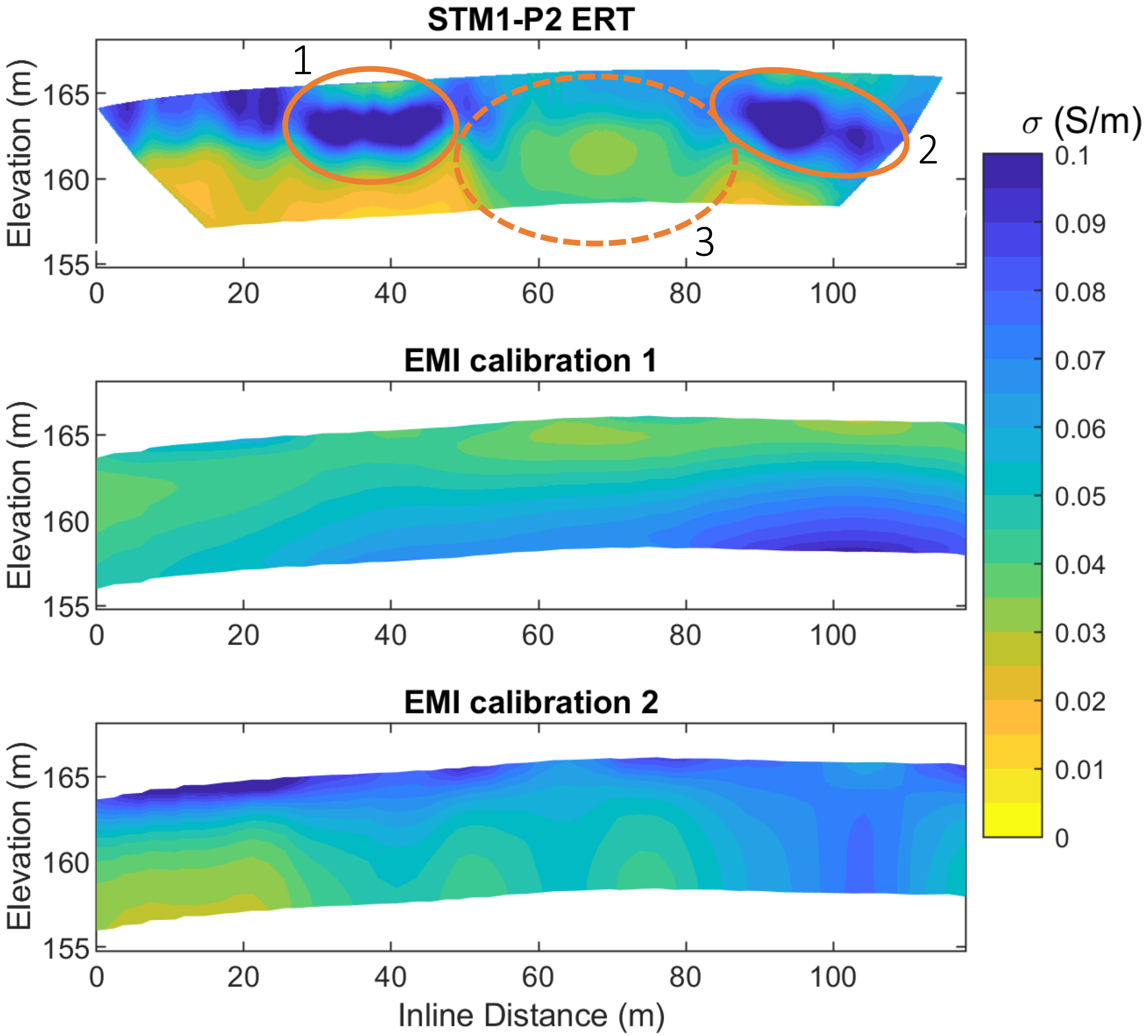
Inversion protocol from Guillemoteau et al. (2016 – Nea Surface Geophysics).

CALIBRATION ANALYSIS – 1D INVERSION

P2 ERT line is represented between the surface and 8m depth. The conductive horizon thickens from south to north. Two important conductors can be seen around 40 and 100m apart (circle 1 and 2). In the center between 55 and 80m (circle 3), the area corresponding to a basin is almost not represented. We find a breach in the deep resistant substratum but the surface horizon remains resistant.

The results of the first calibration do not correspond at all with the stratification of the subsoil imaging a resistive layer above a conductor.

The second calibration allows to find results that are more comparable to the ERT line. We can note than, (i) the superficial horizon is nevertheless more resistant, (ii) the two highly conductive zones are quite fairly represented, and (iii) the substratum breach is rather poorly imaged.



