IMPORTANCE OF A HIGH RESOLUTION LITHOLOGICAL AND GEOMETRICAL KNOWLEDGE FOR MEDITERRANEAN COASTAL SEDIMENTARY AQUIFERS MANAGEMENT. APPLICATION TO THE ROUSSILLON BASIN, SOUTH OF FRANCE

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Abstract

A good understanding of coastal aquifers is particularly important for their management and preservation, as well as for specific implementations (artificial recharge). A detailed knowledge of the lithology and geometry of the aquitards and aquicludes is as important as that of the aquifers, particularly for seawater encroachment dynamics. A new methodology, based on reservoir geology, is used to contribute to high-resolution lithological and geometrical knowledge of coastal sedimentary aquifers. The proposed methodology is being applied on the Roussillon Basin, located along the southernmost part of the French Mediterranean coast, near the Spanish border. This basin covers an area of 700 km^2 and comprises two Pliocene aquifers whose characteristics are linked to the Messinian event, and is overlain by the Quaternary aquifer whose geometry is linked to eustatic variations. All these aquifers consist of alluvial and coastal deposits. A detailed lithology and geometry model of this basin has been made mainly on the basis of reservoir geology methods: (i) on-shore, through genetic stratigraphy and (ii) off-shore, through seismic stratigraphy. A detailed mapping of the elevation of the top and base of the aquifers and aquitards/aquicludes is thus available and will be used in a hydrogeological finite difference model. This model will be used for various applications such as aquifer management, location of the outflow areas of the aquifers and sensitivity analysis on geometry (on-shore-off-shore).

Keywords: Sequence stratigraphy, on-shore and off-shore geology, saltwater intrusion, Roussillon basin, Mediterranean sea, well logging, eustatism, groundwater, hydrodynamic modelling.

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Introduction

A good understanding of coastal aquifers is particularly important for their management and preservation, as well as for specific implementations (e.g. artificial recharge). In fact, a detailed knowledge of the lithology and geometry of the aquitards and aquicludes is as important as that of the aquifers, particularly for up-coning risk evaluation, salt water encroachment dynamics through surfaces water bodies (rivers, lagoons…) or directly through the sea, etc.

A new methodology is applied to the Roussillon basin in southern France: It is based on high-resolution geology and correlation between off-shore and on-shore domains. Continuity of geometry between off-shore and on-shore fields should permit the testing of new boundary conditions within groundwater modelling.

Case study

The Roussillon basin is located along the southernmost part of the French Mediterranean coast, near the Spanish border, and lies between Albères in the south, Aspres in the west, Corbières in the north and the Mediterranean Sea in east (Figure 1). This basin has an area of approximately 700 km^2 and contains three major aquifers, from bottom to top: the Quaternary aquifer, the continental Pliocene aquifer and the sandy marine Pliocene aquifer. These geological units are embedded within a Miocene structured margin.

A detailed lithological and geometrical-geological model of this basin has been built, mainly on the basis of reservoir geology methods:

– on-shore, through genetic stratigraphy performed with BRGM (French Geological Survey) public underground database (more than 500 wells in that area, with about 120 logging), the interpretation of well logging, and cross checking the outcrops;
– off-shore, through seismic stratigraphy (existing sections provided by oil companies and high-resolution seismic profiles provided by the University of Perpignan).

Detailed mapping of the elevation of the top and base of the aquifers, the aquitards and aquicludes, of their lithology, their internal relationships and with other aquifers (especially a karstic one, whose structure, also influenced by the sea level variations, has been studied separately) is thus available, and is being implemented in an hydrogeological finite difference model.

Methodology

Reservoir geology and some of its tools, used in oil prospecting, are applied to hydrogeology. Tools such as genetic stratigraphy (on-shore domain) and seismic stratigraphy (off-shore domain) were used on pre-existing data (logging -on-shore, seismic profile -off-shore). From established sedimentary process, interpretations have resulted in a better knowledge of the sedimentary geometry, following correlation between on-shore and off-shore domains (Duvail *et al.*, in press). It is thus possible to precisely differentiate coastal groundwater aquifers and to establish their relative connections.

