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# Combining Electrical Resistivity Tomography and Ground Penetrating Radar to study geological structuring of karst Unsaturated Zone

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ABSTRACT

This paper highlights the efficiency and complementarity of a light package of geophysical techniques to study the structure of karst Unsaturated Zone (UZ) in typical Mediterranean environment where soil cover is thin or absent. Both selected techniques, 2D Ground Penetrating Radar (GPR) and Electrical Resistivity Tomography (ERT), are widely used in environmental studies and their application is accessible for a lot of scientists/engineers. However, GPR or ERT alone is not able to provide an enhanced characterization of geological features in karst media. In the present study, GPR results supply a near surface high resolution imaging and thus can provide relevant geological information such as stratifications and fractures. Despite the quality of the results GPR's investigation depth remains limited to around 12 m. Apparent and inverted resistivity provided by ERT surveys shows strong lateral and vertical variations. These variations can inform about general geological structuring and feature orientation. ERT is able to prospect down to 40 m but it's a low resolution integrative technique. In the study area the investigated limestone is a commonly electrical resistive formation (more than 2000 Ω.m). However deeper than 5–7 m, the ERT profiles reveal several zones of moderate resistivity (around 900 Ω.m). In these zones a stratification change corresponding to slanted bedding is clearly identified by GPR results. The combination of both GPR and ERT results can allow a well-established geological interpretation. These moderate resistivity zones with slanted beddings can explain the presence of a perennial water flow point 35 m below the surface of the studied site within the underground gallery of the Low-Noise Underground Laboratory (LSBB).



## 1. Introduction

The structure of karst hydrosystems is highly heterogeneous and the related hydrodynamic functioning mechanisms can be complex in both unsaturated and saturated zones (e.g. Bakalowicz, 1995; Ford and Williams, 2007; Goldscheider and Drew, 2007; Mangin, 1975; White, 2007). The karst aquifers represent important groundwater resources around the world. 25% of the world population is supplied with water from karst aquifers (Ford and Williams, 2007). Due to the triple porosity (matrix rock, fracture and karst conduct), the complexity of a karst environment makes water exploitation and protection difficult and challenging. The study methods used in classical hydrogeology (bore holes, pumping tests and distributed models) are generally invalid and unsuccessful for karst aquifers because the results cannot be extended to the whole aquifer nor only a part, as is done in non-karstified aquifers. Generally, karst hydrogeologists use a specific investigation methodology (described in Bakalowicz, 2005), which is comparable to that used in surface hydrology. Most of the time, these aquifers are modelized using rainfall–runoff models (e.g. Emblanch et al., 2003; Fleury et al., 2007; Labat et al., 2000a, 2000b; Mangin, 1975; Marsaud, 1996; Moussu et al., 2011). This lack of knowledge makes the parameterization of distributed hydrogeological models difficult and only few authors take up the challenge (e.g. Worthington, 2009). Thus, it's still necessary to improve our knowledge and understanding of karst structures and functioning.

This research is focused on the Unsaturated Zone (UZ) which plays an important role for water storage in the karst hydrosystem (Emblanch et al., 2003). Karst UZ is particularly complex because matrix rock and fracture play a major role in water flow regulation but this mechanism is still poorly known.

Ground-based geophysical methods can play an important role in the study of these systems. But suitable characterization of heterogeneities in the karst environment is very challenging and the choice of adequate methods remains mainly site related (Chalikakis et al., 2011). This paper is part of a larger hydrogeophysical project in karst media. Our global goal is to develop an effective methodology for near surface geophysics aiming towards a better understanding of water transfer and storage within the UZ of karst hydrosystems. This project aims at answering the following question: can we link water storage and water transfer, within karst UZ, with parameters

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measured from surface geophysics? This paper is devoted to the first step of this project. We will exhibit efficiency and complementarity of Ground Penetrating Radar (GPR) and ERT surveys for geological feature-enhanced descriptions.

Seismic surveys could also provide relevant information in karst media (Šumanovac and Weisser, 2001). However, acoustic waves which are widespread in Rustrel limestone present a wide wave length (about 40 m). This wide wave length induces a low resolution of seismic surveys. Time domain electromagnetic techniques have only been used a few times successfully (Chalikakis, 2006; Ezersky et al., 2006, 2009), mainly to locate the upper part of a sedimentary buried karst system and characterize the overlying sedimentary covering. Very Low Frequency was successfully used in several studies to detect epikarst, also to map karst near-surface heterogeneities (e.g. Bosch and Müller, 2001, 2005; Guérin and Benderitter, 1995; Ogilvy et al., 1991; Turberg and Barker, 1996) but this technique provides a limited resolution compared to the aims of this present study. Slingram EM31 and EM34 are efficient in finding zones of interest like sinkholes (e.g. Jardani et al., 2007; Valois et al., 2010) but in the studied site, this material touches its limit of sensitivity range and measurements are unstable. With adequate environmental conditions, the self potential technique is well fitted to detecting preferential pathway in karst media (e.g. Jardani et al., 2006; Robert et al., 2011) but the intense plant activity and presence of an electrical line within the Low-Noise Underground Laboratory (LSBB) tunnel excluded this technique. Guérin et al. (2009) successfully used mise-à-la-masse to detect water-filled cavities. Air-filled cavities are routinely detected with gravimetric surveys (e.g. Benson and Floyd, 2000; Beres et al., 2001; Camacho et al., 1994). Gravimetry is used in hydrogeological surveys to study rock density variations over time (e.g. Deville et al., 2012; Jacob et al., 2008, 2009). Magnetic Resonance Sounding (MRS) is particularly efficient in detecting water-filled cavities (Boucher et al., 2006; Vouillamoz et al., 2003). MRS is recently used to study water content within karst UZ (Mazzilli et al., 2012) but this technique is inefficient in studying karst structures.

