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Marine Geology 222–223 (2005) 267–298

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

www.elsevier.com/locate/margeo

High resolution stratigraphy and evolution of the Rhône delta plain during Postglacial time, from subsurface drilling data bank

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Received 8 June 2004; received in revised form 20 November 2004; accepted 15 June 2005

Abstract

This study is based upon a large set of core drilling data (lithology and well logs) of the Rhône delta plain extracted from the French geological survey (BRGM) databank. The main goals are to set up a sequence stratigraphy model of the postglacial sedimentary bodies of the Rhône delta plain and to evaluate the relative importance and influence of the main controlling factors and processes (subsidence, eustasy, sediment yield, climate, anthropic influence) that led to their formation.

First, a detailed study (60 drill holes with tenth meters spacing) was performed on a restricted area (Saint Ferréol lobe, 1.5 km^2). Correlation between well logs data and lithological data allows to identify the main sediment lithofacies and key surfaces, and to set up a detailed stratigraphic framework. Postglacial deposits are subdivided into a lower member of coastal plain and backbarrier deposits and an upper member of marine deposits (coastal barrier environments).

Following, the analysis of 160 wells distributed on the whole delta plain depicts the large scale architecture of postglacial deposits. In the upper delta plain, fluviatile coastal plain and palustral deposits prevail. In the lower delta plain, the deposits are made of a lower part of coastal plain deposits organized into four units (T1–T4) stacked in a retrograding pattern. This lower member is truncated by an erosional surface progressively deepening seaward. Above, an upper member of marine deposits thickening seaward and coarsening upward is organized into five units (P1–P5) arranged in a prograding pattern.

The core drilling data have been correlated with high resolution seismic data on the adjacent shelf and are interpreted in sequence stratigraphy terms. The retrogradational units (T1–T4), with coastal plain deposits, are correlative of shelf units and constitute together trangressive parasequences deposited during phases of slowing down of postglacial sea level rise. The upper marine units (P1–P5), arranged in a prograding pattern, represent parasequences of the Highstand Systems Tract which have prograded since the period of reduced rate of sea level rise at the end of the Holocene. During this period, the evolution of the sedimentary Rhône system was controlled by major changes of the hydrologic regime. Periods of increased sediment discharge, aggradation of the floodplain and progradation of the coastline are correlated with the development of the deltaic lobes of the

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0025-3227/$ - see front matter
doi:10.1016/j.margeo.2005.06.017

Rhône d'Ulmet (unit P3) and of the Rhône du Bras de Fer (unit P4). Unit P5 correlates with adjacent prograding shelf unit that developed seaward of the present Rhône river mouth.

Comparison of sea level history between the Eastern part of the Rhône delta plain and the rocky coast to the east of Marseille suggests that tecto-subsident movements account for part of the changes in relative sea-level. Moreover, the truncation of transgressive and progradation surfaces, the unevenness of the MFS, the dilatation of sedimentary record and deformations of key surfaces are also in favor of differential subsidence.

Keywords: Rhône delta; continental shelf; postglacial; well logging; sequence stratigraphy

1. Introduction

The main objective of the EURODELTA concerted action is to pool existing geomorphological, geophysical, stratigraphic, sedimentological and oceanographic data about the formation and evolution of Mediterranean and Black Sea deltas during the last thousand years. The recognition of long term trends due to interactions between eustatic changes, subsidence and sediment yield should provide a basis to understand how deltas have evolved, to evaluate the impact of human activity and how they can best be managed so as to balance economic activities with the natural environment.

The Rhône delta (Fig. 1) has been the subject of a number of sedimentological studies. Kruit (1955) mapped the superficial deposits of the delta plain and the main morphological features (active and abandoned channels, lakes and lagoons, beaches patterns). He showed from well data that Holocene delta deposits rest on a coarse grained (conglomeratic) layer gently dipping southward. He noted that in the northern part of the delta plain, filling is made of coastal plain to fluviatile deposits (20–30 m thick) whereas in nearshore areas drilling cut across marine deposits (50–60 m thick).

During the sixties, Shell Petroleum Company conducted drilling at 29 locations distributed over the delta plain. Four major lithofacies (fluviatile sand, beach barrier sand, coastal plain silt and clay, marine clay) are discriminated from a detailed lithologic and faunal analysis (Oomkens, 1967, 1970). These facies (Fig. 2) are organized into depositional units (transgressive or regressive). The controlling depositional factors are at once autocyclic (abandon and/or lateral migration of distributaries) and allocyclic (eustatic changes).

More recent studies (Arnaud-Fassetta, 2000, 2002; L'Homer et al., 1981; Vella, 2002; Vella and Provansal, 2000; Vella et al., 1998) have combined geomorphologic analysis, lithologic and archeological data and biological markers to reconstruct the palaeogeographic evolution of the delta-plain at the late Holocene. They recognized and dated periods of rapid and irregular rise of the water level and/or major hydrological changes of the Rhône river.

On the adjacent shelf, high-resolution seismic studies (Gensous and Tesson, 1997, 2003; Gensous et al., 1993; Marsset and Bellec, 2002) show that Postglacial deposits comprise prograding units arranged in a retrogradational pattern, constituting parasequences of the Transgressive Systems Tract. The more recent units extend under the delta plain where they are overlaid by the prograding deposits of the Highstand Systems Tract (Fig. 3).

Other Mediterranean deltaic systems like Pô Delta (Amorosi and Marchi, 1999; Amorosi et al., 2004; Bondesan et al., 1995a; Roveri et al., 2001), Ebro delta (Somoza et al., 1998) and Nile delta (Stanley, 1990) show a similar stratigraphic organization: (1) alluvial plain development during the late Quaternary lowstand and the early stages of transgression, (2) formation of a rapidly migrating barrier–lagoon system during the late transgressive phases (8800–6000 years BP), (3) construction and progradation of the delta during the following sea-level highstand (6000–800 years BP), and (4) development of the present-day alluvial plain.

