Hydrogeophysical Tools for Investigating Groundwater Storage in the Subsurface of a Karst System

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1. Introduction and Aim of the Research

Karst **A**quifer **R**ese**A**rch by **G**eophysics Project

Present knowledge of karst systems has evidenced the importance of the **unsaturated zone** on water dynamics. However, this zone is the lesser known part in the karst water balance. For a better understanding of the infiltration processes within **the epikarst**, a **continuous monitoring** of spatial and temporal changes in the water content has been applied in the subsurface of a karst system.

Gravimetric monitoring is crucial to evidence water storage changes through time. An **electrical resistivity tomography** (ERT) monitoring system is also needed to image, at least on a daily basis, the spatial variability of resistivities due to the complex geometry of the epikarst. ***H/V* spectral ratio** analysis provide valuable data to help the characterisation of the subsurface.

The field site of this experiment forms part of the Rochefort Cave Laboratory, which is located in the Variscan fold-and-thrust belt (South Belgium), in a region that shows many karstic networks within Devonian limestones units. Epikarst, and its temporary reservoir, are supposed to occur within the first 5 meters below a thin soil layer (20 to 50 cm of clayish materials). The saturated zone starts at a depth of 70 meters, which in ourt case is below the main part of a cave that is located at an average depth of 35 meters.

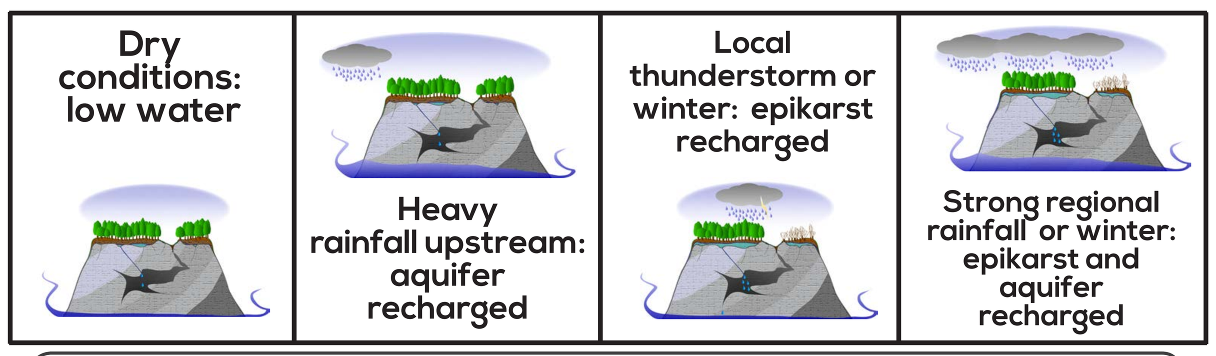


Fig.1: 4 stages of groundwater content are expected to occur in a karst system given the climatic conditions

Karst systems for dummies

They show **deep heterogeneities** in terms of **ground porosity**, **water content** and **weathering rates** that lead to high variations in the hydrodynamics of the unsaturated zone. Due to changes of climate conditions, the lack of evapotranspiration in the winter and differences of porosity relative to deeper layers, **temporary perched aquifers** can appear in the subsurface.

The **vadose zone** starts from the surface and extend at depth until the aquifer table. Its subsurface layer is called the **epikarst** and consists in highly weathered rocks (i.e. limestones). It shows a **high potential of water storage**.

Main geomorphological features: **Dolines** or sinkholes, swalow holes, **springs**

At depth, the **saturated zone** takes place at the bottom of the vadose zone. It is often highlighted by the occurence of **underground rivers** that enter the karst massif through sinkholes, cross the karstic formations all the way to a resurgence. The aquifer is also charged by water infiltrating the massif from its top, crossing the unsaturated zone.

Water infiltration has complex dynamics given the alternance of macroporosity (**caves**, **fractures**, **bedding joints**, ghost rocks) and microporosity (fissures, porous matrix, calcite joints). These characteristics leads to: unknown connections, highly non-linear dynamics, time dependent geometry.

