OCEANOGRAPHY AND MARINE BIOLOGY SERIES
SEAS AND OCEANS SET

The Land–Sea Interactions

Edited by
André Monaco and Patrick Prouzet

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From the ***Seas and Oceans*** Set
coordinated by
André Mariotti and Jean-Charles Pomerol

The Land-Sea Interactions

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Foreword

We have been asked by ISTE to stimulate work in the area of the environment. Therefore, we are proud to present the "Seas and Oceans" set of books, edited by André Monaco and Patrick Prouzet.

Both the content and the organization of this collection have largely been inspired by the reflection, initiatives and prospective works of a wide variety of national, European and international organizations in the field of the environment.

The "oceanographic" community, in France and internationally – which is recognized for the academic quality of the work it produces, and is determined that its research should be founded on a solid effort in the area of training and knowledge dissemination – was quick to respond to our call, and now offers this set of books, compiled under the skilled supervision of the two editing authors.

Within this community, there is a consensus about the need to promote an interdisciplinary "science of systems" – specifically in reference to the Earth's own "system" – in an all-encompassing approach, with the aim of providing answers about the planet's state, the way it works and the threats it faces, before going on to construct scenarios and lay down the elementary foundations needed for longterm, sustainable environment management, and for societies to adapt as required. This approach facilitates the shift of attention from this fundamental science of systems (based on the analysis of the processes at play, and the way in which they interact at all levels and between all the constituent parts making up the global system) to a "public" type of science, which is finalizable and participative, open to decision-makers, managers and all those who are interested in the future of our planet.

In this community, terms such as "vulnerability", "adaptation" and "sustainability" are commonly employed. We speak of various concepts, approaches or technologies, such as the value of ecosystems, heritage, "green" technologies, "blue" chemistry and renewable energies. Another foray into the field of civilian science lies in the adaptation of research to scales which are compatible with the societal, economic and legal issues, from global to regional to local.

All these aspects contribute to an in-depth understanding of the concept of an ecosystemic approach, the aim of which is the sustainable usage of natural resources, without affecting the quality, the structure or the function of the ecosystems involved. This concept is akin to the "socio-ecosystem approach" as defined by the Millennium Assessment (http://millenniumassessment.org).

In this context, where the complexity of natural systems is compounded with the complexity of societies, it has been difficult (if only because of how specialized the experts are in fairly reduced fields) to take into account the whole of the terrestrial system. Hence, in this editorial domain, the works in the "Seas and Oceans" set are limited to fluid envelopes and their interfaces. In that context, "sea" must be understood in the generic sense, as a general definition of bodies of salt water, as an environment. This includes epicontinental seas, semi-enclosed seas, enclosed seas, or coastal lakes, all of which are home to significant biodiversity and are highly susceptible to environmental impacts. "Ocean", on the other hand, denotes the environmental system, which has a crucial impact on the physical and biological operation of the terrestrial system – particularly in terms of climate regulation, but also in terms of the enormous reservoir of resources they constitute, covering 71% of the planet's surface, with a volume of 1,370 million km^3 of water.

This set of books covers all of these areas, examined from various aspects by specialists in the field: biological, physical or chemical function, biodiversity, vulnerability to climatic impacts, various uses, etc. The systemic approach and the emphasis placed on the available resources will guide readers to aspects of value-creation, governance and public policy. The long-term observation techniques used, new techniques and modeling are also taken into account; they are indispensable tools for the understanding of the dynamics and the integral functioning of the systems.

Finally, treatises will be included which are devoted to methodological or technical aspects.

The project thus conceived has been well received by numerous scientists renowned for their expertise. They belong to a wide variety of French national and international organizations, focusing on the environment.

These experts deserve our heartfelt thanks for committing to this effort in terms of putting their knowledge across and making it accessible, thus providing current students with the fundaments of knowledge which will help open the door to the broad range of careers that the area of the environment holds. These books are also addressed to a wider audience, including local or national governors, players in the decision-making authorities, or indeed "ordinary" citizens looking to be informed by the most authoritative sources.

Our warmest thanks go to André Monaco and Patrick Prouzet for their devotion and perseverance in service of the success of this enterprise.

Finally, we must thank the CNRS and Ifremer for the interest they have shown in this collection and for their financial aid, and we are very grateful to the numerous universities and other organizations which, through their

researchers and engineers, have made the results of their reflections and activities available to this instructional corpus.

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Continent–Sea Interface: a Hydrogeological Continuum

The section of land between continent and ocean is the hydrogeological continuum. Geological reservoirs containing groundwater resources do not stop at the shoreline. These formations are continuous and may be covered by less permeable formations on the continental shelf. This interface on the coast takes the form of a transition zone between freshwater and saltwater due to the difference in density, the geometry of aquifers and the heterogeneity of their physical properties as well as how the coastal aquifers are used (supply of drinking water, agriculture, tourism, industry, etc.) and also, as freshwater inputs into the ocean. The proper management of coastal aquifers inevitably involves the risk assessment of saltwater intrusion, based on geological and hydrogeological knowledge of formations, observation and alert networks, management models integrating geological, hydrogeological and geophysical data and technical management solutions. Using methods to characterize clastic sedimentary geological reservoirs by sequential stratigraphy and seismic stratigraphy both *onshore* and *offshore*, respectively, helps suggest appropriate management tools for coastal aquifers that develop within sedimentary basins. In addition, characterizing the paleo-geographic evolution of the development of carbonate platforms over the course of geological time associated with the changes in sea level and vertical tectonic movements is essential in order to establish conceptual models required for monitoring and managing karstic coastal aquifers. Airborne geophysics provides information about the structure and intrusion of saltwater in formations, both sedimentary and volcanic. Different examples of coastal aquifers, primarily Mediterranean, show the specificity of this continuum, characterization and monitoring tools as well as management tools.

1.1. Introduction

Coastal zones form an interface between the land and the sea surface. Underground, coastal aquifers in turn form a hydrogeological continuum, an interface between the ocean and continent. Groundwater flows in geological formations, usually perpendicular to the coastline, toward continental and marine outlets on the continental shelf with the release of groundwater or occasionally underwater sources.