ERT line direction are reversed from slide 7

Calibration analysis – 1D Inversion

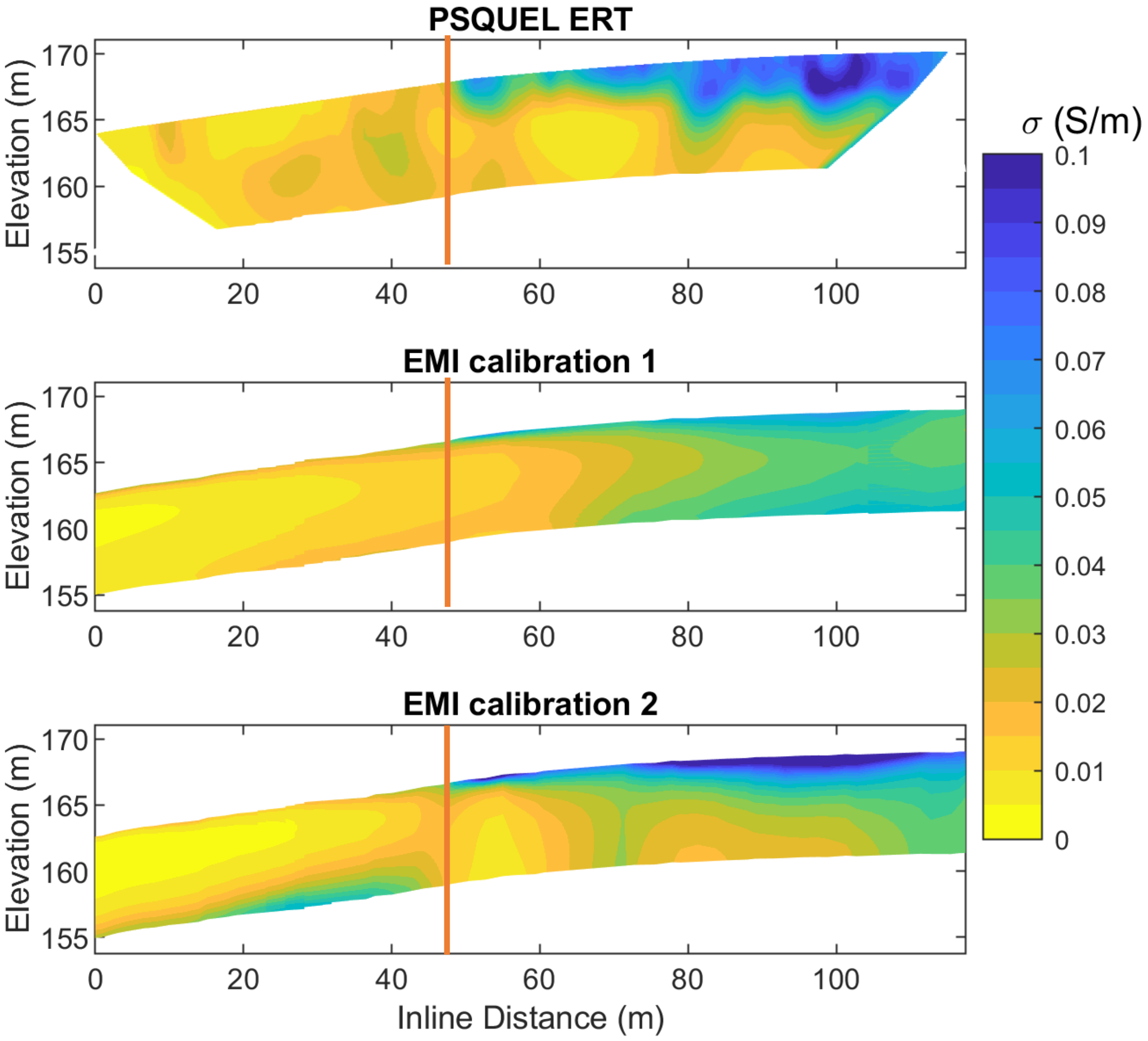
Psquel ERT line can be divided into two zones with (i) a resistant part up to 50m, (ii) the occurrence and deepening of the surface conductor.

The two calibrations represent fairly well the two sectors and the limit around 50m. Nevertheless, the first calibration does not allow to correctly image the evolution of the conductor creating a rough break around 80m of distance. On the other hand, the second calibration is quite close to the ERT results.

The results obtained on both profiles demonstrate:

(i) the inversion of first calibration dataset is poorly or purely not consistent with the ERT imagery.

(ii) the second calibration fairly images conductivity contrasts. Nevertheless, in the most complex parts, the EMI seems to be influenced by lateral effect.