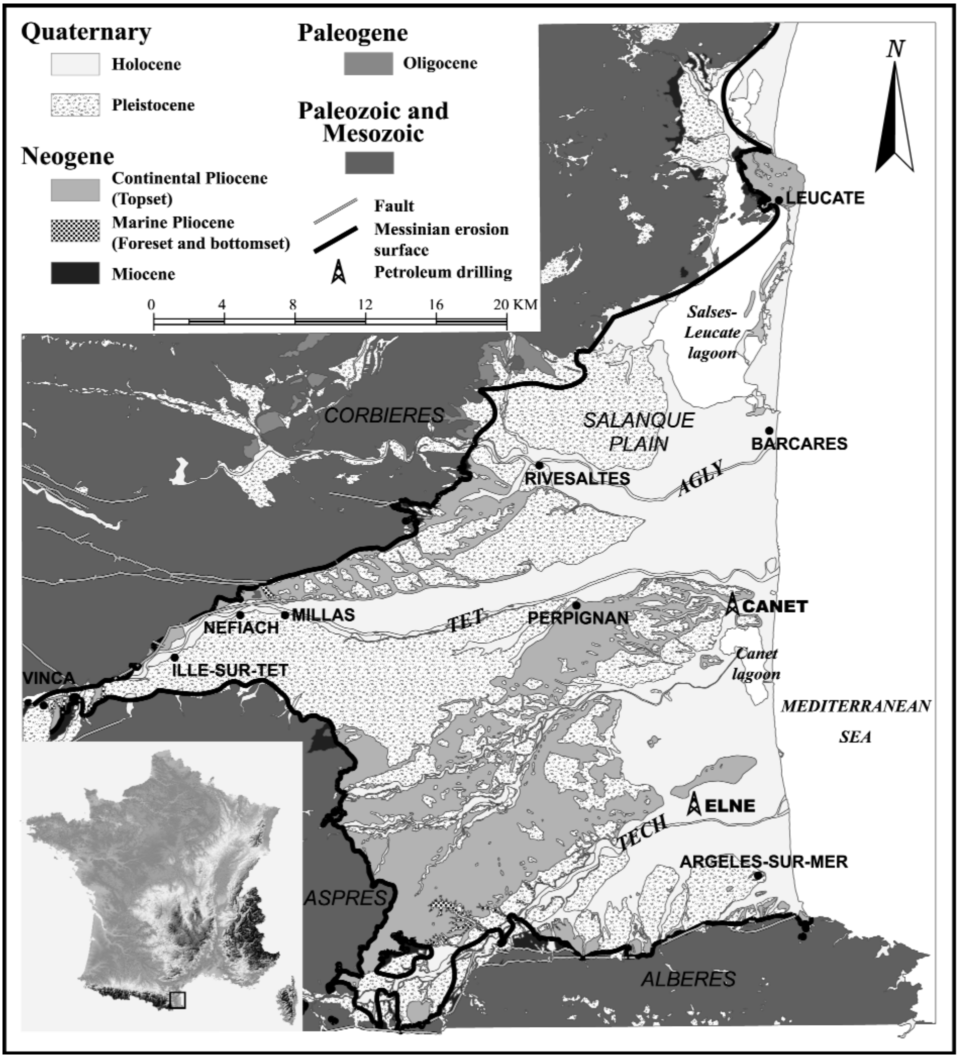

Figure 1. Location of the Roussillon basin.

Short review of the geological background

During the Miocene, there was a marine regression, following the Messinian salinity crisis (partial drying of the Mediterranean Sea; approximately 6 My). A major phase of erosion induced the depression of the fluvial networks and the formation of deep canyons that have been identified in the Roussillon (Clauzon *et al*., 1987; Clauzon, 1990). These strucutures have been called the Messinian estuaries (*Duvail et al*., 2001). In the Pliocene (5 My), the opening of the Gibraltar Strait (the only connection between the Mediterranean sea and the Atlantic ocean) enabled the sea water to return, which penetrated the deep valleys and transformed the Roussillon basin into an estuary. All the on-shore Pliocene sediments were deposited within 1.2 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 (sea-level rise) resulted in some coastal constructions (e.g. dunes) and a lagoon area from Leucate to Argelès. Today only the Salses-Leucate and Canet lagoons remain (Dörfliger, 2003).

