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Contribution of EM airborne geophysics to characterise seawater intrusion within a Plio-Quaternary coastal Mediterranean aquifer in order of improving management and early warning system

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Introduction :

Airborne methods are used to characterize the physical parameters of the subsoil such as magnetic suceptibility, resistivity, etc…. These methods are usually the most cost-effective tools available for both large regional surveys (ie geological mapping) and for more detailed studies of located target areas. With adequate line spacing the resolution of the airborne surveys can be suitable for mapping local features but also to characterize large-scale physical field parameters through an extensive coverage.

The Mediterranean coastal aquifers constitute fragile environments due to potential seawater intrusions. Classically point measurements of salinity allow to identify only local intrusions, but not to map the 3D distribution of the subsoil salinity.

The airborne electromagnetism (AEM) method is widely used in the field of ore or mineral ressources prospecting. A pilot area located in the Roussillon basin (Plio-Quaternary multi-layers aquifer) in Southern France, near Perpignan, was surveyed in the framework of an EUFAR project, to map the ground conductivity in order to delineate seawater intrusion. Interpretation of these data is part of the ANR "GRAIND'SEL" project which objectives are to develop and to validate new approaches to improve the knowledge and the monitoring of coastal detrital aquifers at various scales, from regional with airborne geophysics to local with borehole monitoring observatories.

Location map

Fig. 1 Studied area location map

Geological setting (fig. 2):

The Roussillon basin history began during the Oligocene rifting resulting from relative movements of Africa and Europe at the end of the Eocene. During the Miocene, a marine regression followed the Messinian salinity crisis. The Roussillon sedimentary basin is of graben type. The onshore Pliocene sediments deposited within 1.7 My (i.e. 75 cm/1000 years, Clauzon *et al.*, 1987). The Quaternary deposits were due to the interglacial transgression and regression phases. The last transgression resulted a lagoon area from Leucate to Argelès. Currently, only the Salses-Leucate and Canet lagoons remain.

According to [Duvail et al., 2001], the Roussillon basin filling is characterized by the presence of a quaternary geological unit composed of Pleistocene river terraces and modern Holocene deposits, lying on two geological units named Continental Pliocene and Marine Pliocene. This plio-quaternary unit is in discordance on various Miocene formations synchronous to the formation of rift basins of Roussillon to the formation of Roussillon rift basin.

Around the northern part of the Roussillon plain, near the Corbieres area, outcrops of Lower Cretaceous limestones are observed. In the southern part of the studied area, the massif of Albera is formed from a metamorphic basement of Precambrian age (gneiss and schist).

Knowledge of the Roussillon basin geology allows us identifying units that could be potential aquifers.

Hydrogeological setting:

The Roussillon basin aquifer is a muli-layer aquifer. Each aquifer layer is characterized by several small size aquifers having different hydrogeological properties.

Aquifers are grouped according to the following hydrogeological entities:

Pliocene aquifer :

Marine and fluvial sands constitute the two main Pliocene aquifers.

- **Continental Pliocene aquifer** : The water in this aquifer is only excessively mineralised in the northern part of the basin, along the lagoon and even more along the coast at Barcarès.
- **The sandy marine Pliocene aquifer** : Sandy marine Pliocene sediments correspond to the prograding deltaic shoreface. Theoretically, this aquifer is not connected to the sea and it is preserved from seawater intrusion; however, some areas contain highly mineralised water. The origin of the contamination is the vertical leakage from the partially contaminated Quaternary aquifers to the Pliocene ones, due to the existence of defective boreholes. New boreholes drilled next to the old ones show a strong decrease in the salt content (Dörfliger, 2003).
- **The Continental Pliocene aquiclude** : Usually, layers of lignite with plant remains alternating with plastic marsh clays are found beneath the Continental Pliocene aquifer. This non-continuous impervious layer separates the continental Pliocene aquifer from the sandy marine Pliocene aquifer.

Quaternary aquifer : The quaternary aquifer is mainly composed of alluvium (conglomerates) and coastal deposits. The unconfined Quaternary aquifer lies along the main rivers and the coastline. The water quality of the Quaternary upper aquifer is poor near the coast due to a high chloride concentration.