2. Hydrogeophysical Monitoring Results

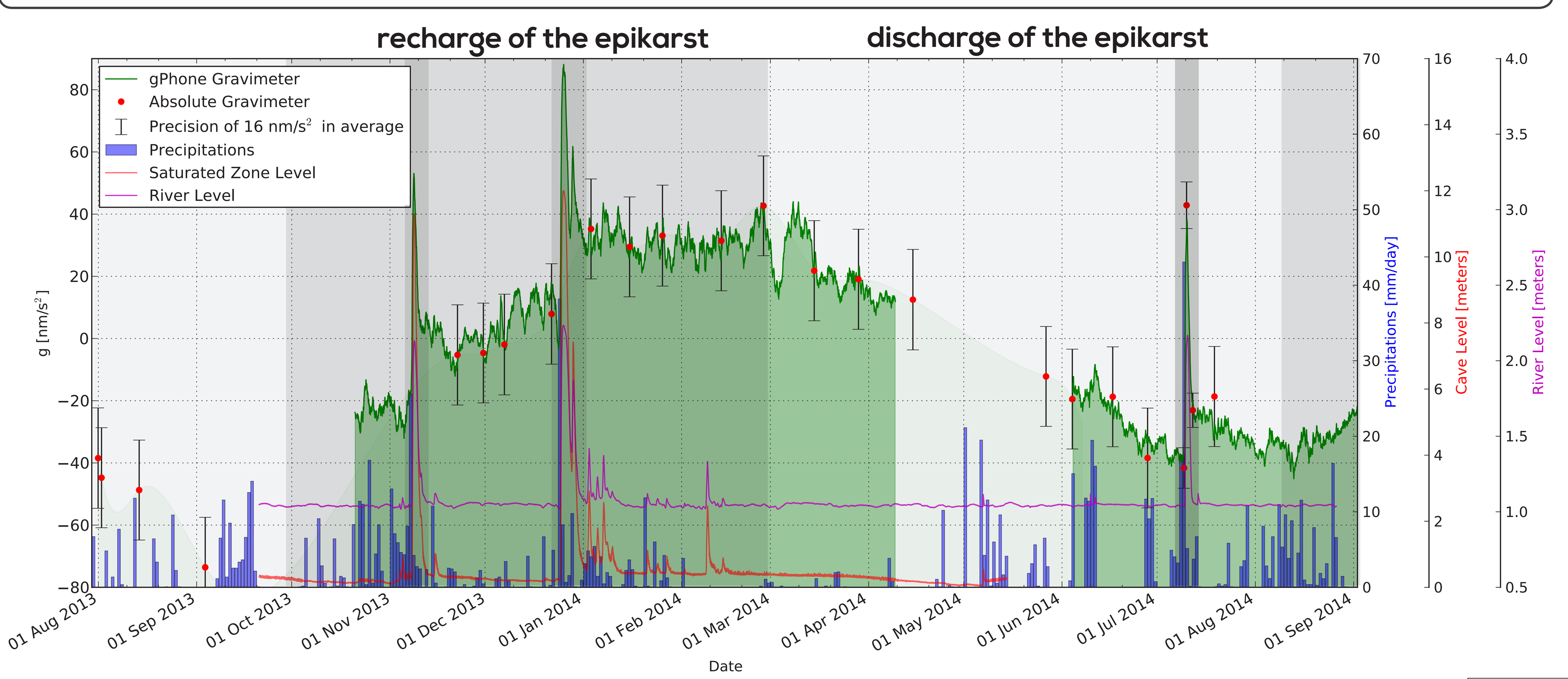
2.1. Gravimetric monitoring

- Continous monitoring with a gPhone relative spring gravimeter (Micro-g LaCoste)
- FG5 Micro-g LaCoste absolute gravimeter for calibration; measuring ± every 2 weeks
- Surface laboratory of Rochefort Cave

Perspectives

- A supraconducting gravimeter will be installed in the cave while keeping monitoring in the surface.
- Better ability to highlight vadose zone and especially epikarst water storage

Fig.2: Level of the river at the entrance of its sinkhole in Rochefort (purple), piezometric surfaces in the saturated zone (red), precipitations (blue), relative gravity measurements (green) and absolute gravity measurements (red dots). Tidal, atmospheric, and polar motion effects were removed. For legibility, the average value ofthe gravity at Rochefort Site was removed. Three rapid increases in gravity (shaded in the graph) can be observed when the cave was flooded after heavy rainfalls.
A power outage occured the 8 April leading to 2 months relaxation drift of the gPhone gravimeter. These data have been removed for convenience.



