A new kind of high-resolution downhole hydrogeophysical observatory for real-time salt intrusion management.

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ABSTRACT

Initially as part of the EC-funded ALIANCE project (FP5), a new kind of near-field, high frequency downhole hydrogeophysical observatory was designed and set-up at two different field sites in terms of geological context, hydrological regime and local human impact. The new downhole method was conceived for long-term *in-situ* monitoring and prevention of brine intrusion in coastal aquifers. The principle of the observatory is based on the high frequency (such as daily) probing of the formation electrical resistivity around a borehole, over periods of several years. For so-called “real-time” salt intrusion management, this device is aimed at producing accurate near-field boundary conditions to reduce uncertainties in models, and thereby contribute to the decision-making process for endangered aquifer management.

The first prototype was deployed for instrumental purpose at Maguelone (Languedoc, France) in 2004, within unconsolidated sand-shale sequences of the Mediterranean shoreline. It was tested there to 40 m depth in a dipole-dipole mode, using an instrumented PVC liner as downhole support, then calibrated against induction resistivity logs. It has now kept functioning in this hostile environment (including both seawater and H2S gas in the pores) for more than 5 years. An improved prototype was later installed through the reefal platform of SE Mallorca (Baleares, Spain), where a deeply penetrating seawater intrusion enhanced by overdrafting. It is located to the SW of Campos, 6 km inland from the coast. In the consolidated Miocene carbonates, a flute was deployed down to 90 m and across the 20 m thick transition from fresh water to seawater.

At both sites, a metre-scale spacing was chosen for vertical resolution, providing the needed spacial resolution to study dynamic subsurface processes. From this, time-lapse measurements were made on a daily basis, automatically, underlining gradual changes over time in formation electrical conductivity. Taking into account all components of electrical conduction at each site (including surface processes at pore scale), the *in-situ* electrical conductivity of pore fluid can be derived and interpreted in terms of equivalent NaCl pore fluid salinity. From this, the contribution of individual layers to the overall salinity profile in the sediment can be revealed, emphasizing the role of heterogeneities, anisotropy and permeability in the development of pore fluid salinity profiles at depth. In the near future, further developments in terms of technology and applications of these observatories will be tested in the context of dedicated projects, or that of industrial applications. The generic nature of this new kind of precise, autonomous and high-resolution *in-situ* groundwater observatories is paving the way for a wide range of shallow depth applications for seawater intrusion management.

INTRODUCTION

The Maguelone site is located to the SE of Montpellier (Figure 1) and near the medieval Maguelone cathedral historically settled between the Mediterranean and the Prevost coastal lagoon. It was initially developed to study coastal sedimentary processes with the drilling of a cored hole (MAG1) into a fresh water reservoir discovered below 40 meters depth. MAG4 was drilled for instrumental reasons 50 m to the NW of MAG1, 150 m from shore. It was equipped and instrumented with a PVC tubing down to 46 m in June 2004.

MAG1 &
•MAG4

Figure 1. Location of the MAG1 and MAG4 boreholes along the Mediterranean shoreline, 10 km to the south of Montpellier.

RESULTS AND DISCUSSION

Surface electrical resistivity profiles (Figure 2) were recorded in a triangle with 64 electrodes spaced a meter apart from each other, with one of the sides of the triangle relating MAG 1 and MAG4 (Profile 3). Near surface resistivities (> 1 m) are generally in excess of 20 Ω.m 10 to 15 m away from the Prevost lagoon. Below 3.0 m, the resistivity is always under 1.0 Ω.m, showing the presence of brackish water and conductive clays elsewhere cored by MAG1.