Geophysical airborne survey :

A high resolution geophysical airborne survey (~ 4500 km flight lines) has been carried out from 15th to 25th of September 2008 by the Joint Airborne-geoscience Capability (JAC) established between the Geological Survey of Finland (GTK) and British Geological Survey (BGS) within the framework of the EUFAR (European Fleet for Airborne Research)

Characteristics of the survey:

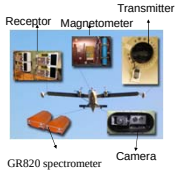
- Dimensions of the studied area : 10 km x 45 km
- Flight line spacing : 100 m (fig. 1)
- Flight line direction : N – S
- Cross line spacing : 10 km
- Cross lines direction : E - W
- Flight height : 50 m above ground
- 1 measurement every ~15 m
- Frequencies : 912 Hz, 3005 Hz, 11962 kHz, 24510 Hz
- Coil configurations : broadside VCX (vertical coaxial) coils with a 21.4 m Tx-Rx separation (this configuration has an optimal S/N ratio in a fixed-wing aircraft).

Simultaneous measurements :

- Spectral Gamma-ray
  Exploranium spectrometer GR820
  Detector total volume : 42 l
- Magnetics
  2 magnetometers (Cesium) : 1 on the wing and 1 on the nose + a magnetometer for the base station

JAC System

De Havilland Twin-otter aircraft (OH-KOG)



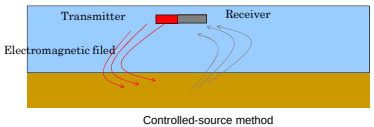
Frequency Domain Electromagnetic method :

The frequency-domain electromagnetic method measures the earth's response to the magnetic signal transmitted by an induction coil. The induction coil produces a primary magnetic field alternating at various frequencies. This primary field induces electric currents in the ground, which in turn produces a secondary magnetic field. The receiver measures the secondary magnetic fields.

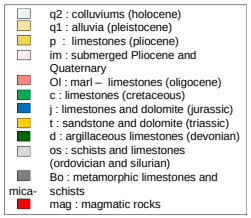
The response at high frequency is mainly influenced by near-surface resistivity structures, while lower frequencies correspond to deeper structures.

The airborne electromagnetic (AEM) method is characterized by a high resolution close to the surface and is sensitive to the physical parameters resistivity and magnetic susceptibility, themselves connected to porosity, saturation and salinity of the pore fluid and the presence of clays.

The multi frequency EM is used mainly to map in 3D the resistivity of the subsoil at shallow depths between the surface and 150 m with the lowest frequency. If the studied area is characterized by high conductivity, the penetration depth may be lower than 100 m.



Controlled-source method



Geological map legend

Mapping and preliminary interpretation :

The apparent resistivity maps (Fig. 3 and Fig. 4) at the two extreme frequencies (0, 9 kHz and 25 kHz) plotted with a 0 to 25 ohm.m color scale range, show low resistivity (<0.5 ohm.m) for sea and lagoon waters in accordance with literature values (0.18 to 0.5 ohm.m). The 25 kHz map, which describes shallowest layers (10 m depth), shows an apparent resistivity of about 10 ohm.m for the barrier beaches. With the assumption of a saturated salty water medium, the Archie's law gives a 15% to 20% porosity for this formation.

The same map plotted with a 0 to 200 ohm.m color bar (Fig. 5), allows a better identification of high resistivity formations. In the northern part, the Corbieres limestone are well outlined. In the southern part, a high resistivity area cannot be associated with any lithological formation.