2.2 Electrical Resistivity Tomography monitoring

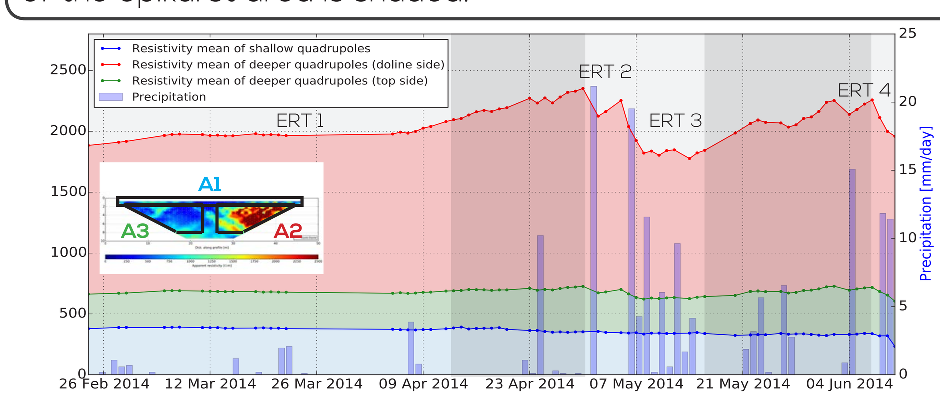
Methodology

- ALERT acquisition system BGS (Kuras et al., 2009)
- 48 electrodes - 1 m spacing
- Located on top of the limestone massif; 20 electrodes settled along the side of a sinkhole
- Repeated dipoles-dipoles and Wenner-Schlumberger's
- Started in February 2014; a breakdown occured in the middle of June 2014.

Discussion

- The high resistive area at the top of the limestone massif shows the highest variations through time.
- It is interpreted as changes in the water content within the epikarst.
- The significance of low resistivities next to the side of the doline is not clear.
- Bedding joints filled with clayish materials could indeed lead to anisotropy that will be investigated in the next steps of the research.

Fig.4: Evolution of the apparent resistivities of 3 arbitrary chosen areas tgiven the Rochefort Sit characteristics. These areas are highlighted in the plot sections in the left of the graph. The area of high resistivities shows the highest contrasts. Suspected recharges of the epikarst area is shaded.