The present study draws from a large set of data stemming from the French geological survey (BRGM). The main goals of this study are: (1) set up an accurate model of the geometry and stratigraphy of the Postglacial sedimentary bodies of the

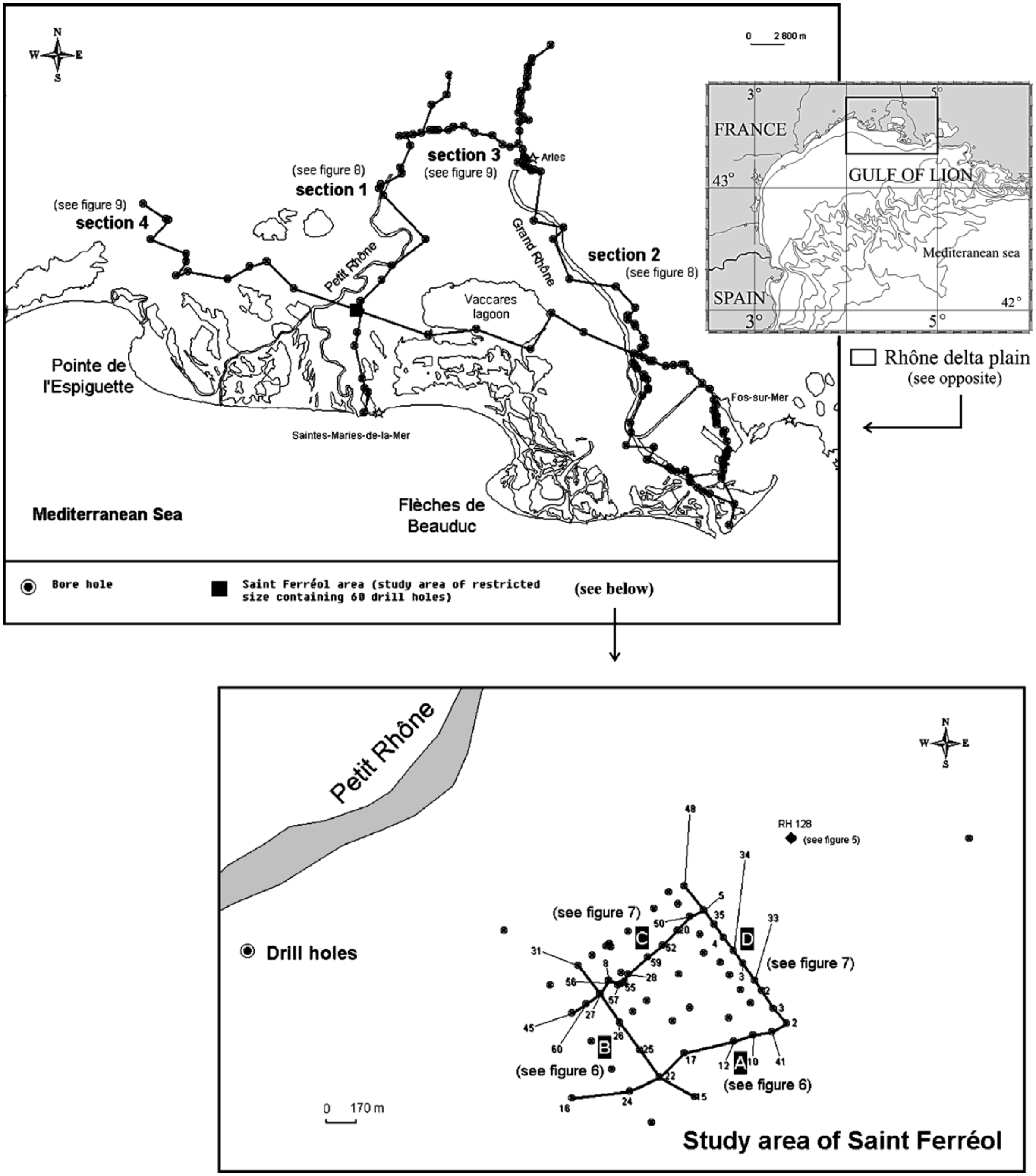

Fig. 1. Location map of the Rhône delta, with position of well logging sections of Figs. 6 and 7 and of the four major sections spread on the whole delta plain presented on Figs. 8 and 9.

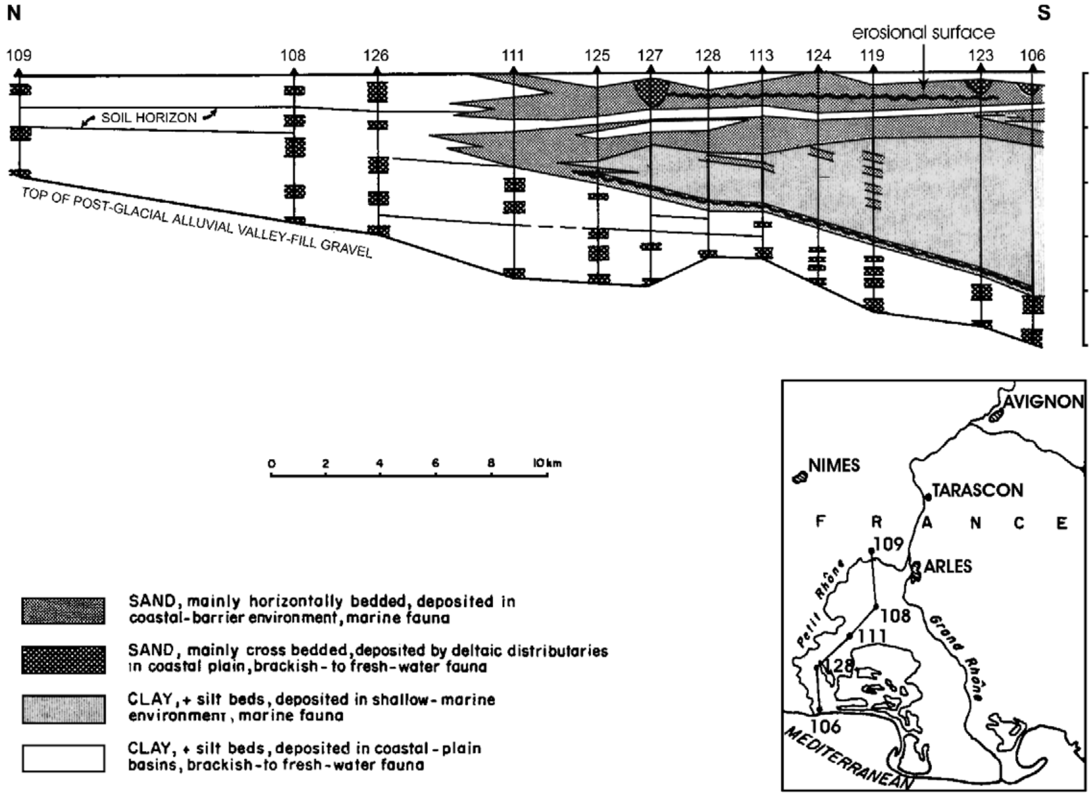

Fig. 2. Lithologic correlations, along a North–South section, in the Rhône Postglacial deltaic complex, from Oomkens (1970) modified. Four major lithofacies, discriminated from a detailed lithologic and faunal analysis are organized into transgressive or regressive depositional units.

delta plain via sequential analysis of core drill sections; and (2) evaluate the main controlling factors and processes (subsidence, eustasy, sediment yield, climate, anthropic influence).