Analysis of on-shore well logging

More than 2000 boreholes (exploratory drilling and exploitation boreholes) were carried out for the geotechnical, hydrogeological and petroleum purposes in the sedimentary Roussillon basin. Lithological descriptions of these, with varied quality and depth, are available in the BRGM database. Well-logging and/or precise lithological description exist for approximately 300 boreholes and this information was used to determine the geometry of sedimentary sets and the distribution of internal facies.

For each borehole, cuttings and well logging data (Serra, 1985) provide information on sedimentary depositional environments (Duvail and Le Strat, 2002). Preliminarily, sedimentary facies must be recognised by cross checking on outcrops (Clauzon, 1987; Clauzon *et al.*, 1990, 1995; Calvet, 1996; Duvail and Le Strat, 2002). Genetic stratigraphy principles (Galloway, 1989; Cross, 1988; Guillocheau, 1991; Homewood *et al.*, 1992) are used to (i) determine the vertical stacking of the depositional environments for each borehole and to (ii) build correlation between boreholes. This methodology of analysis (Duvail *et al.*, in press) provides the stacking pattern of the genetic sequences (on-shore domain), identified in terms of progradation, aggradation and retrogradation. Fall in the relative sea level corresponds to erosion surfaces.

Vertical units stacking are a function of subsidence, eustatism and supply of sediments. With the aim of correlating stacking patterns along the same deposit profile, it is necessary to know and measure the influence of local variations (local subsidence and supply of autocyclic sediments), influences of regional variations (margin subsidence and allocyclic sediments supply influenced by climate) and influences of global variations (eustatism). Thus, one dominant stacking pattern is characterised for all studied boreholes. It permits to highlight local perturbations. In order to be able to dissociate the global and regional influences, it is necessary to study several sedimentary basins.

In this paper, we will use the term of "system tract" in the off-shore domain and "sequences" in the on-shore domain. When correlations between on-shore and off-shore domains will be established, we will use the term of "system tract". In the on-shore domain this methodology helped to determine six sequences of the same order and their stacking pattern (Duvail *et al*, in press). For our case study these six zanclean sequences are the following (Figure 2):

(i) sequences 1, 2 and 3, on-shore, are mainly composed by stacking of argillaceous bottomset beds. The top of sequence 3 constitutes the first aquifer, named the sandy marine Pliocene aquifer. It corresponds to beach and shore face sands (thickness: 30-40 m);
(ii) sequence 4, on-shore, begin by paludal deposit like lignite (aquiclude thickness: 0-5 meters). Argillaceous flood-plain deposits with intersected stream-channel are atop marsh deposits. They constitute part of the continental Pliocene aquifer. Sequence 5, on-shore, is a downward shift surface without sedimentary deposit preserved;
(iii) sequence 6, on-shore, is characterized by the modification of the sedimentological mode linked to sequence boundaries. Higher sedimentary contribution increases the hydrodynamic properties of the continental Pliocene aquifer-top (Pliocene continental aquifer thickness: 50-150 m).