Groundwater is found in a variety of geological formations, between the sea and land: in detrital sedimentary formations (deltas, sedimentary basins, alluviums, etc.), in karstified limestone formations (Mediterranean, Mexico, Florida, etc.), bedrock formations (Britain, Scotland, Scandinavia, etc.) or volcanic formations (Reunion, Mayotte, Caribbean, Canaries, Azores, etc.). This space between the continent and ocean is an interface between salt and freshwater. Saltwater can penetrate the continent depending on natural conditions and abstractive conditions. As its density is higher than that of freshwater, it forms below freshwater, which we call a saltwater intrusion (theoretical abrupt interface) or a transition zone (diffuse interface).

This continent–ocean interface is a zone of interest both for human societies, with more than 60% of the world’s population living on the coastline less than 60 km wide, and for lagoon and marine ecosystems. This coastal zone attracts populations and tourists, both due to climatic conditions and quality of life as well as economic development (sea transport, import–export). Water resources are necessary for the development of this zone. Groundwater in aquifers of this sea–land continuum is an important source both for the supply of drinking water and for human activities (agriculture, industry, tourism, etc.). Specific ecosystems develop in the ocean or in lagoons next to groundwater outlets and may also be zones of economic interest (fishing, oyster farming, fish farming, etc.).

The Mediterranean basin and the French overseas islands are ideal for illustrating this continent–ocean interface. Three types of geological land–sea continuums are presented: sedimentary basin, karst and volcanic islands, as well as a description of the characteristics of the saltwater–freshwater interface for different geological contexts. Characterization tools, mainly geological, hydrogeological and geophysical, as well as the management of groundwater resources at this interface are also detailed.

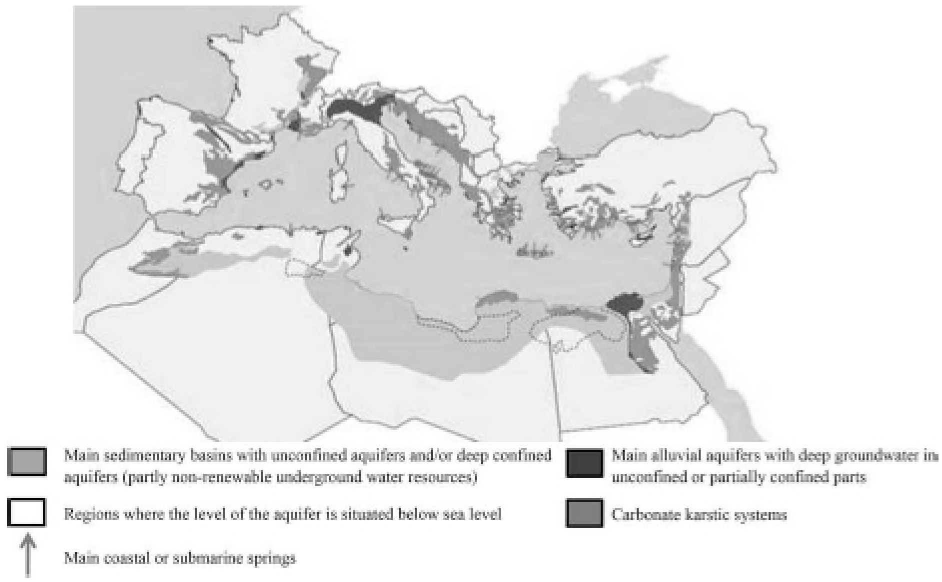
1.2. Land–sea interface: from geology to the hydrogeological continuum

The land–sea interface covers 2 million kilometers of shoreline worldwide, distributed around different continents and numerous islands. Coastal zones, carbonate, volcanic (in the absence of lagoons) or bedrock, are steep except in large depressions associated with the main river basins, where large low-altitude areas occur: Rhine (Netherlands), Rhône, Garonne (France), Thames (United Kingdom), Vistula (Poland), Danube (Ukraine/Romania), Ebro, Guadalquivir (Spain) in Europe, for example.

Recent geological phenomena, such as glaciation and formation of reliefs, which effect sedimentary deposits and eustatic variations, have influenced the development of coastal aquifers occurring in the continent–ocean interface. During the last glaciation (≈ –18,000 years), a large part of the continents was covered with ice. Valleys were cut into rocky formations and ancient marine sediments, and then filled with fluvioglacial, fluvial, estuary, marine or even wind sediments. The Messinian salinity crisis in the Miocene (–5.95 to –5.3 million years) in the Mediterranean, isolating it from the Atlantic Ocean, significantly decreased sea level (up to 1,500 m) accompanied by salt deposits and the incision of deep valleys and karstic network development within carbonate massifs. These valleys were filled as the sea level rose with sediments, including clays and marls.

Figure 1.1 illustrates the position of the main alluvial and karstic carbonate aquifers, with the presence of the main submarine springs in the Mediterranean basin [AUR 08]. The flow rate of groundwater discharge into the Mediterranean Sea is, on average, estimated to be 43.5 km^3/year (29 km^3/year northern shore, 14 km^3/year eastern shore and 0.5 km^3/year southern shore), 10 times less than the discharge from surface water [MAR 08].