2. Data and methods

Data used for this study come from previous published studies, surface data (geological maps of the BRGM at 1/50,000 and 1/250,000 scale), subsurface data (lithologic and log data) extracted from the BSS (Banque du Sous Sol) French database of the BRGM (Boyer et al., 2003).

A geological synthesis of the Rhône delta area (Fig. 4) has been compiled from available geological maps at 1/250,000 scale (Alabouvette et al., 2001; Rouire et al., 1980, 1979). The main steps in the compilation were to: (1) digitize the geological maps; (2) georeference with the MapInfo Software; (3) digitize the main geological areas.

A detailed study has been conducted on the Saint Ferréol lobe of the delta plain. Data were extracted from a set of about 60 wells, 35–40 m depth, which have been drilled by the Shell Company in 1963. Wells are distributed in a close grid (10th meters spacing) along 4 sections (Fig. 1). Well log data (Gamma ray and resistivity) were stored in the subsurface databank of the BRGM. As these records date from the sixties, the absolute values of the parameters (Gamma ray and resistivity) are not available. The study of these log data is so based on the relative amplitude of the parameters.

Detailed lithologic data are available from some drill holes (Oomkens, 1970) and have been used to calibrate the log data. The methodology was as follows: for each well, log data were digitized and calibrated by correlation with nearby core holes. Key surfaces were

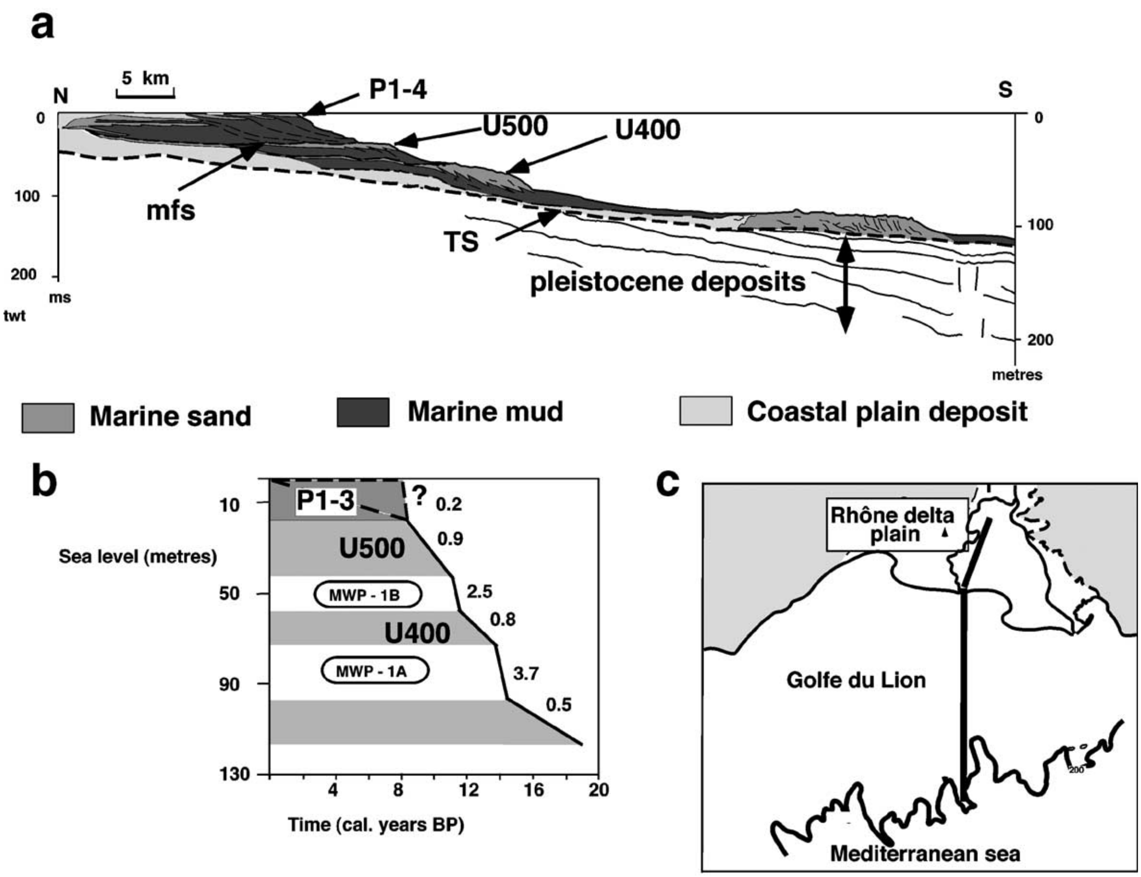

Fig. 3. (a) Line drawing showing the global stratigraphic organization and the lithology of Postglacial deposits, from Gensous and Tesson (1997, 2003) modified. U400, U500: transgressive parasequences; P1–4: highstand parasequences; TS: transgressive surface; mfs: maximum flooding surface. Established from seismic, cores and boreholes data. Note the decreasing sand content from early transgressive to late transgressive and highstand parasequences. (b) Eustatic curve showing the alternating periods of increase and decrease rates of sea level rise (from Bard et al., 1993). Numbers indicate the rate of sea level rise in cm/year. MWP-1A, MWP-1B: periods corresponding to brief periods of accelerated melting (i.e., meltwater pulse, MWP) of continental ice and increased rate of sea level rise (3.7 cm/year and 2.5 cm/year) (from Bard et al., 1996). Transgressive parasequences (U400 and U500) are correlated to periods of reduced rate of sea level rise (0.8 and 0.9 cm/year). (c) Location map of the line drawing.

identified and correlated, and major depositional units were characterized and correlated.

Following, a study at scale of the whole delta plain has been carried out, based on lithologic data of about 3000 drillings distributed all over the delta plain and cutting across Postglacial deposits (Fig. 4). The analysis and correlation of 160 selected drillings (Fig. 1) distributed along 4 major sections (2 orientated N/S and 2 orientated W/E) have been performed in order to get a global insight of the three dimensional stratigraphic organization of the Rhône delta plain infilling.