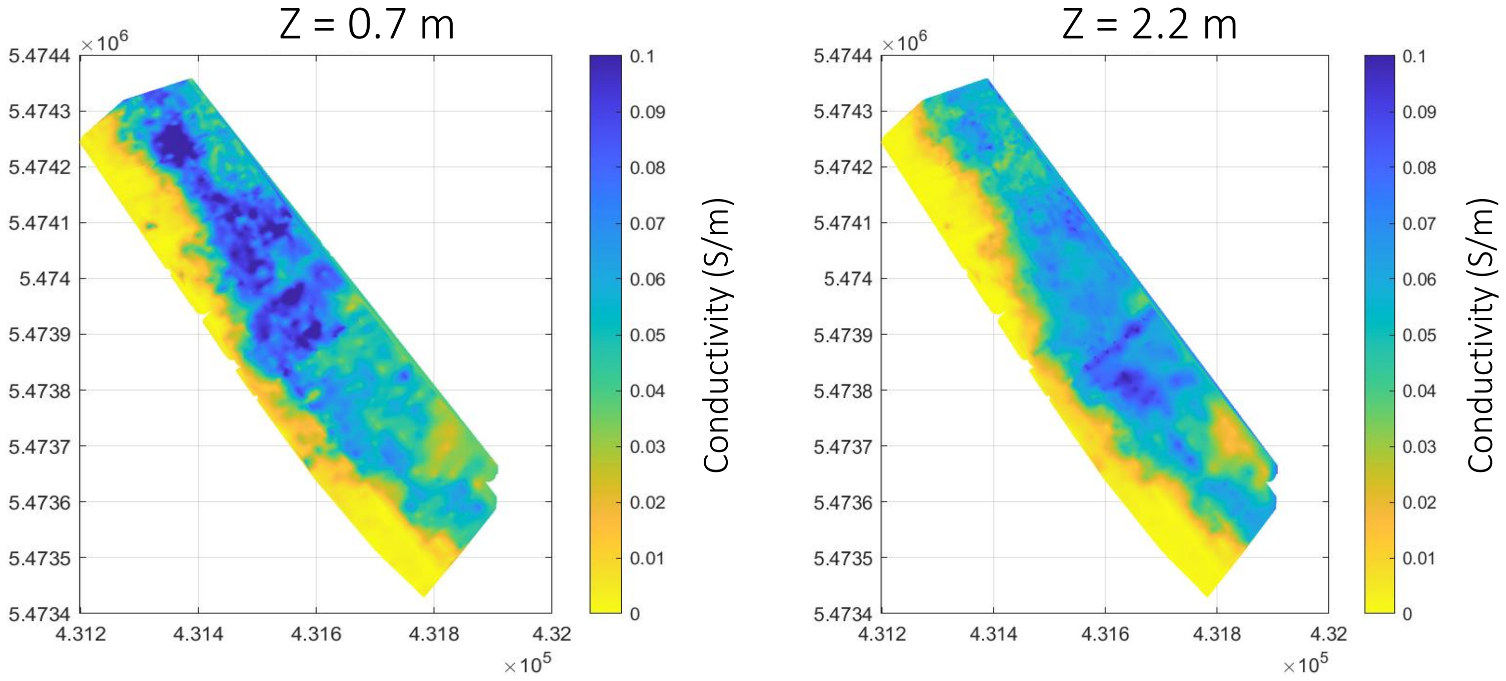


ERT line direction are reversed from slide 7

INTERPRETATION AND CONCLUSION

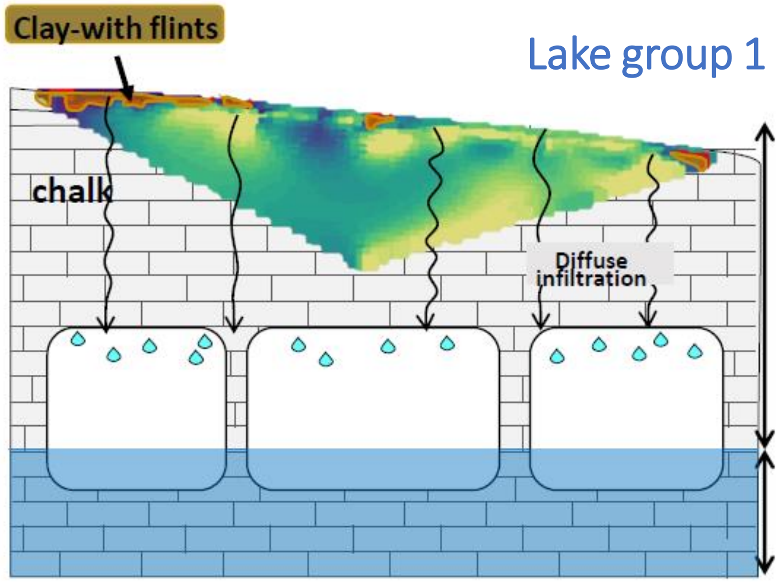
These initial results highlight the need to perform a robust calibration of the EMI data in order to obtain an inverse model consistent with the subsurface structure. Nevertheless, this study highlights the possibility of acquiring calibration ERT profiles in heterogeneous sectors. Indeed, a light processing of the ERT data allows to obtain a very good quality calibration.