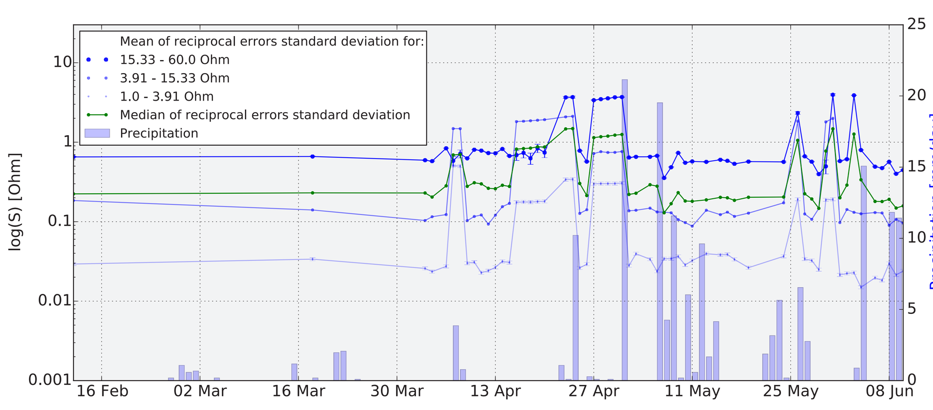
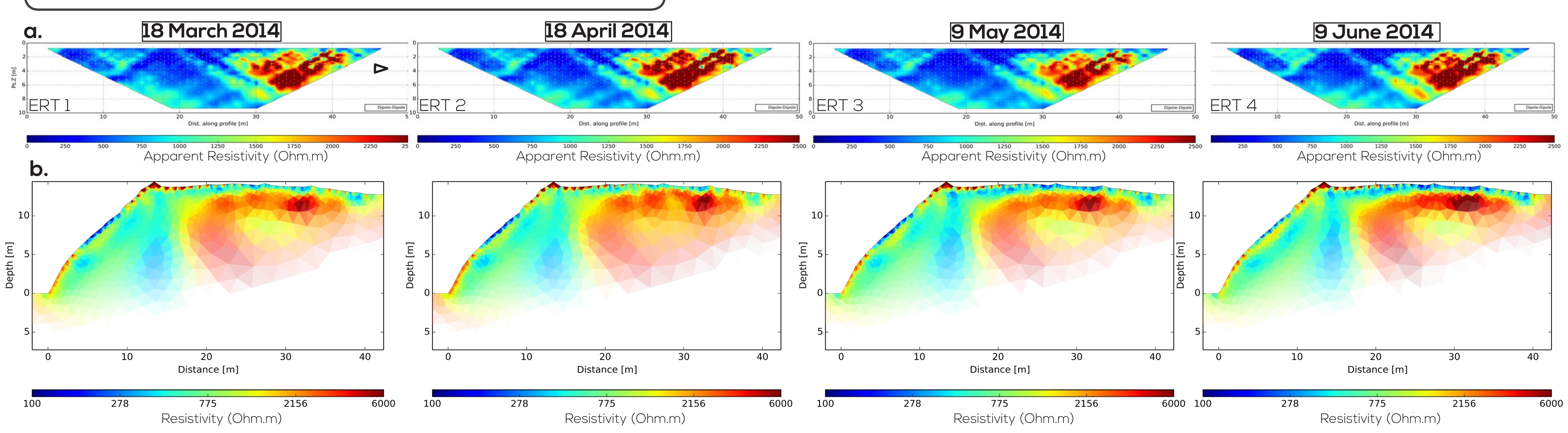


Fig.5: Evolution of the means of reciprocal error's standard deviations (STD) for dipoles-dipoles datasets of 3 groups of resistances (logarithmic spaced) based on Koestel (2008) approach. Errorbars shows the standard error of the STD estimator. Median of reciprocal errors STD's of each datasets is shown in green.

Fig.3: **a.** Plot sections of the apparent resistivities for four datasets of dipoles-dipoles measured at various weather conditions. **b.** Results of the inversion of a mixed of dipole-dipole's and Wenner-Schlumberger's measured same days as the upper plot sections. Inversion was performed using BERT software (Günther et al., 2006; Rücker et al., 2006).



3. What brings H/V Spectral Ratio Analysis?

Methodology

- 10 minutes of measuring time
- CityShark II connected to three-component seismometer (LE-3D/5s Lennartz)
- Profile T every 2 meters along the top of ERT profile
- Profile P every 10 meters above the main room of the cave

Processing

- Geopsy software
- Semiautomatic window selection (5 - 15 sec)
- Konno and Ohmachi smoothing

Discussion

- High frequency H/V peaks (20 - 40 Hz) variations are correlated to ERT shallow interpretations => epikarstic morphology
- Significance of lower frequency H/V peaks, interpreted as deep regional contrasts, are not clear. Cavities influence the signals.

Fig.7: H/V Profile T for 10 of the 13 stations.