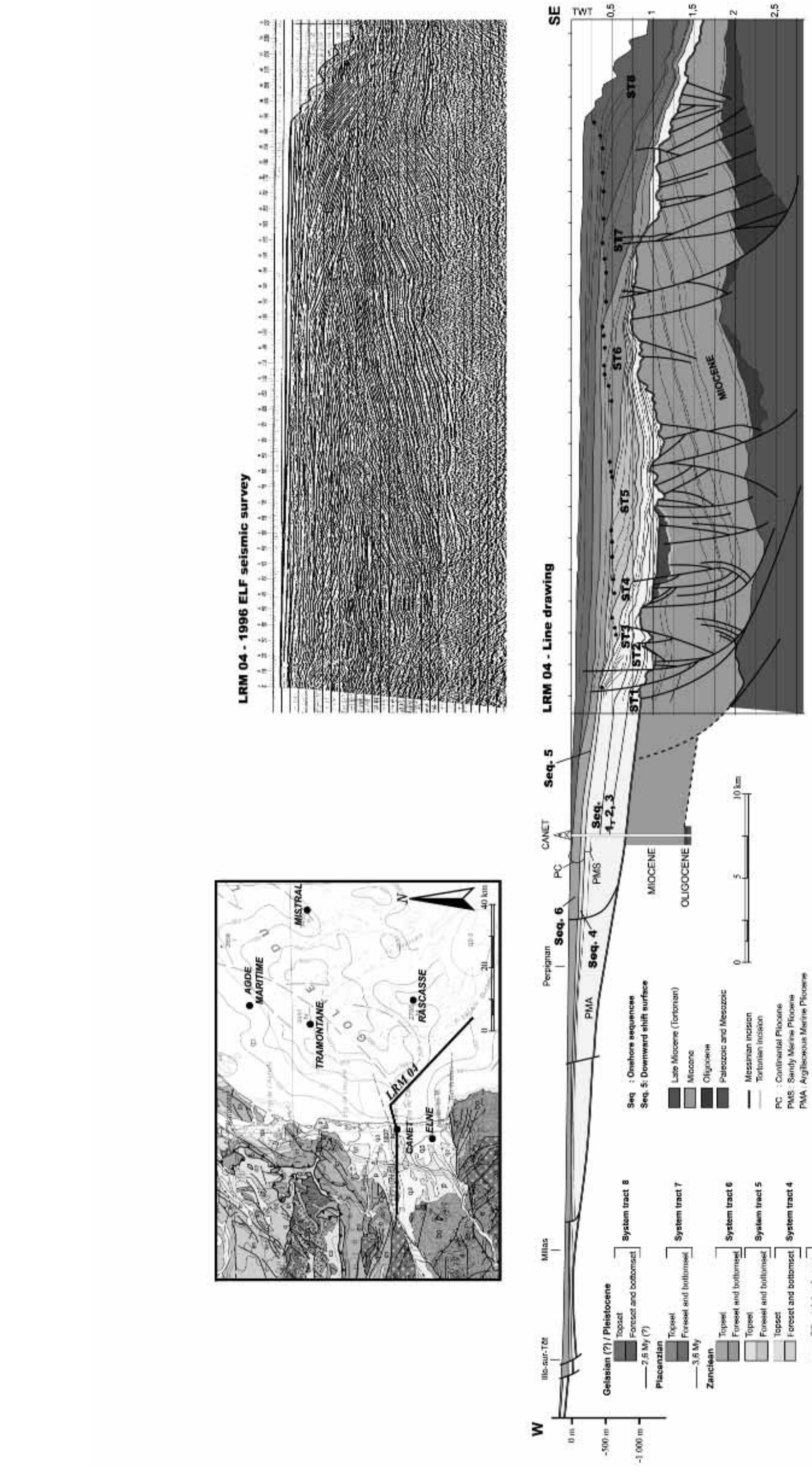

Figure 2. Pliocene and Quaternary correlation between on-shore and off-shore (seismic profile LRM 04) formation at the Roussillon Basin level (Duvail *et al.*, in press)

Quaternary terraces are the answer to glacio-eustatic dynamics in a context of generalized tilting, underlined by the on-shore downstream convergence of the levels of the most ancient fluviatile terraces (Duvail *et al.*, 2001).

Analysis of the off-shore seismic section

In the off-shore domain, the Pliocene-Quaternary series have been analysed from 1968 and 1996 Elf Aquitaine seismic data (Figure 2) and Labaune *et al.*, 2003 (Figure 3). These data have been provided by Total within the "GDR marge" framework and the University of Perpignan (BDSI Laboratory).

In the off-shore domain the classical method of sequence stratigraphy (Vail *et al.*, 1977; Posamentier and Vail, 1988; Posamentier *et al.*, 1988; Van Wagoner *et al.*, 1988) is used to analyse seismic profiles. Thus, sequence boundaries (unconformities) individualise the top and base of the major system tracts. Offlap break-picking (Homewood *et al.*, 1999) characterises the different systems tracts. Spatial evolution according to time of this reference point helps to determine the stacking pattern of each system tract identified in terms of progradation, aggradation, retrogradation and forced regression. This methodology helped to determine eight systems tracts (Duvail *et al.*, in press), not detailed in this paper (Figure 2).