3. Geological setting

The Rhône delta plain (65 km length, 35 km width) is located in the northern part of the western Mediterranean basin, at the north of the Golfe du Lion (Fig. 1).

It is bounded to the West by the Nîmes fault and to the East by the Salon-Cavaillon fault and seaward by a wide continental shelf. The Nîmes fault is oriented NE–SW and is a major structural trend reaching to the antetriasic basement; it has been active since the early Mesozoic. This fault system, more than 100 km in length, extends seaward into the Golfe du Lion. Pre-

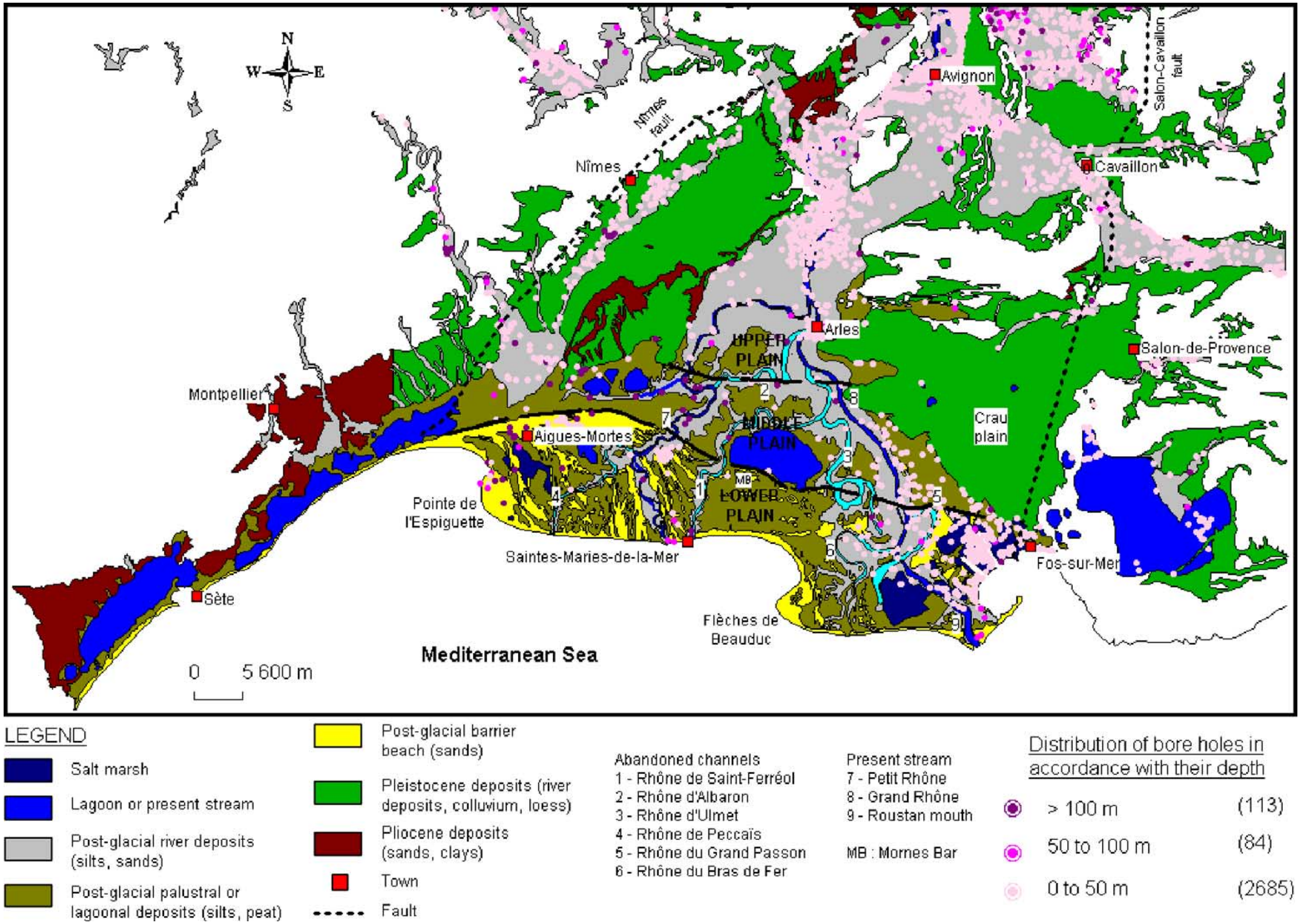

Fig. 4. Map of the depositional environments of the modern Rhône delta and location of bore holes of the BRGM subsurface data bank. It also shows the location of the abandoned channels and the present stream.

sently, the Nîmes fault is a sinistral strike slip fault with a reverse component (Terrier, 2002). The Salon-Cavaillon fault system, orientated NNE–SSW, is inherited from the late Hercynian tectonics. It has an uncertain path and recent studies (Combes, 1984; Terrier, 1991; Peulvast et al., 1998) show that it has been active during the Pleistocene and Holocene with a 1-m lowering of the western compartment.

Subsidence resulting from this recent tectonic activity has been confirmed by archeological data (Arnaud-Fassetta, 2000; Vella and Provansal, 2000; Vella et al., 1998) and long range tide recording (Emery et al., 1988; Suanez et al., 1997).

The Rhône delta is located in a microtidal sea. Coastal currents are wind driven and may be west or east directed. The only long-period waves come from the east to south-east and give rise to a dominant westward littoral drift. Combination of wave dynamics and lateral migration of the distributaries mouths give rise to a rapid shoreline evolution. During the historic period, some parts of the coast have retreated (4–5.5 m/year in front of the Camargue), other areas have prograded (sand spits of Beauduc, Espiguette and La Gracieuse) (L'Homer, 1988).

From the geological synthesis (Fig. 4), five main depositional/geological environments are recognized:

– Coastal system comprises extensive modern and relict coalescing beach ridges and sand spits. In the western part of the delta plain, relict sand ridges are well preserved while in the eastern part, they are partially eroded and/or buried;
– Fluviatile system comprising channels, levees, paleomeanders, cuts the delta plain;
– Lagoons and ponds isolated between distributaries and beach ridges;
– Pleistocene deposits, with relict fluviatile deposits, loess and screes, are mostly located at the edges of the delta plain;
– Pliocene deposits outcropping at the western end of the delta plain.