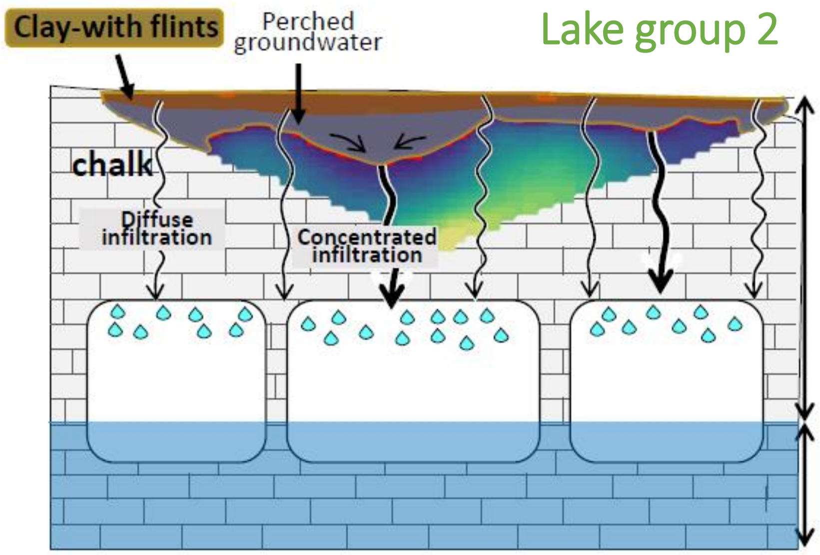
Our study has allowed (i) to obtain a 3D resistivity model over the entire quarry thanks to EMI survey, and (ii) to validate the geometry of the crypto-sinkholes in depth thanks to the ERT 2D lines.



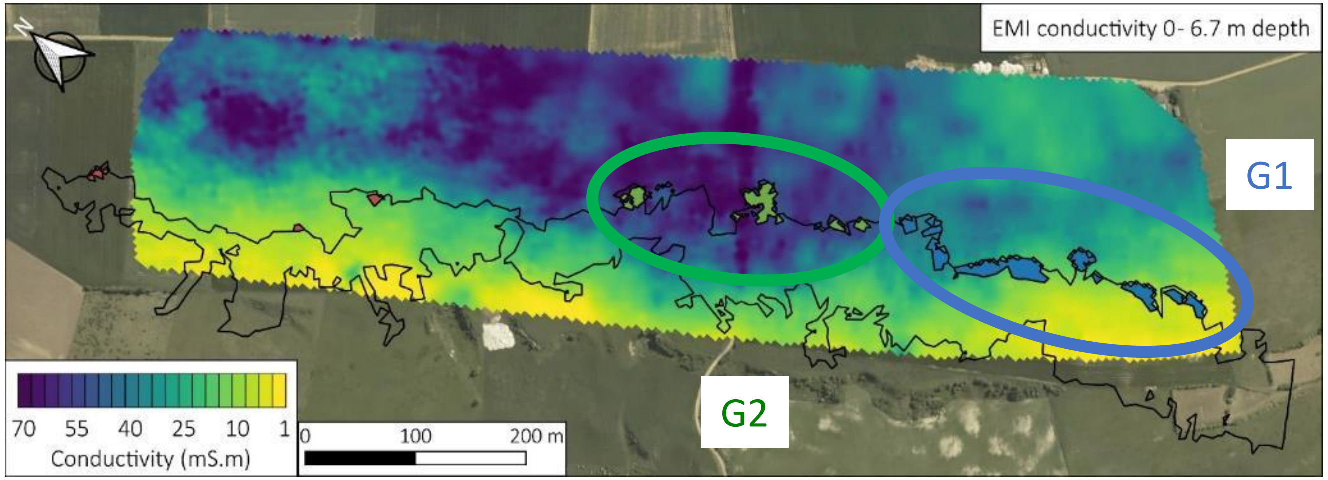
Please note that the sensitivity analysis of the EMI inversion has not been processed yet.

INTERPRETATION AND CONCLUSION





These new results are encouraging, demonstrating the value of both methods. While 2D profiles have made it possible to highlight crypto-sinkholes structures, EMI mapping allows defining the sectors with different groundwater behaviors.



More information on groundwater interpretations on Valdès et al. presentation (EGU2020-20390 – Transfer processes in the chalk critical zone – Multidisciplinary study of the undergound quarry of Saint Martin le Noeud)

Lsquel lake inside the underground quarry