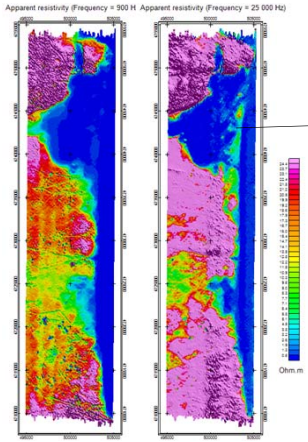


Fig. 3

Fig. 4

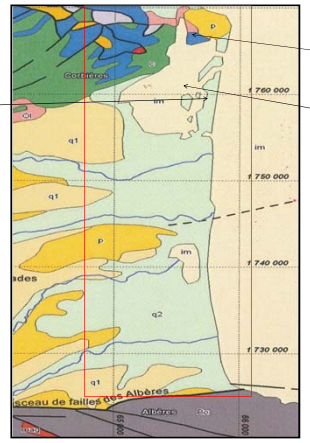


Fig. 2 Geological map (1:1 000 000)

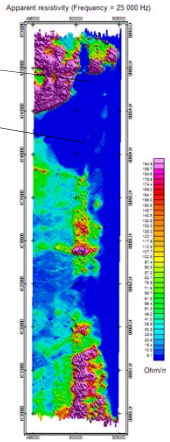
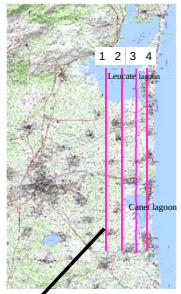


Fig. 5

Laterally Constraint Inversion (LCI) :

A LCI has been performed using the Workbench software developed by Aarhus University (Denmark). This method allows to apply horizontal and vertical constraints along profiles (quasi 2D).

Obtained results (fig. 6) show a good correlation between the inverted profiles and the limits of the lagoons. A transition zone is observed which should correspond to the seawater intrusion. However, the inverted values of the resistivity are a bit high for the lagoons and sea water (~ 0.5 Ohm.m). As the survey was carried out in September, the salinity of the lagoons should be higher due to evaporation and therefore the resistivity values should be lower (~ 0.2 Ohm.m). This could be explained by a bias in calibration data. The profile 4 shows salinity on the coastal sand dunes.



LCI profils results

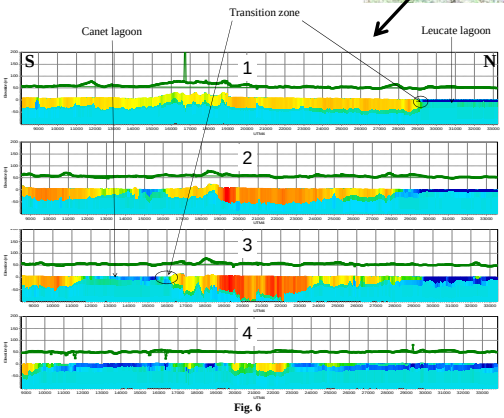


Fig. 6

Resistivity map = LCI results – layer 0 -5 ; 10-20 ; 20-40 ; 40-60 m)

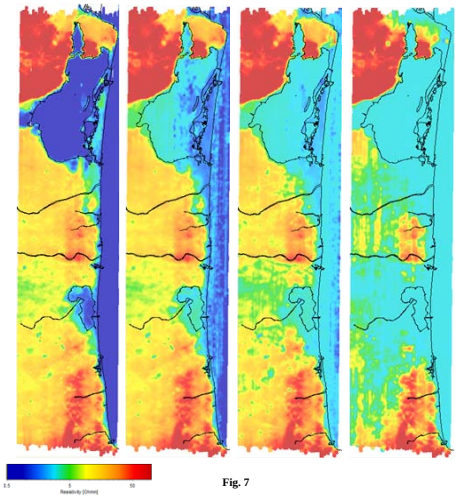


Fig. 7

Discussion :

AEM data leads to a good display of soil and sub-soil electrical resistivity lateral variations (fig. 7) which allow a qualitative interpretation based on physical properties distribution.

Leucate lagoon looks clearly seated within a deltaic shape delineated by surficial resistive formations (few 10 ohm.m). They are interpreted as Quaternary conglomerate or continental Pliocene detritic formations. The last, made of gravel and clay, can have a wide range of porosity. Low porosity bodies saturated with fresh water will come out with the same resistivity response as high porosity bodies filled with salty water.

But the conductive bodies (< 1 ohm.m) extension mostly corresponds to marine area and present lagoons. Although salty-water invasion looks limited to a restricted invasion zone. This restriction is obviously related to more conductive clayish aquiclude formations underneath (3 ohm.m) and probably to low porous surrounding detritic formations.