Geological results

Correlations between on-shore and off-shore domains

Modifications of regional and global geological factors are identified, in the on-shore domain, by the stacking patterns of the genetic sequences, and in the off-shore domain, by the stacking pattern of the offlap breaks. Stacking pattern comparisons between both domains allow proposing correlations between the Roussillon basin and the Gulf of Lions occidental shelf within respected biostratigraphic knowledge (Clauzon and Cravatte, 1985; Cravatte *et al.*, 1974, 1984; Aguilar *et al.*, 1999; Fauquette *et al.*, 1999). Off-shore – on-shore correlations are not based on geometrical or lithological arguments but on geological events, and they are expressed as variations in sedimentary dynamics. These are identified and put in coherence on a same deposit profile thanks to the stacking pattern between both domains. Four correlations have been determined (Duvail *et al.*, in press) (Figure 2):

- (i) the earlier Zanclean (on-shore): sequences 1, 2 and 3 are correlated with systems tract 1, 2 and 3 off-shore;
- (ii) the late Zanclean (on-shore): sequences 4 and 6 are correlated with systems tract off-shore 4 and 6, off-shore; system tract 5 is correlated with the downward shift surface, intermediary with sequences 4 and 6;
- (iii) the Piacenzian (?): systems tract 7 is limited at its base by the eustatic fall, estimated at 3.8-3.6 My. On-shore, it is likely that the first fluviatile incisions, posterior to the roof of the Pliocene filling, are induced by the eustatic fall of the Zanclean-Piacenzian limit. The first level of fluviatile terrace observed on-shore may correspond to the installation of the prograding systems tract 7;
- (iv) the Gelasian (?) - Pleistocene: this period is marked, off-shore, by a tendency of aggradation of system tract 8. In the on-shore domain it shows a base-level falling tendency, underlined by