GPR techniques appear to be the most popular geophysical tools for identifying and locating near surface karst features (cavities, conduits and fractures) at less than 20 m depth (e.g. Al-Fares et al., 2002; Benson, 1995; Beres et al., 2001; Grandjean and Gourry, 1996; McMechan et al., 1998; Pueyo Anchuela et al., 2009). The ERT technique, robust and reliable, is also widely used on karst media for identifying and locating sinkholes, shallow conduits or enlarged fractures (e.g. Guérin et al., 2009; Šumanovac and Weisser, 2001; Valois et al., 2010; Van Schoor, 2002; Zhou et al., 2002; Zhu et al., 2011).

GPR and ERT were used jointly (Elawadi et al., 2006; El-Qady et al., 2005) but never to image successfully karst near surface features. The combination of GPR and ERT surveys is routinely used in other geological contexts. Beauvais et al. (2004) used it on crystalline basement rocks. Quaternary glacial sediments were recently studied with coupled ERT and GPR surveys (Burke et al., 2012; Pellicer et al., 2012). These two techniques are also efficient in investigating water table depth in weathered granites (Mahmoudzadeh et al., 2012).

This paper highlights how GPR and ERT could be combined to study the structure of karst UZ in typical Mediterranean carbonate/karstified formations. After a summary of geological and hydrogeological knowledge the adapted field methodology and the results of each method are presented. Together with their combined interpretation provide a well established geological and hydrogeological understanding of the local karst UZ.

## 2. Geological and hydrogeological background

The test site is located within the karst hydrosystem of the Fontaine de Vaucluse (FdV) in the South of France (Fig. 1a, b) on the LSBB site (http://www.lsbb.eu). The catchment area is about 1130 $km^2$ (Puig, 1990) (Fig. 1b). The FdV spring (the only outlet of the system) is the biggest karst spring in Europe with an average discharge of 19 $m^3/s$ from 1970 to 2006 (Cognard-Plancq et al., 2006). The karst system is partially developed in the low Cretaceous limestone (Urgonian) described in detail by Masse (1976).

The LSBB (http://www.lsbb.eu) is an underground gallery having been dug for a military purpose and converted into a research laboratory in 1997. It is located near Rustrel village, in the southern part of the FdV catchment area (Fig. 1b). The gallery is 3.8 km long with a diameter varying between 2 and 4 m. It is almost horizontal under the mountain so that the rock cover above the gallery varies from 0 to 519 m due to the topography. As the gallery comes across the karst medium, the fault throws and the fault networks, it also intersects arbitrarily some flow paths throughout the UZ.

Consequently, several perennial and intermittent flow points are identified in the gallery, at different depths (from 35 to about 440 m). Those have been observed and regularly sampled (hydrodynamics and hydrochemistry) inside the LSBB since 2002 (Blondel, 2008; Garry, 2007; Perineau et al., 2011). One of these permanent flow points is located 50 m before the western extremity of the LSBB tunnel (Fig. 1c) where the tunnel is located only 35 m below the surface. This point is called “point D” and its average discharge is around 80 mL/min (Perineau et al., 2011). Such a geometrical context encouraged us to focus our investigations on the area located above point D (Fig. 2). Beyond the usual approach which consists in surface geophysical investigation, the LSBB tunnel provides unique underground information about karst UZ: geology, geotechnics, hydrodynamics, tectonics or hydrochemistry. This information provides useful knowledge in order to interpret geophysical results.

At this place, the outcrops correspond to the U3 subdivision of Urgonian facies (Leenhardt, 1883). The U3 subdivision presents several facies (Fig. 1d) that are not always laterally continuous. Therefore, interpretations of geophysical results are very challenging and require comprehensive geological knowledge. The limestone facies outcropping on this site is a biocalcarenite with possible crossbedded stratifications. The limestone stratigraphic dip varies from 15° and 20° in a southerly direction. The whole study area is affected by two main sets of faults and fractures: 10 to 25°N and 100° and 120°N identified on aerial photos (Fig. 2c) and in situ measurements (Fig. 2b). The topography dips approximately to around 13° to the South and the surface is covered by a typical Mediterranean shrubby forest mainly composed by Holm oak (called in French garrigue). At the surface we can identify humus horizons, clayey soil and some *terra rossa* (Banerjee and Merino, 2011) with limestone fragments and mainly outcropping limestone (Fig. 5a). This makes the GPR and ERT implementations difficult and generates locally some variations in the geophysical measurements.

## 3. Methodology and tools

### 3.1. Implantation strategy and constraints

The geomorphological conditions and soil occupation on the site were not very favorable for ground-based geophysical acquisition. The typical dense shrubby Mediterranean forest is not the easiest place for geophysical measurements. Field and material conditions exclude any 3D acquisition. Thus, an alternative option was adopted, based on multi-2D acquisitions along parallel and perpendicular profiles. The slope, the vegetation and the gravel cover induced a very important preparation work to clear the investigable sections. Preparations of a 126 m long section on this site necessitated one day for two people to cut trees and prepare the ground. It was necessary to rake and flatten ground to ensure a good contact between GPR antennas and the ground. In addition, for the ERT profiles the implantation of electrodes mainly at limestone outcrops was quite difficult, saltwater and mud were used and sometimes electrode holes were mechanically dug within the rock to ensure good ground contact.