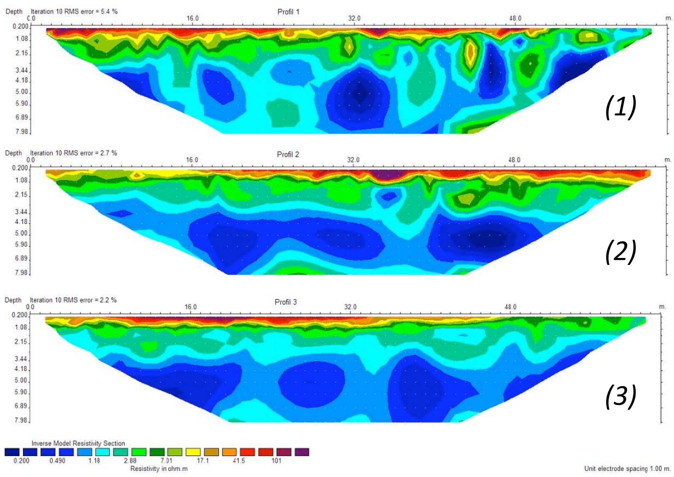

Figure 2. Surface electrical profiles obtained in a triangle oriented along a NE-SW strike from MAG1 (Profile 1), a NE-SW strike from MAG4 to MAG1 (Profile 3), and NS for that closing the triangle (Profile 2). Vertical penetration does not exceed 8 m depth.

MAG4 was drilled destructively down to a depth of 46 m, 50 meters North of MAG1 (Figure 1). A metallic pipe was lowered gradually in the hole during drilling to avoid collapsing. Black fluids charged with products from the reduction of the iron drillpipe by H2S were extracted from the hole every morning, when drilling resumed, demonstrating the downhole reducing conditions. The drilling progressed down to 36 m, where a natural gamma profile was obtained (Figure 3) to evaluate the lateral continuity of the sedimentary structure and whether the fresh water reservoir had been reached. It was consequently decided to drill down to 42 m.

The natural gamma record obtained in MAG4 down to 36 m compares well with that obtained in MAG1 (Figure 99), requesting a 80 cm shift to overlap the records in the Holocene section (from 7 to 16 m), indicating a one degree dip in the direction of MAG1, towards the shore, and demonstrating the lateral continuity of the sedimentary sequence at the site. Equipped with 5 mm thick gold-plated copper electrodes located downhole every meter, the observatory reconstructs with plain PVC the hydraulic structure present prior to drilling. The permanent electrodes are connected to surface allowing for repetitive electrical probing and imaging of the formation surrounding the hole. The observatory was lowered in 2.8 m-long sections, taking an overall time of 14 hours to deploy. Measurements were made on June 23, immediately after deployment, and the next day (June 24) to check the repeatability of the system. The probing was done using the Wenner, dipole-dipole and pole-pole techniques, which gave very similar results. Only the dipole-dipole measurements are presented here (Figure 3).

The dipole-dipole measurements from the observatory in MAG4 compare well with the medium induction resistivity from MAG1 (Figure 3; orange profile). Small changes are recorded overtime in the more permeable intervals (with little clay content), while more clay-rich intervals give constant values overtime (19 to 23 m). The effect of near-surface desaturation during summer months is recorded in September (purple dots). The brackish water reservoir (down to 32 m), CH4 and H2S gases at about 15 m, and the fresh water reservoir (deeper than 36 m) are imaged by both electrical methods.

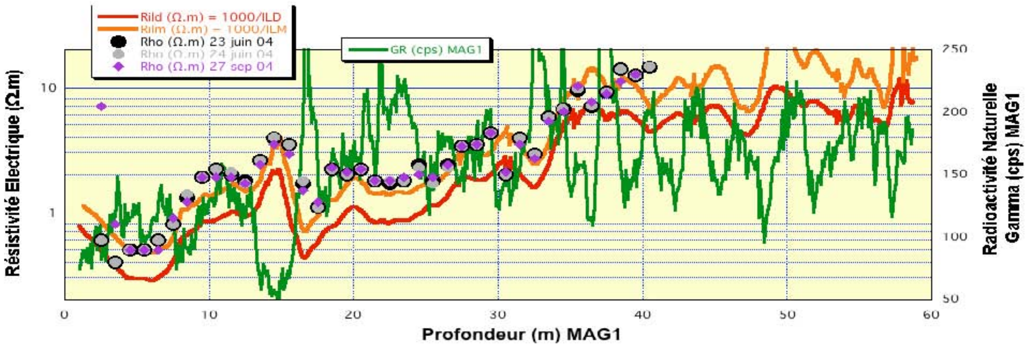

Figure 3. Natural gamma (green) with induction electrical resistivity (orange and red) profiles measured in MAG1. Dipole-dipole measurements from the observatory in MAG4 recorded on June 23 (black), June 24 (grey) and September 27 (purple) 2004.