Figure 1.1. *Map of main coastal aquifers in the Mediterranean basin [AUR 08]*



1.2.1. *The continent–ocean continuum*

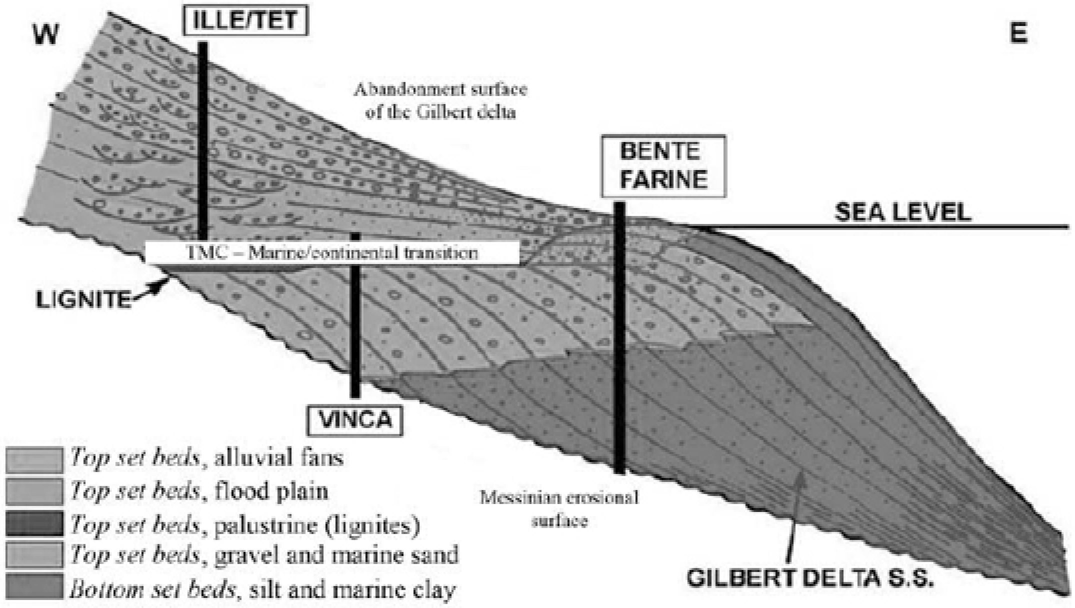
The continent–ocean continuum is described by considering two representative cases: sedimentary basins or deltas and carbonate platforms.

1.2.1.1. *Sedimentary basins or deltas*

Mediterranean coastal sedimentary basins are good examples to show this type of continuum. Mediterranean coastal aquifers in sedimentary basins are found in Italy in the Pô plain, in Egypt with the Nile delta, in France with the Camargue plain in the Rhône delta and, to a lesser extent, along the coast of Languedoc-Roussillon from the Vistrenque plain to the Roussillon plain, all associated with the same evolution of the shelf of the Gulf of Lion and finally in Spain, with the Llobregat delta (Barcelona) or even the Ebro delta.

The geometry and three-dimensional (3D) field of hydrodynamic properties of aquifers and aquitards (semi-permeable) occur within sedimentary layers deposited over time. The occurrence of these formations can be explained using the Gilbert delta genetic model [DUV 08] (Figure 1.2).

Figure 1.2. *Genetic model of the filling of a Pliocene river. Distribution of features in a Gilbert delta and characteristic surfaces (according to Clauzon et al. 1990, in [DUV 08])*



As we pass from the Pliocene (–5.3 to –1.35 million years) to the Quaternary (–1.35 million years to present), sedimentary deposits, generated through the active erosion of watersheds situated upstream of deposition zones, prograde toward the center of the basin. At the base of the Gilbert delta, the sedimentary prisms are composed of silt and clay, from upstream to downstream. The top section of marine prisms is characterized by the presence of gravel and sand.

Marine prisms are overlaid by lacustrine layers and sediments from floodplains and alluvial fans. The sediment layers, which are deposited in the accommodation space in the basin, are influenced by erosion and transport of solids in the water as well as by sea level variations and vertical movements (subsidence in the basin, vertical movements associated with tectonics).

Restoring geometries of sedimentary layers is an important stage in the study of coastal aquifers occurring in alluvial depositions or sedimentary basins. Sequential or genetic strategy is an essential tool for analyzing the development of sedimentary layers along a land–sea continuum, using drilling data, observations of outcrops as well as geophysical data (seismic profiles). Sequential stratigraphy is defined as a method that defines a chronostratigraphic framework on a global scale based on accurate dating of time lines among discrepancies of eustatic origin (variation in sea level), which restrict genetic sediment units [VAI 91]. This method was applied to the Roussillon plain (South of France) [DUV 08, AUN 07] (Figures 1.3 and 1.4), and to the Llobregat delta (Spain) [GAM 09].

From a hydrogeological point of view, the Roussillon plain is a groundwater body subdivided into two vertical sections, namely the quaternary aquifer of a generally unconfined aquifer and confined aquifer if covered by impervious silt over 5 m deep in the coastal zone, composed of quaternary alluvial deposits and the deep Pliocene aquifer (Figure 1.5). The continental fluvial–lacustrine Pliocene deposits show superposition of permeable lenticular sandy layers within a less permeable clay matrix; the most permeable layers are located at the top of the prisms, along with arkosic sand. At the base of the continental pliocene deposits lies plastic clay, which forms the upper part of the marine pliocene deposits giving them a confined characteristic. The marine pliocene sediments partly composed of micaceous clays and silts are generally less permeable, but there are still local variations in characteristics, with lightly compacted sandy sections which form good aquifers. The base of the marine pliocene sediments, with blue marl, is impervious. Due to its architecture and geometry, this aquifer is heterogeneous: the hydraulic conductivity of different aquifer terrains as well as the position of the freshwater/saltwater interface can strongly vary [AUN 06]. Finally, the underlying aquifer is the sandy marine pliocene aquifer, separated from the continental Pliocene aquifer by layers of lignites and plastic clays resulting from depositional environments of flood plains or wet lands; these layers are not continuous throughout the area. The sandy marine pliocene aquifer develops within sediments of prograding prisms of the delta in the distal part of the basin. This aquifer, in theory, is not in direct contact with the sea; however, certain sections are affected by mineralization associated with chlorides. The origin of this mineralization is quite probably due to contamination from being hydraulically connected to the quaternary aquifer by defective boreholes. Without pumping, the hydraulic load of the sandy marine pliocene aquifer is greater than that of the continental pliocene aquifer [AUN 06].