From North to South, the delta plain can be divided into three parts:

– The Upper plain, located in the northern part, where the Rhône valley opens out. Fluviatile deposits (crevasse, point bars, levee) of the Rhône river dominate the morphology.
– The Middle plain is a mixed environment with fluviatile deposits forming elongate sand bodies with meanders pattern isolating freshwater to brackish water ponds. The modern Rhône river divides into two main active distributaries (Grand Rhône and Petit Rhône) delimiting a main swamp area ("Camargue") with an extensive lake ("étang du Vaccares").
– The Lower plain comprises delta front and barrier beach deposits. They are arranged in an extensive pattern of abandoned and active beach ridges enclosing highly saline backbarrier lagoons. They are dissected by abandoned and active distributaries. Prodelta systems develop in front of the main distributaries.

4. Results

4.1. Lithofacies and depositional model

A detailed stratigraphic analysis was performed on a restricted area (Saint Ferréol area) using data from a close grid (10th meters spacing) of 60 drillings distributed along 4 sections (Fig. 1).

4.1.1. Correlation of lithofacies and well logfacies

Log data (Gamma ray and resistivity) have been correlated with a core drilling, located near the boring studied, on which Oomkens (1970) performed a detailed lithologic and faunical analysis (Fig. 5).

Seven main lithofacies and correlative logfacies are identified from base to top:

1. Basal Pleistocene gravels with very high resistivity values and low gamma ray values. They are capped by an erosional surface sometimes overlain by a thin (decimetric) coarse grained lag deposit showing very high resistivity values (reworking of heavy minerals coming from the erosion of the next crystalline blocks?).
2. Lower postglacial clay and silt deposits with brackish to fresh water fauna and containing abundant plant detritus. They are characterized by medium values of gamma ray and resistivity.

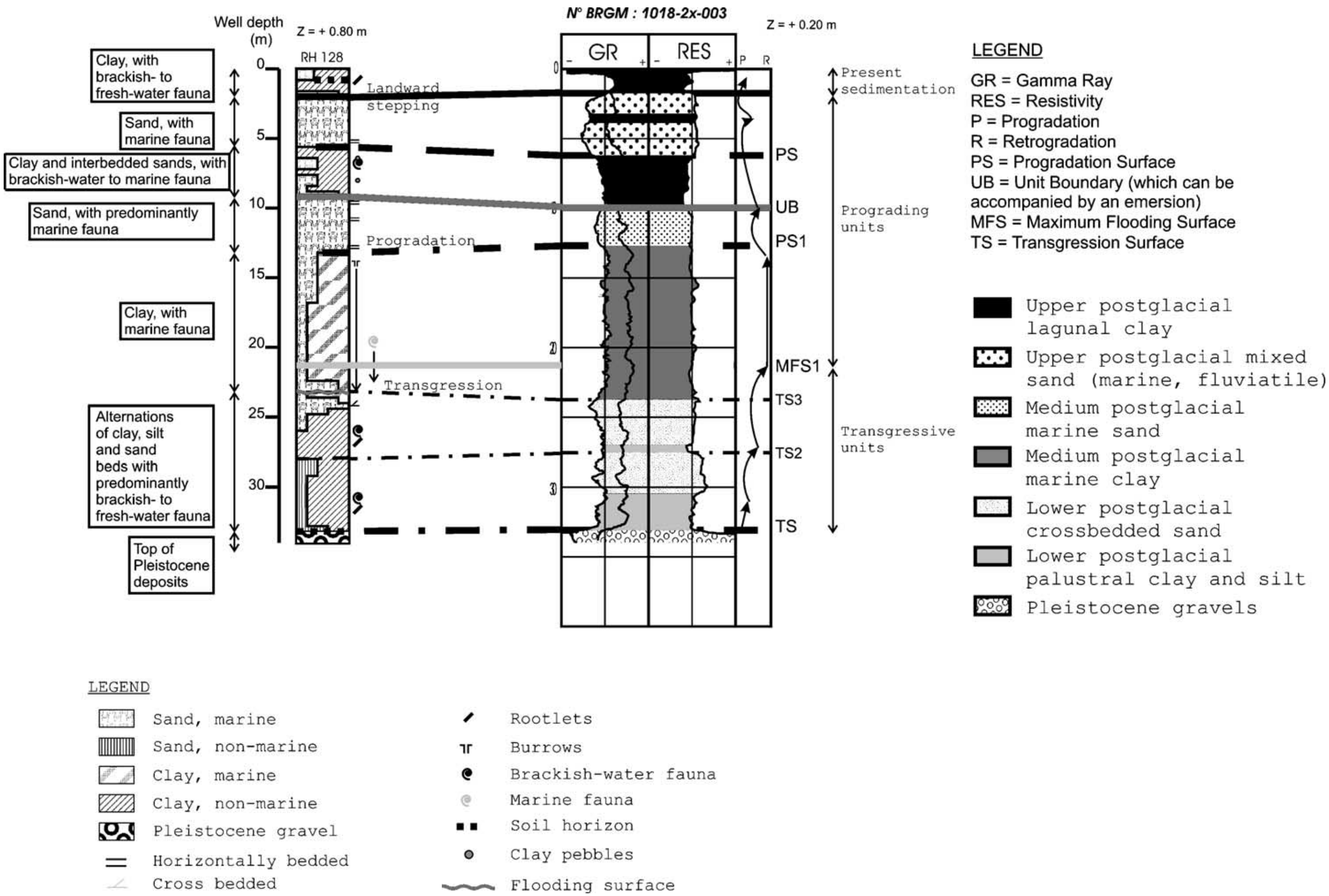

Fig. 5. Calibration of well logging data by the core drilling RH 128 from Oomkens (1970). See location on Fig. 1. This calibration allows us to identify, on log data, seven main lithofacies and four main kinds of key surfaces.