CONCLUSIONS

This observatory for permanent downhole monitoring of electrical resistivity in a coastal aquifer was then the first ever of this kind deployed in the subsurface (June 2004). In 2010, more than 5 years later, it is found to operate without drift from initial measurements. A similar device was deployed in the context of ALIANCE at the Campos experimental site in SE Mallorca, Spain, in 2005 (Figure 5). This site drilled reefal carbonates and straddles, 6 km from the shore, a salt water intrusion with a diffusive interface from 64 to 80 m. As for the sand-clay sequences of Maguelone, a good fit between dipole-diploe measurements of the observatory and induction logs is obtained.

These new dowhole geophysical observatories thereby provide a potential answer to the problem of longterm detailed monitoring of coastal aquifer invaded with salted water. The downhole array was automated in April 2006, with solar panels and batteries to create a fully autonomous system. An improved version of the initial prototype was designed after the end of ALIANCE to offer a more compact system, with a smaller energy need and a simplified sensor adressing system via a downhole bus. The downhole computer system with bus was patented in France in November 2006 and at European level in March 2007. A start-up company called "imaGeau" was founded in 2007 to market these observatories for risks assessment associated with water quality changes in subsurface aquifers.

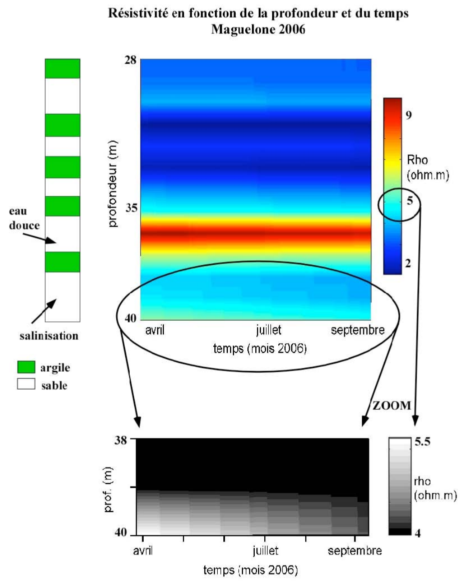

Figure 4. Automated measurement of electrical resistivity as a function of depth (from 28 to 40 m) in MAG-4 and time (from April to September 2006), with simplified lithology to the left indicating the presence of clay layers (bright green), and zoom at bottom on resistivity changes as a function of time in the bottom two meters, showing a gradual salinisation.

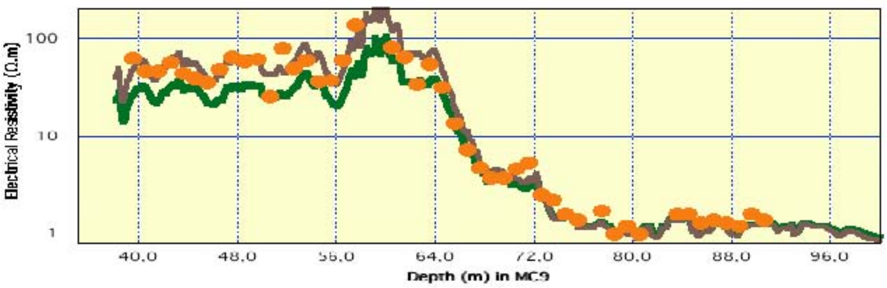

Figure 5. Measurement of electrical resistivity as a function of depth (from 40 to 100 m) in Hole MC9 (Campos, Mallorca, Spain), showing that recorded with the downhole stringer (yellow dots) in comparison to that obtained with an induction resistivity tool (green and brown profiles for deep and medium sounding into the formation, respectively).

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