Figure 1.3. *Methodology for the sea–land interpretation and correlation of Pliocene and Quaternary sedimentary formations [DUV 08]*

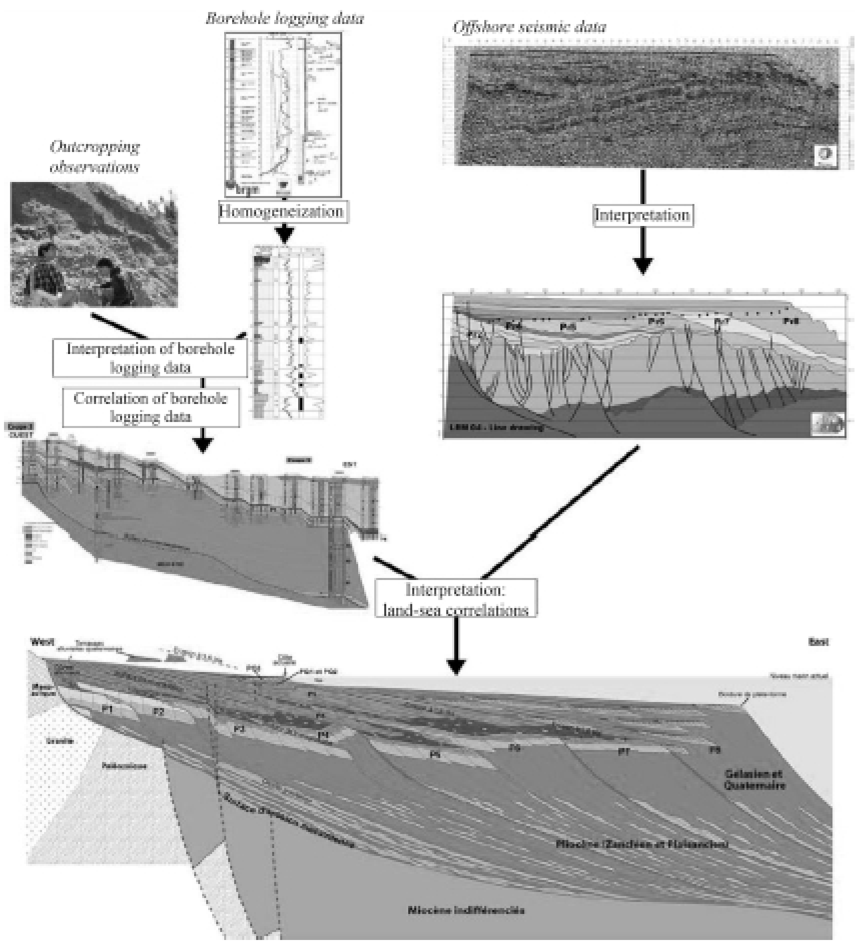


Figure 1.4. *Correlation between Quaternary and Pliocene deposits in the continental and oceanic domain, interpreted in terms of hydrogeological characteristics [AUN 04]*

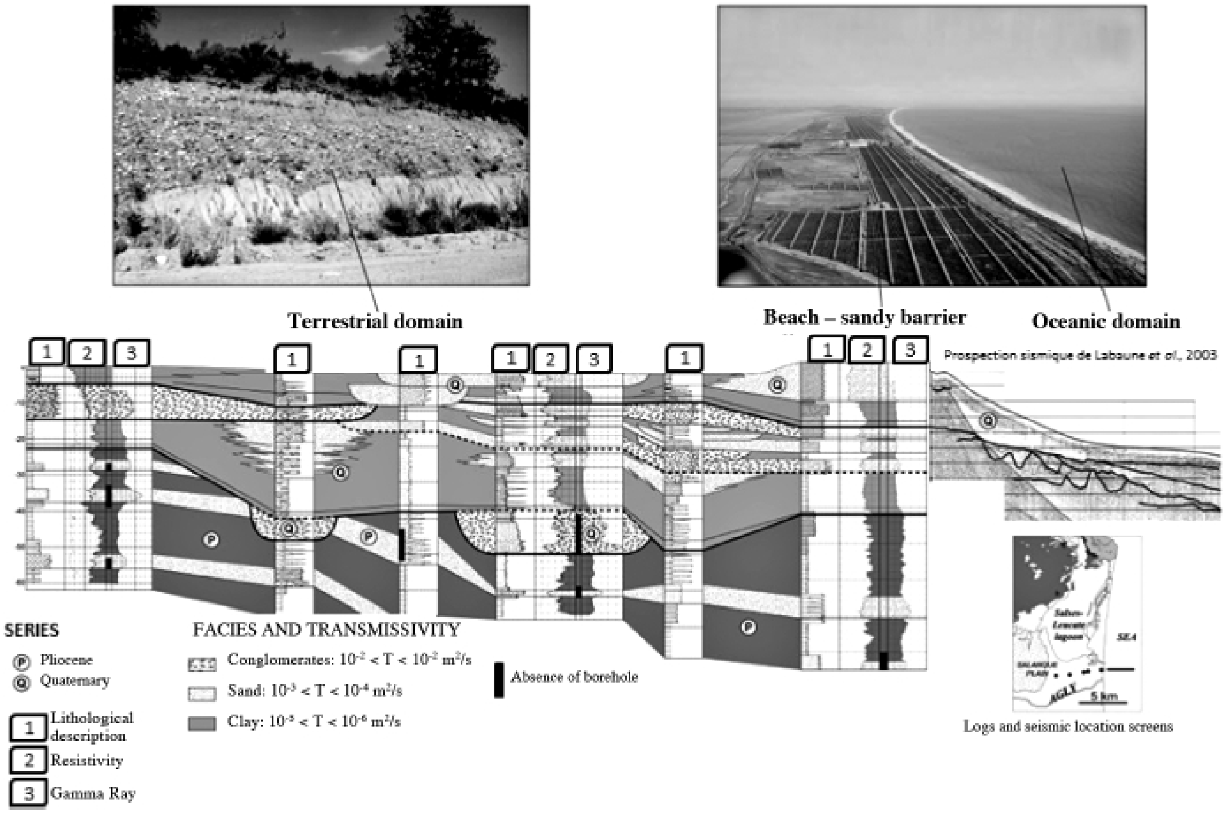
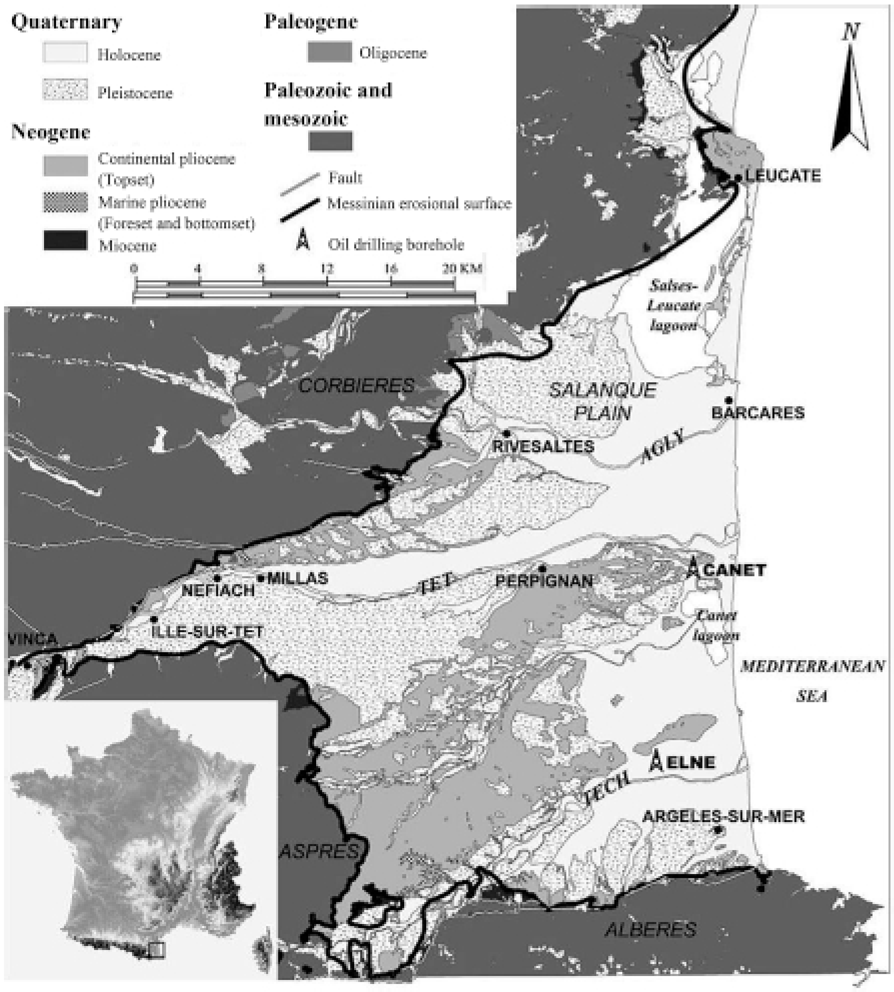