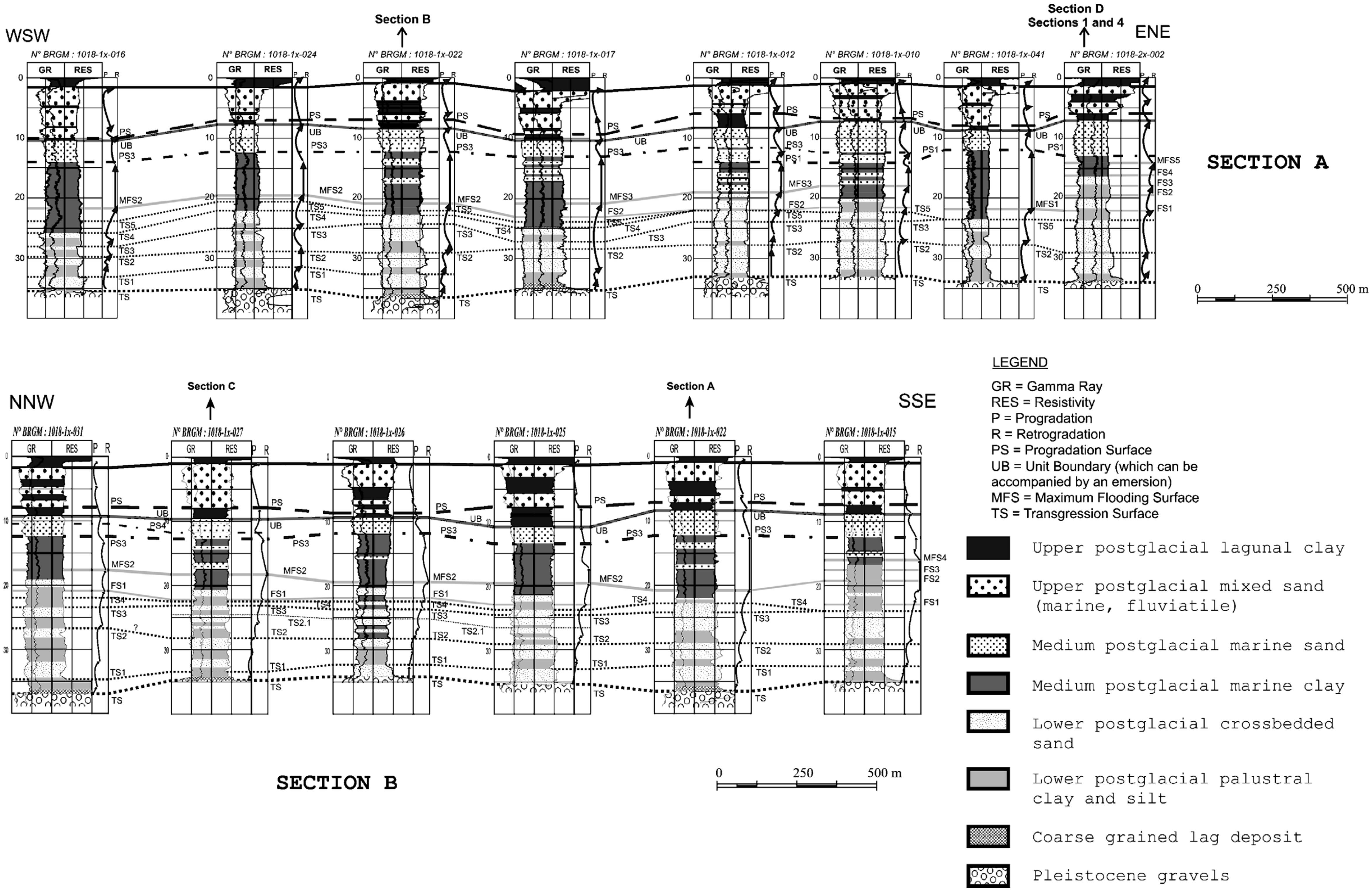

Fig. 6. High resolution correlations in the Saint-Ferréol lobe (Sections A and B) from log data, showing the good correlation of lithofacies and key surfaces at a restricted area scale: spacing of the wells is about tenth meters and the area of the studied box is about 1.5 km^2. See location on Fig. 1.