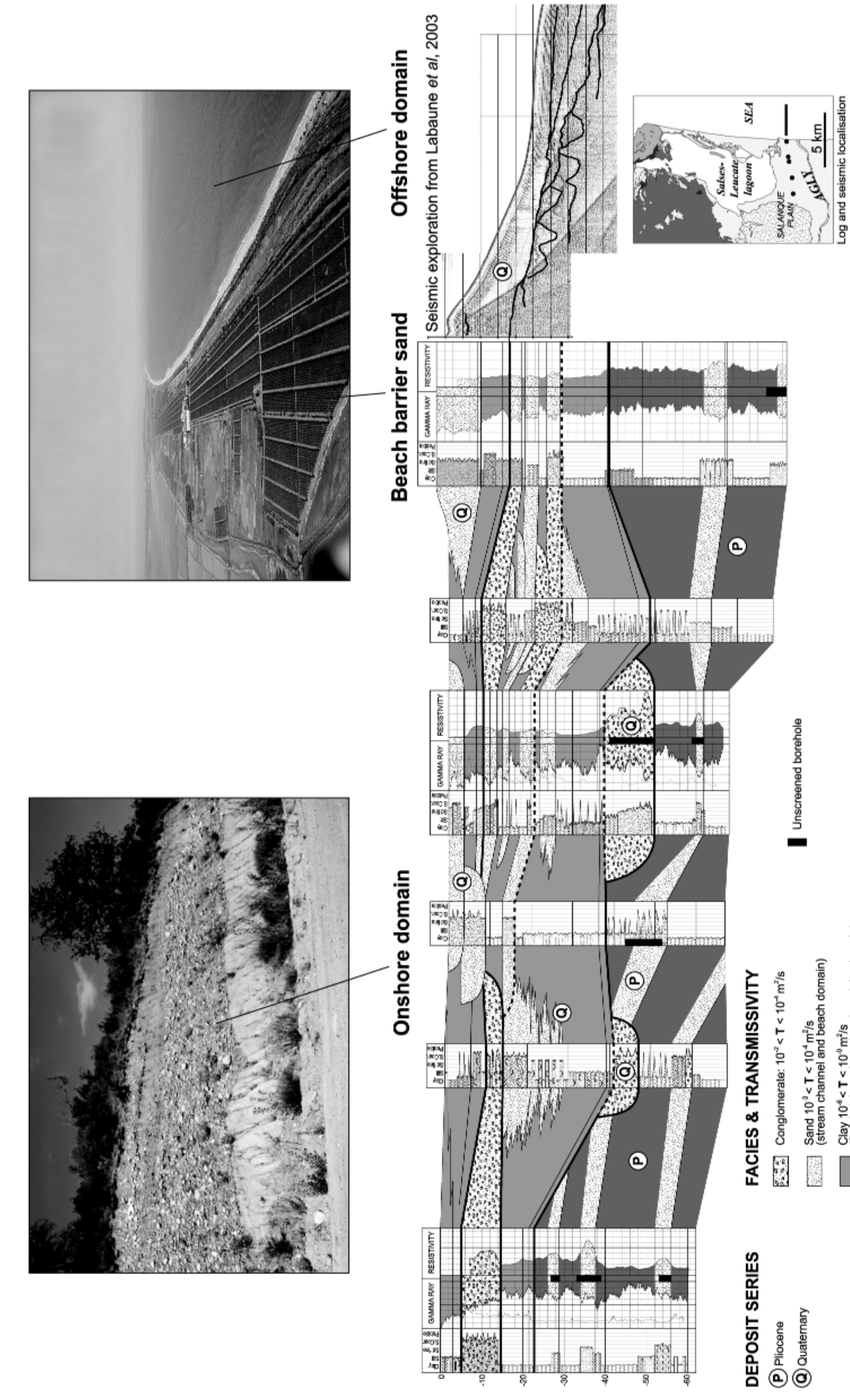

Figure 3. Correlation between Quaternary and Pliocene deposits of the on-shore and off-shore domains, interpreted in terms of hydrogeological characteristics.

fluviatile incisions and the settling of the alluvial terraces staged system (Clauzon, 1998 ; Le Strat *et al.*, 2001). The existing differences between the two domains correspond to the appearance of a hinge point around which the on-shore domain uplifted and the off-shore domain subsided. The tilting of the margin was described by modelling of the Quaternary systems tract (Rabineau, 2001).

Correlations between data logs and hydrodynamic parameters

Hydrodynamic parameters of the new formations identified are not always known. In order to characterise the hydraulic conductivity (K), the transmissivity (T) and the storage coefficient (S), the numerical logs values numerical, followed by field tests, will be used to obtain the parameters. This extrapolation will be carried out based on a principle of lithological similarity. New extrapolation of parameters will be provided by the geostatistical approach.

Hydrogeological results

The Quaternary aquifer

The Quaternary aquifers are mainly composed of alluviums (conglomerate, flood-plain) and coastal deposits whose geometry is linked to the Pliocene-Quaternary glacio-eustatic variations (Figure 3). Two types of deposits are distinguished:

(i) old and recent banks of stream terraces with gravel and pebbles (Figure 3), for the old banks (average thickness 2 m), and sand, gravel and pebbles for the recent banks (average thickness 5 m);
(ii) Holocene layers corresponding to the last post-glacial sedimentation. The lithology corresponds to a regressive prism composed by sand, clay and marsh facies.

The Quaternary aquifer lies along the main rivers and the coastline. Its thickness varied from 10 m for the sectors located in the upper parts of the valleys (Agly, Têt and Tech) to 20-30 m for the coastal fringe. The porosity of the aquifer is about 7×10^{-2}. This aquifer is confined at the coastal fringe, where its specific storage coefficient varies from 0.1 to 0.4×10^{-5} m^{-1}. The transmissivity values differ according to the sectors: thus, current values in the Têt valley are $4\text{-}5\times10^{-3}$ to $1\text{-}2\times10^{-2}$ m^2/s, with pumping rates going from 50 to 100 and even to 200 m^3/h. In the Tech valley, on the coastal fringe, values are 5×10^{-3} to 10^{-2} m^2/s and even locally higher, whereas at Salanque they are 5×10^{-3} to 2×10^{-2} m^2/s (Chabart, 1996). The coastal part of the Quaternary aquifer associated with the Agly, Têt and Tech valleys is affected by seawater intrusion (Cl > 300 mg/L) (Dörfliger, 2003).