Figure 1.5. *Simplified geological map of the Roussillon basin and the geophysical location [AUN 04]*



From stratigraphic and hydrogeological data, a diagram helps propose a hydrogeological conceptual model (Figure 1.6) as well as an interpretive hydrogeological profile from west-east [AUN 07] to represent the characteristics of aquifers within aquitards (Figure 1.7). The groundwater level of the Quaternary superficial layer (TQ and PQ) in general follows the topography; this aquifer is recharged by precipitation, exchanges with rivers and drainage canals for irrigation of the plain for agriculture. Upstream of the basin, the quaternary surface aquifer recharges confined aquifers of sandy pliocene prisms 1 and 2. In addition, due to the thinness of palustrine and clay layers, the flows are divided equally among the three first sandy pliocene prisms. Approximately 15 km from the shore, the lower hydraulic conductivity of sandy pliocene prisms and the increase in the granulometry of the continental pliocene deposits favor flows within continental channelized systems. The problem of the saltwater–freshwater interface begins not only in the coastal zone, but also in the offshore zone. Knowledge of the geometry and permeability of geological layers of the offshore domain is essential to determine the vulnerability of water resources. The hydrodynamic properties of slightly permeable and semi-permeable layers are central to this issue. In addition, downstream, i.e. along the coast, hydraulic heads are greater within deep aquifers than within shallow aquifers. Natural drainage is ascending. The difference in water heads between each aquifer is metric. Due to exploitation of the deep resource by drilling, the local hydraulic water head of the underlying aquifer may decrease, due to inversion of the hydraulic water head gradient (vertical leakage).

Figure 1.6. *Interpretive geological a) and hydrological b) sections of the Roussillon plain orientated west-east [AUN 07]. Vertical drainage associated with an inversion in hydraulic gradient is shown in the hydrogeological section. Vertical drainage takes place via continental sandy formations with lignite or via faulty drilling sites*