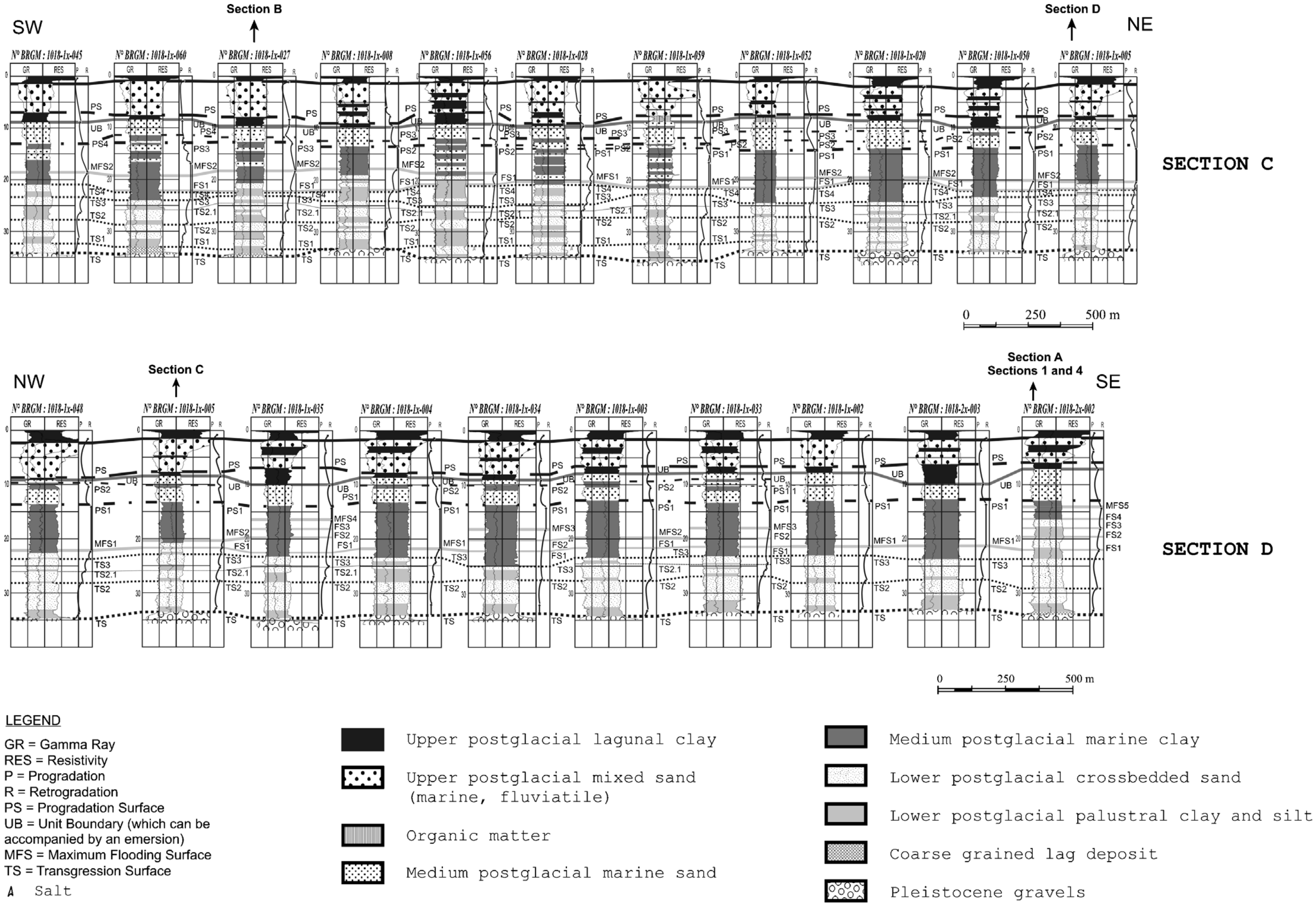

Fig. 7. High resolution correlations in the Saint-Ferréol lobe (sections C and D) from log data, showing the good correlation of lithofacies and key surfaces at a restricted area scale: spacing of the wells is about tenth meters and the area of the studied box is about 1.5 km^2. See location on Fig. 1.

3. Lower postglacial crossbedded sand layers interbedded in the lower postglacial clays. They show medium to high resistivity values and medium to low gamma ray values.
4. Medium postglacial marine clay with high gamma ray values decreasing upward (lithologic coarsening upward trend).
5. Medium postglacial marine sand well sorted and horizontally bedded deposited in beach barrier environment. Log data show very low gamma ray values and high resistivity values.
6. Upper postglacial mixed sand (marine, fluviatile) resulting from the migration and/or breaching of distributaries with low gamma ray values and high resistivity values.
7. Upper postglacial clay deposited in modern lagoonal areas. They are characterized by high to medium gamma ray values and low to medium resistivity values. Organic rich layers (peat layers or soil horizons) are sometimes interbedded in these upper clay deposits. They are characterized by very high gamma ray values.

Four main kinds of surfaces marked by abrupt variations of the log values are identified:

– Erosional transgressive surfaces (TS), between 25 and 35 m depth, located at the top of lower crossbedded sand layers. They indicate a deepening of the environment (increase of gamma ray values and decrease of resistivity values). They are the result of phases of transgression. The main one, located at the top of Pleistocene deposits, marks the beginning of the postglacial eustatic sea level rise.
– Several flooding surfaces (FS) are identified in marine mud between 10 and 25 m depth. They are marked by maxima of radioactivity and minima of resistivity. They are correlated with enriched shell layers. Among them is probably the maximum flooding surface (MFS) which marks the transition to upper coarsening deposits.
– Progradation surfaces (PS) located between 5 and 15 m depth at the boundary between marine sands and marine clays (decrease of gamma ray values and increase of resistivity values).
– Units boundaries surfaces (UB), around 10 m depth, are erosional and separate prograding units.

4.1.2. Main depositional systems

From logfacies and lithofacies analysis, the Postglacial sedimentary section may be subdivided into two main members which are separated by the maximum flooding surface:

– A lower member, above the Pleistocene alluvial fill, composed of clay and silt deposits with brackish to freshwater fauna and interbedded sand layers. They correspond to coastal plain and back-barrier deposits.
– An upper member of marine deposits developed above the maximum flooding surface. The lower part consists of burrowed clays with marine fauna; the upper part coarsens upward and grades into well sorted horizontally bedded sands interpreted as a coastal barrier environment. The uppermost part is formed by modern continental deposits.

The good correlation of key surfaces and genetic units, along the four chosen sections, is obvious in Figs. 6 and 7.

4.2. Large scale architecture

The findings obtained from the stratigraphic analysis of the Saint Ferréol area have been used to carry out the analysis of 160 wells distributed on 4 major sections spread on the whole delta plain (Fig. 1). The stratigraphic correlations provide a basis to construct a large-scale architecture of Postglacial delta plain deposits.

Sections 1 and 2 extend roughly North–South along the Petit Rhône and the Grand Rhône courses, respectively. Sections 3 and 4 are transverse and respectively located in the upper part and the lower part of the delta plain.

Section 1 stretches along the Petit Rhône path in the western part of the delta plain (Fig. 8). Postglacial deposits rest on Pleistocene gravels through a very irregular surface with incisions inherited from the previous lowstand period.

In the upstream part of the section (upper delta plain) drillings cut across coastal plain, fluviatile and palustral facies. Deposits are generally fine grained with some sandy beds (channel incisions) and soils horizons.

In the downstream part, the section comprises two members separated by the maximum flooding surface:

– A lower part of coastal plain deposits organized into four units (T1–T4) arranged in a retrograding pattern. The top is truncated by an erosional surface which progressively deepens seaward.
– An upper part of marine deposits coarsening upward. The basal deposits consist of marine clays thickening in a seaward direction. They grade upwards to marine sands. This wedge of marine deposits is organized into four units (P1–P4) arranged in a prograding pattern. Uppermost deposits are coastal plain and lagoonal deposits of the modern delta plain. The more recent unit P4 crops out at the coast and is expressed as the modern coastal ridge. It is approximately dated between 2950 ± 40 years BP and 2420 ± 50 years BP from North to South (Vella et al., this volume).

Section 2 is orientated North–South and spreads in the eastern part of the delta plain along the Grand Rhône distributary. It shows the same stratigraphic organization pattern as Section 1 that is a lower member of coastal plain deposits (T1–T4) and an upper wedge of marine deposits (P2–P5) thickening shelfward (Fig. 8). The basal transgressive surface is distorted and this distortion also affects underlying Pliocene deposits. Lateral correlation with Section 1 indicates that in this sector the prograding unit P1 is absent but a more recent prograding unit P5 develops at the present coastline. Moreover, on the map, the Northern limit of sandy barriers beach corresponds to the limit between prograding units P2 and P3. This is also visible on Section 1.

Section 3, orientated East–West, is located in the upper delta plain. From base to top, drillings cut across Pliocene deposits, Pleistocene gravel and Postglacial nonmarine deposits (Fig. 9). The latter member shows several channel incisions at different levels, the uppermost corresponding to the modern Rhône river. This alternates with aggradation periods in palustral facies.