The Pliocene aquifer system

The characteristics of the system are linked to the Messinian event: (i) digging out of huge canyons during the Messinian Salinity Crisis (5.9 - 5.3 My), during which the mean sea level dropped down to 1500 m below present mean sea level (pmsl), and (ii) filling-up of these canyons, after the sea level rise up to 80 m above pmsl (5.3 - 3.8 My) (Hardenbold *et al*, 1998), with the marine and fluvial sands that constitute the two main Pliocene aquifers. The sediments settled according to the "Gilbert delta" genetic model (Figure 4).

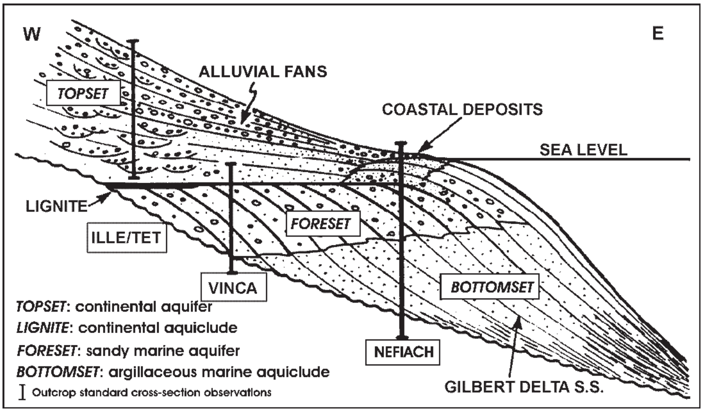

Figure 4. "Gilbert delta" genetic model (Clauzon *et al.*, 1990).

- The continental Pliocene aquifer (topset beds)

Prograding fluvial sands filled the distributary channels of the deltaic complex and covered the marine sands, forming this aquifer. It contains excessive water mineralisation in the northern part of the basin, along the lagoon and even more along the coast at Barcares.

The aquifer is very productive, especially in the Salanque plain, with a transmissivity of 10^{-2} to 3×10^{-2} m^2/s ($T = 10^{-4}$ m^2/s at the edge of the aquifer). It is a confined aquifer with a storage coefficient between 2.2 and 6.4×10^{-5} m^{-1} (Chabart, 1996). Locally there are some connections between the Quaternary and the Pliocene aquifers, mainly because of two reasons:

- leakage from pre-existing borewells;
- incision of the Pliocene aquifer by Quaternary channels (Figure 3). One consequence of the Pliocene subsidence is the shifting of Pliocene sediments (Clauzon, 1990; Duvail *et al.*, 2001).

- The continental Pliocene aquiclude

This aquiclude is located between the continental Pliocene and the marine Pliocene aquifers.
It is formed by diachronous layers of lignite with plants remains alternating with marsh plastic-clays. These layers are not present everywhere: 20 km to the west of Perpignan, lignite layers disappear in several wells and they reappear in the west side of the basin. This fact implies the local connection between the continental and the marine Pliocene aquifers.

- The sandy marine Pliocene aquifer (foreset beds)

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 sandy marine Pliocene aquifer is characterised by transmissivity values of 10^{-3} to 3×10^{-3} m^2/s (Chabart, 1996) and a storage coefficient of between 0.2 and 1×10^{-5} m^{-1}. In the southwest of the Roussillon plain, the Pliocene aquifer is semi-confined, having a storage coefficient about 5×10^{-2}.

- The Marine Pliocene aquiclude (bottomset beds)
The grain-size distribution decreases with water depth and the marine sands (foreset beds) gradually changes to plastic-blue-clays. As a result, hydraulic conductivity decreases gradually from the on-shore domain to the off-shore domain.

Discussion

According to the previous hydrogeological work carried out in Roussillon (Auroux and Noyer, 1992; Chabart, 1996), three main on-shore aquifers had been identified (Figure 5): (1) the Quaternary aquifer, (2) the Salanque Pliocene aquifer and (3) the deep Pliocene aquifer. The upper aquifer is in contact with the Mediterranean sea and was contaminated by seawater either directly by marine intrusion or as a result of earlier overexploitation. Saline contamination is present in the Salanque Pliocene aquifer as well as due to vertical leakage from the partially contaminated Quaternary aquifer through defective boreholes.