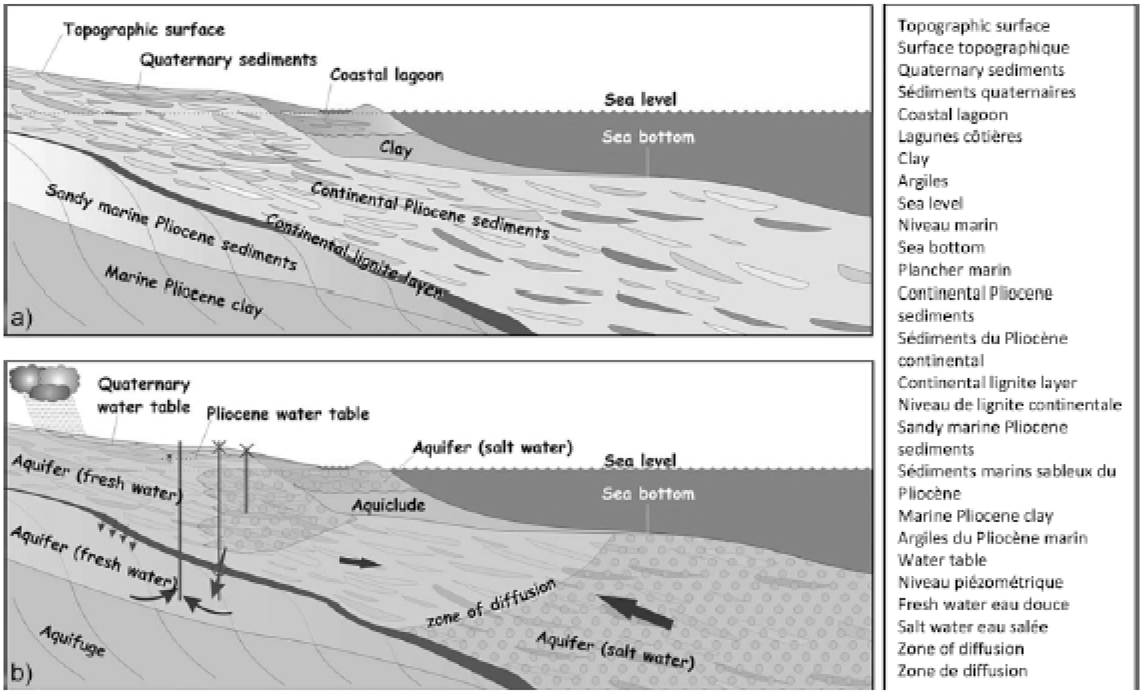
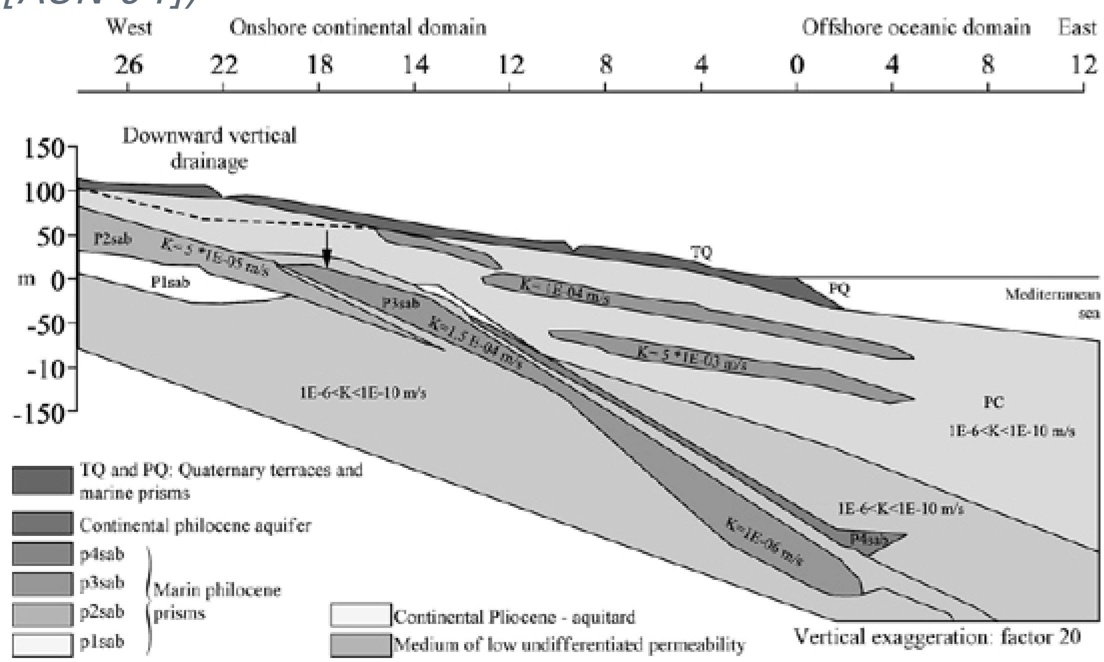


Figure 1.7. *Interpretive hydrogeological section of the Roussillon plain orientated west-east (adapted according to [AUN 04])*



1.2.1.2. *Carbonate platforms*

Carbonate platforms giving rise to potentially karstified coastal carbonate massifs are present in many sites around the world: Mexico, Florida in the Americas, China and Vietnam in Asia, Spain, France, Italy, Croatia, Greece, Turkey, Syria, Libya in the Mediterranean basin, the Parisian Basin, London Basin, or even Ireland in Europe, for example.

Due to the many changes in sea level [HAQ 87] over geological time and, in particular, since the Miocene [BLA 02, HAL 84, ROU 92], it appears that the sea level variation has had more influence on the development of coastal karstic aquifers than more localized tectonic movements with slower dynamics. The evolution of karstic aquifers and their functioning differ depending on the increase or decrease in sea level. Over periods of relatively low sea level, the karstic springs are therefore situated above sea level. The increase in the resulting karstification potential makes possible the development of a new karstic conduit network, connected to the pre-existing karstic network as well as to the new base level [FOR 89]. On the other hand, an increase in sea level causes submersion and the potential fossilization of karstic networks.

The location of submarine springs and submerged karstic conduits indicates the existence of sea level variations along the coast. Throughout the Quaternary, the lowest sea level was 120–140 m lower than the current sea level. During the interglacial period, the sea level was close to the current sea level. These variations have been recorded along all coasts. Moreover, karstic conduits located at significant depths disagree with the lowest sea levels of the ice age take place along in the Mediterranean basin:

– the Port-Miou conduit network (France) has been explored up to a depth of -172 m [ARF 06a, CAV 06];