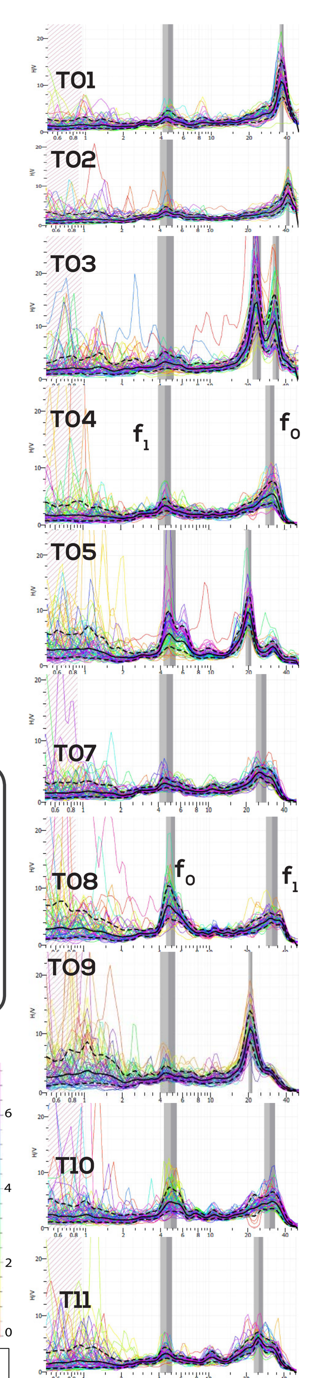


Fig.9: H/V Profile R for the 8 stations.

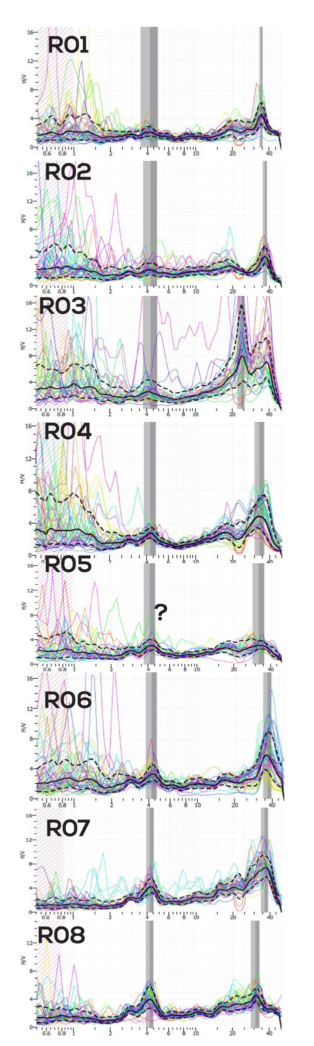
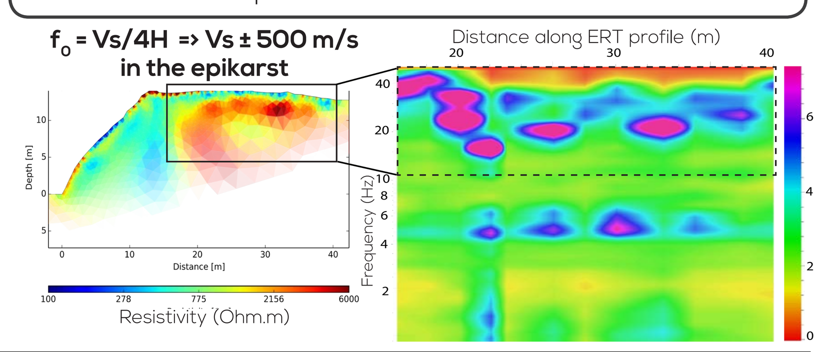


Fig.8: Linear interpolation (topography not included) of individual H/V spectrum over 13 seismic traces measured along the ERT profile (between 16 and 40 meters in relative horizontal positioning from the south of the ERT profile). Colour chart represents the H/V spectrum amplitude. Inversion of ERT data from the same period is shown in the left.