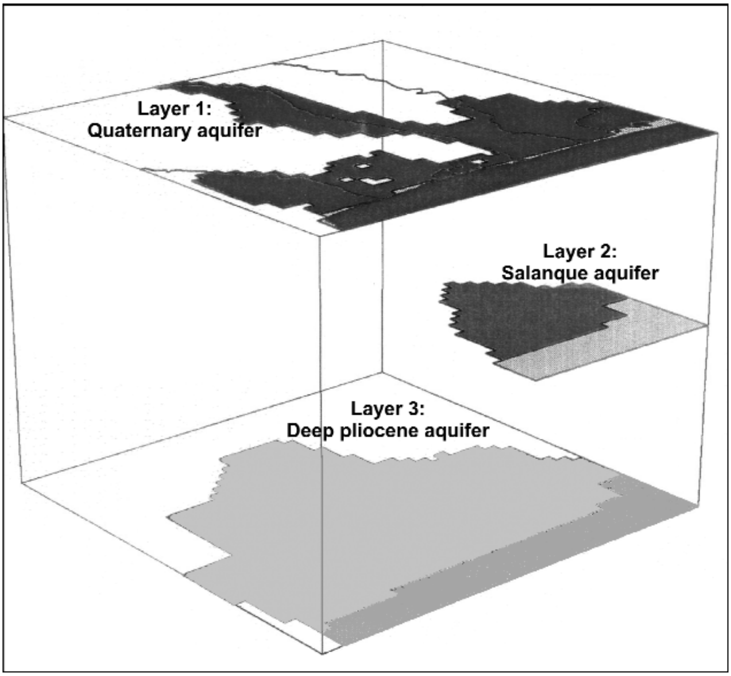

Figure 5. Conceptual model of the Plio-Quaternary aquifer (multi-layers) in Roussillon (Auroux and Noyer, 1992)

The present geological research on the geometry, the structure and the on-shore-off-shore continuum in this area, may require a revision of the groundwater conceptual model: boundary conditions, interconnection between aquifers, new aquifer subdivision within the Pliocene, etc.…

In fact, actual research shows local confusion between the continental Pliocene and the Quaternary aquifers. Moreover, the deep Pliocene aquifers, namely the continental Pliocene aquifer and the marine Pliocene one, are separated by a lignite layer and are independent in part of the Roussillon basin area.

The new fitting of aquifers and aquicludes -according to off-shore and on-shore correlation- will be implemented in a hydrogeological finite difference model. New model results -based on high-resolution geology- will be compared with the classical model (Auroux and Noyer, 1992) in order to determine the influence of high-resolution lithological and geometrical knowledge on groundwater modelling. Sensitivity tests with theoretical groundwater modeling will be carried out in parallel to evaluate the relevance of high-resolution geology.

Conclusions

Contribution to hydrogeology

High-resolution geology of the sedimentary prisms, derived from oil companies, allows a better understanding of the coastal aquifers. It makes possible to have a precise geometry of the aquifers and aquicludes so that the state of relationship (identified connections, compartments) between different aquifers can be precisely known. This knowledge must be integrated at the time of determining new borehole locations. For the existing boreholes already contaminated by saltwater intrusion, high-resolution geology helps to establish the origin of salinity. Indeed, it is possible to determine whether if direct or indirect (e.g. through defective boreholes) connection with seawater exists. Simultaneously, potential submarine spring or basement morphology can be considered.

Applicability of the results

The studied area is a good representation of most of the peri-Mediterranean porous (and also karstic) aquifers, which have, in fact, all undergone the same geodynamic processes and display similar structures. Mediterranean littoral geodynamics is an overall result of the eustatic variations and of the tectonic constraints. Thus, the methodology developed is applicable to most of the Mediterranean coastal areas, particularly to the Pliocene aquifers (linked to filled canyons during the Messinian salinity crisis), and to a lesser extent, to the whole coastal Quaternary aquifers.

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