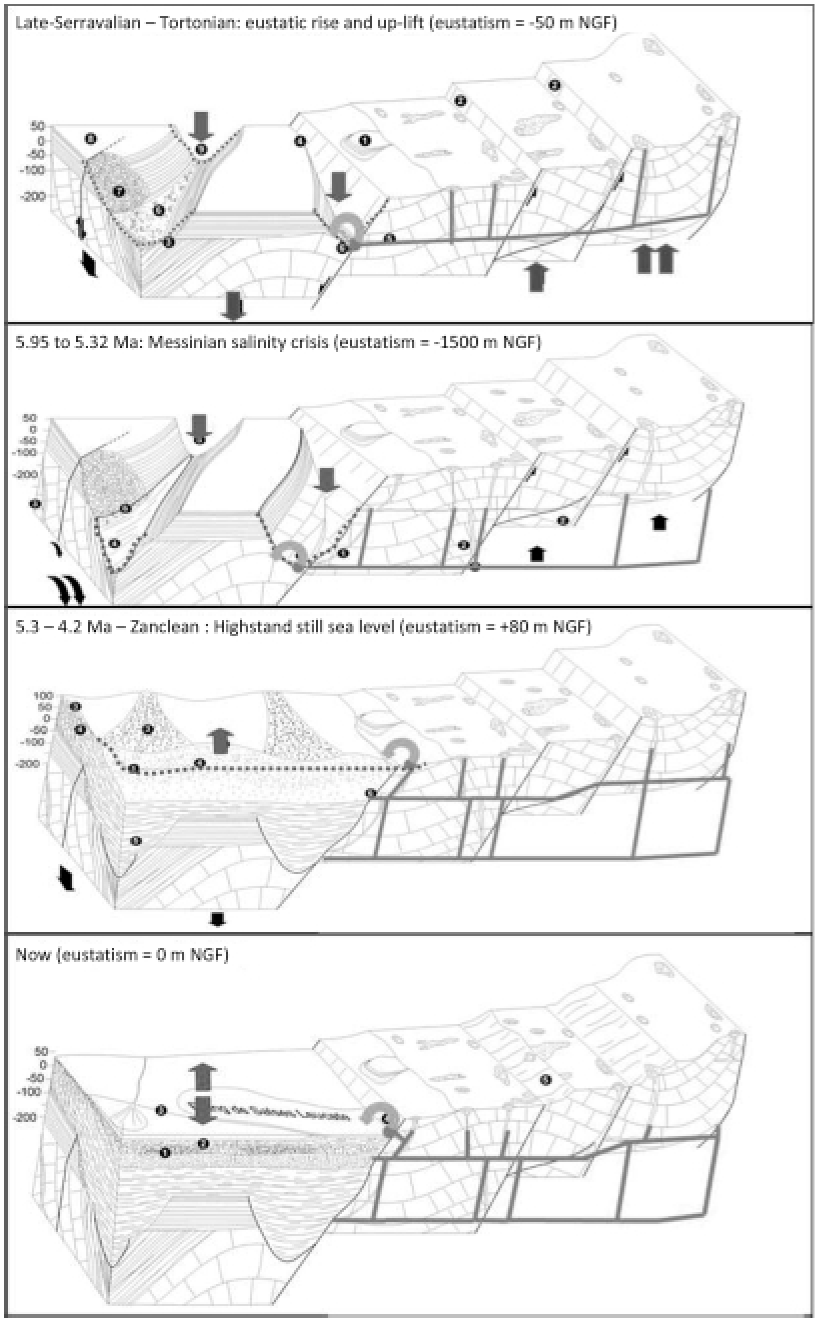
– the karstic network of the Fontestramar spring (France) has been explored up to a depth of –164 m [AUN 03, BRA 97]; in Chekka (Libya), the deepest spring is located at a depth of 110 m and 150 m below the sea level below the sea level [BAK 07b, ELH 06, KAR 67]; in Almyro of Eraklion

(Crete), the marine intrusion has been identified at a depth of 500 m below the current sea level, implying karstification at depth [ARF 02, ARF 04, ARF 06a].

These depths are not consistent with the lowest sea levels of the last ice age. Consequently, developments of coastal karstic systems at depth in the Mediterranean are associated with an event of a much greater magnitude, the Messinian salinity crisis [CLA 82, ROU 99, ROU 06]. Approximately 5.35 million years ago, at the end of the Miocene, there was a significant decrease in sea level due to the closing off of the Mediterranean from the Atlantic Ocean and a high evaporation rate was recorded in the Mediterranean. This geological event allowed the incision of valleys and the development of vertical karstic conduits [BLA 95] below the current sea level, often located below Pliocene sediments, as well as significant evaporite deposits. Depending on the local geological conditions, the karstic conduits may be obstructed or open to the sea.

The development of Mediterranean karstic systems is shown in Figure 1.8, reconstructing the development of an east Corbières system and the Fontestramar-Fontdame karstic system, whose outlets border the Salses Leucate lake (Eastern Pyrenees, South of France).

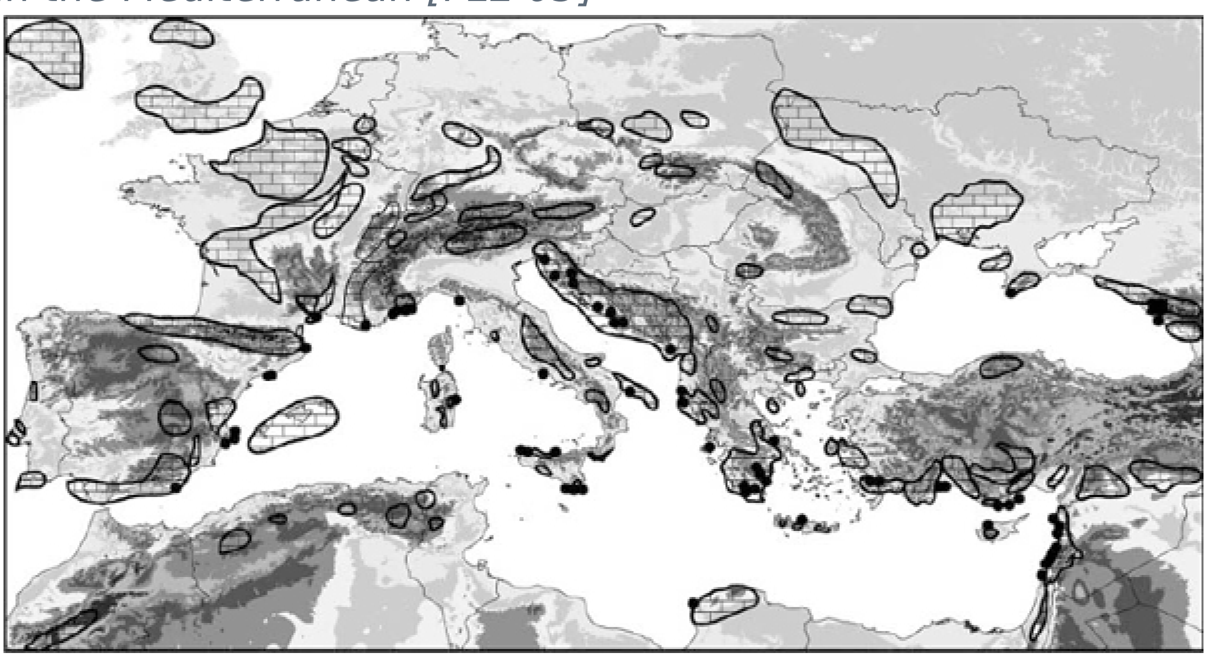
Figure 1.8. *Reconstructed diagram of the implementation of the karstic system in Fontestramar-Fontdame (Eastern Pyrenees, South of France)*