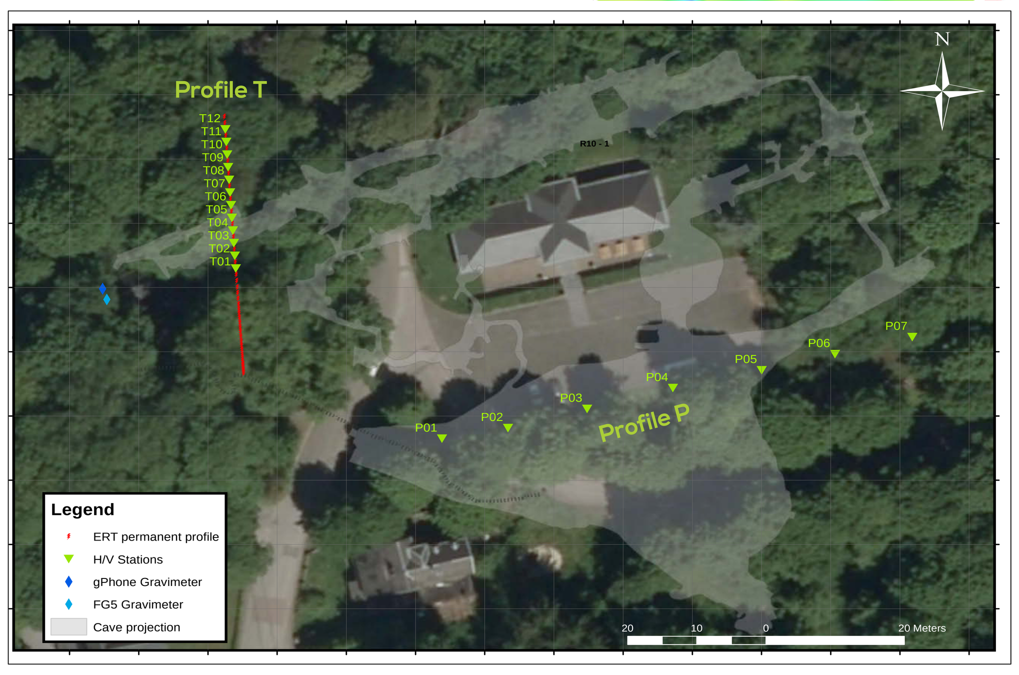
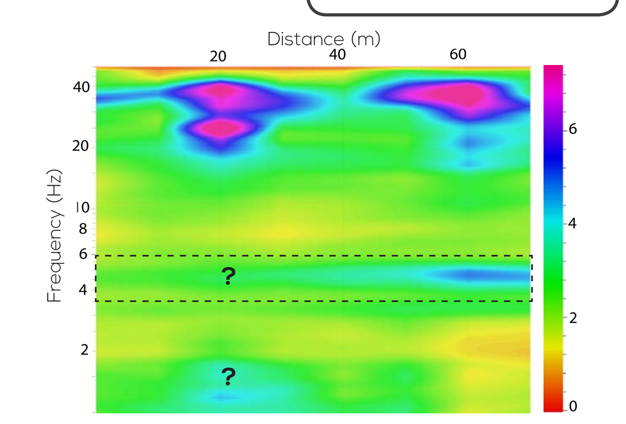


Fig.6: Map of the geophysical monitoring. ERT and H/V location at the Rochefort Site. Cave network indicated in white.

Fig.10: Linear interpolation of individual H/V spectrum over the 8 traces of profile R that crosscut the main room of the cave underneath. The 4 Hz peak shows an attenuation for the station above the cave.



Main remaining questions:

- **Significance of low peak resonance above a cave structure?**
- **Role of the saturation rate with respects to the high frequency peak?**

4. Conclusions

This experiment shows the usefulness of hydrogeophysical monitoring in the case of karst system environements. It highlights the fact that gravimetry combined with ERT are valuable tools to monitor the hydrodynamics of the unsaturated zone of karst systems. The use of HVSR analysis in such environment seems, moreover, to be an additional input to validate ERT data and to calibrate the spatial extension of the epikarst. In dry conditions the use of ERT technique alone could not always help identifying epikarst boundaries because of the lack of clear contrast in saturation.

Gravimetry evidences charges and discharges of the epikarst no matter their dynamics and their origin (slow recharge through winter, rapid saturation due to storms,...)

ERT monitoring shows the infiltration and the dryness process that occur in the epikarst given the weather conditions and is able to spatialize them.

HVSR allows refining the subsurface geology and characterising the epikarstic puzzle reconstitution. Its use and the best approach in terms of monitoring still needs to be specified in the next steps of this research project.

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For more information about this project, please visit www.karag.be

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