The land–sea continuum of carbonate platforms is characterized by the existence of freshwater outlets into the sea with undersea springs located along the coast (Figure 1.9) as well as by saltwater intrusions within fissured limestone massifs and karstic conduits. Undersea springs are situated between several meters and several hundred meters in depth. The amplitude and durability of the flow rate depend on the depth of open karstic conduits and the hydraulic water head within the limestone massif, influenced by precipitations on limestone outcrops in the continental domain.

Different types of coastal karstic systems develop according to the amplitude of variations in the sea level, favorable conditions for karstification and sedimentation (clay or basalt flows) following the rise in the sea level [FLE 12]. Undersea springs show a wide variety of functions: some are permanent such as Port Miou [ARF 06, CAV 06] in the Thau lake with the Vise spring [AQU 03, PIN 04] in France, the Mortola spring in Italy [FLE 07a], Moraig in Spain [FLE 08], Anavalos Kiveri in Greece [MIL 00], Banyas in Syria [BAK 07a] and Chekka (the shallowest) in Libya [BAK 07a, BAK 07b, KAR 67], whereas others are only seasonal. This is the case of the deep spring in Chekka (Libya) and several undersea springs in Croatia [BON 87, BON 95, MIJ 84], Toix in Spain for which there are flows during flooding, the rest of the time this conduit absorbs seawater [FLE 08].

Figure 1.9. *Distribution map of karstic zones (represented by bricks) and coastal and submarine sources (black points) in the Mediterranean [FLE 05]*



During periods of rises in sea levels, the flow rates of some submarine springs may be several m^3/s, which is the case for the deep spring in Chekka and in Port-Miou [CAV 06]. During periods of low water levels, flow rates may be low, or even zero. When the spring dries up, seawater penetrates into conduits. Other springs have a flow rate that remains low and relatively constant at several dozen liters per second, which is the case for the spring of Mortola [FLE 07a].

Several coastal karstic systems are naturally impacted by saltwater intrusions either seasonally or permanently. In fact, few underwater springs discharge relatively freshwater throughout the year, which is the case for Mortola, Banyas and Anavalos Kiveri. In general, undersea springs discharge brackish water at least during periods of low water levels during the hydrological cycle with variations in salinity during rises in sea level (e.g. Port Miou and Moraig).

Three types of coastal karstic system may be distinguished, considering the degree of karstic development and hydrological functioning of the drainage system. The first type (type 1, Figure 1.10) is characterized by springs with a relatively low flow rate varying little during the hydrological cycle (e.g. La Mortola); the water is fresh throughout the year. The functioning is not really karstic, but instead similar to fractured aquifers. The conduits are small in dimension and not organized into a network. Significant losses of hydraulic water head near the springs create a sufficient hydraulic water head to prevent marine intrusion. These aquifers are low extension aquifers with limited reserves with regard to well-developed karstic systems resulting from several karstification phases. The second type (type 2, Figure 1.10) is a network of well-developed karstic conduits, often arranged along horizontal levels and connected to deep vertical conduits resulting from several karstification stages associated with successive decreases in the base level. The conduits are large with regard to the low current flow and cause a decrease in hydraulic water head at the outlet. The hydraulic water head within the aquifer is often too low to prevent saltwater intrusion in conduits, particularly during periods of low sea level. These aquifers drain large recharge zones and have large resources. Systems of karstic conduits are well developed below sea level and are open. The average flow rate of springs is high and is characterized by high seasonal variability; some submarine springs are not permanent. The salinity of water is usually low during rises in sea levels, but high during periods of low sea levels. This is the type of coastal aquifer most frequently observed in the Mediterranean (Moraig, Chekka, Port-Miou, Fontestramar [HEB 06], Almyros of Heraklion [ARF 04] and submarine springs of the Croatian coast). The third type (type 3, Figure 1.10) is associated with coastal karstic aquifers which have been affected by significant karstification according to several phases. They are characterized by submarine springs whose flow rate is large and variable and the water is fresh or very slightly salty during the hydrological cycle. The non-contamination by seawater is due to the obstruction of conduits by continental or marine sedimentary deposits due to karstification phases. Discharge occurs through covering layers. Losses of hydraulic water head are high within conduits, preventing permanent intrusion of seawater into the aquifer. The aquifer may be confined on land and may have a significant storage capacity of water at depth. The karstic aquifer in Banyas, Syria, is representative of type 3 [ALC 07, BAK 07], just like the spring of the Vise.

1.2.2. *The land–sea continuum: islands*

For large islands, the sea–land continuum characteristics do not differ from the continent–ocean continuum, with the exception of the absence of large river basins and therefore large sedimentary basins. For small islands with an area less than 3,000 km², the size of the saltwater–freshwater interface depends on hydrogeological and exploitation conditions. Saltwater intrusions may be local, not affecting the whole aquifer, which is the case for volcanic islands (e.g. Reunion, Canaries, Caribbean, Mayotte, Hawaii and Galapagos) or larger such as Majorca in the Mediterranean. This extreme situation corresponds to partial or complete and continuous intrusion beneath the island. Freshwater floats on saltwater. This situation exists in Malta, in ocean atolls and some Caribbean islets [CUS 02].

Figure 1.10. *Three types of functioning of coastal karstic systems with undersea sources, according to [FLE 12]*