Section 4, orientated East–West, is located in the lower delta plain. It crosses the lower units T1–T4 (Fig. 9). In the central part of the section, only the upper units P2 and P3 are visible (P1 is located upstream and P4 is located downstream). In the eastern part, units P2–P5 are visible. From chronological data performed on the upper units close to the well 1018-2x-007 (Arnaud-Fassetta, 2000), the units P2 and P3 are dated respectively at 4500 BC (5700 Y^{14}C) and 2500 BC (4054 Y^{14}C). From Vella et al. (this volume), the unit P3 which corresponds to the Mornès bar (see location on Fig. 4) is dated 4035 ± 55 years BP on the internal part of the bar. This is consistent with Arnaud-Fassetta's dating.

4.3. Correlations with marine data

On the shelf, seaward of the delta plain, Postglacial deposits are organized in a set of prograding units arranged in a retrograding pattern. The more recent units are located on the inner shelf (Labaune et al., 2005). A correlation has been tentatively performed between seismic data on the shelf and core drilling data on the delta plain. Two seismic lines orientated North–South cutting across the shelf have been joined with the two main delta plain sections 1 and 2 (Fig. 10). The resulting synthetic sections show that the lower coastal plain deposits of the delta plain join up with units U400 and U500 identified on the shelf. The upper member of marine deposits and more precisely units P4 and P5 correlate with adjacent prograding units (U600 and U610) that develop off the present Rhône river mouth (Labaune et al., 2005).

5. Interpretation and discussion

5.1. Sequence stratigraphic organization

Stratigraphic analysis of lithologic and well logging data of the Rhône delta plain allows to conclude the following:

–The retrogradational units (T1–T4), made of coastal plain deposits, are interpreted as trangressive parasequences deposited during slowing down or stabilization phases of sea level rise alternating with periods of fast transgressions.

Units T2 and T3, respectively, correlate with the parasequences of the Transgressive Systems Tracts (U400, U500) recognized on the adjacent continental shelf (Labaune et al., 2005).

The surface capping the transgressive units is the maximum flooding surface resulting from the final inland migration of the shoreline and the submergence

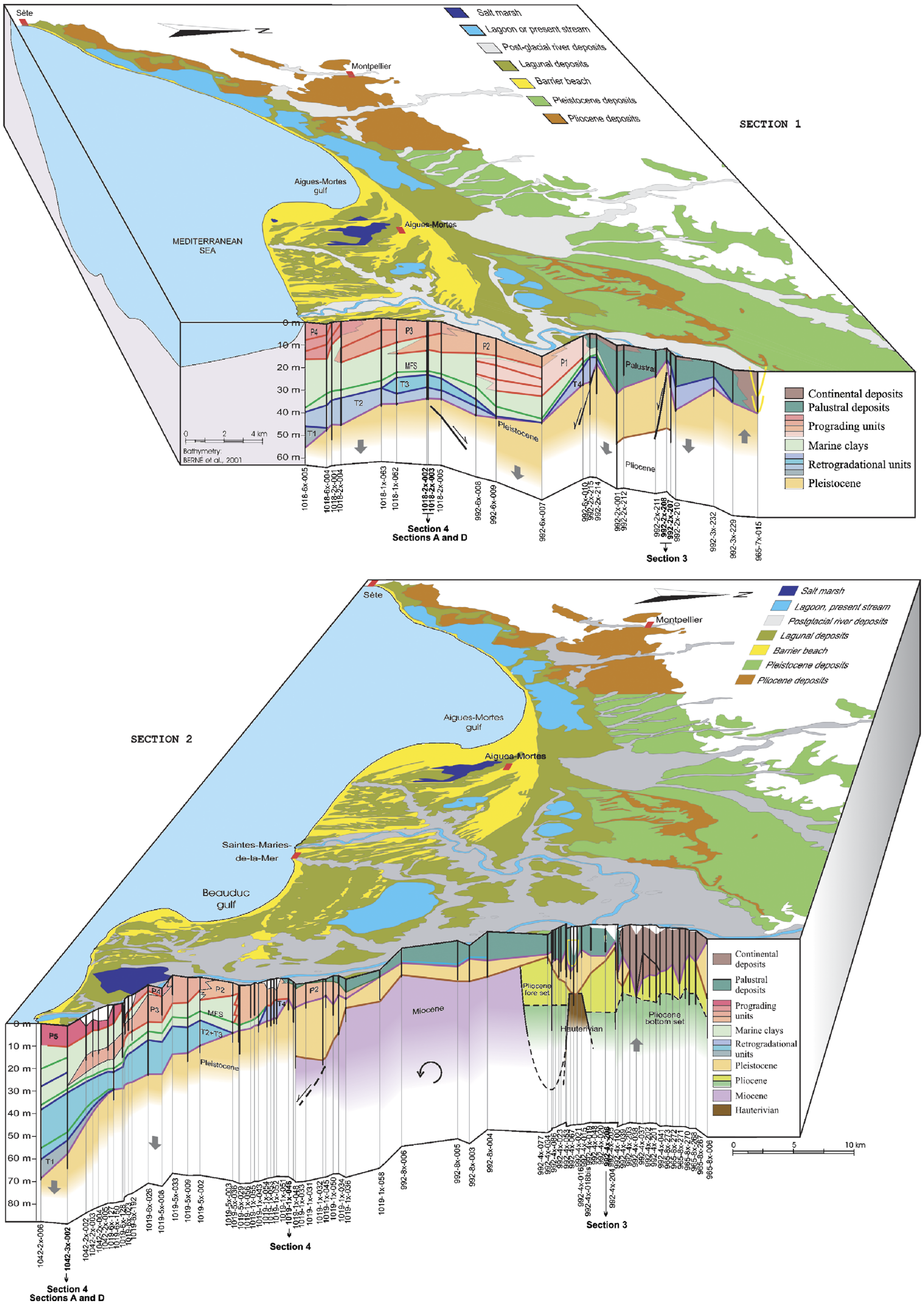

Fig. 8. Blocks diagrams made from the map of the geological domains of the Rhône delta and from the lithologic data along the Sections 1 and 2. In the upstream part of the sections, drillings cut across coastal plain, fluviatile and palustral facies. In the downstream part, the sections comprise two members separated by the maximum flooding surface: a lower part consists of coastal plain deposits organized into four units upward coarsening (T1–T4) and arranged in a retrograding pattern; an upper part of marine deposits coarsening upward and organized into five units (P1–P5) arranged in a prograding pattern. Bathymetry from Berné et al. (2001).

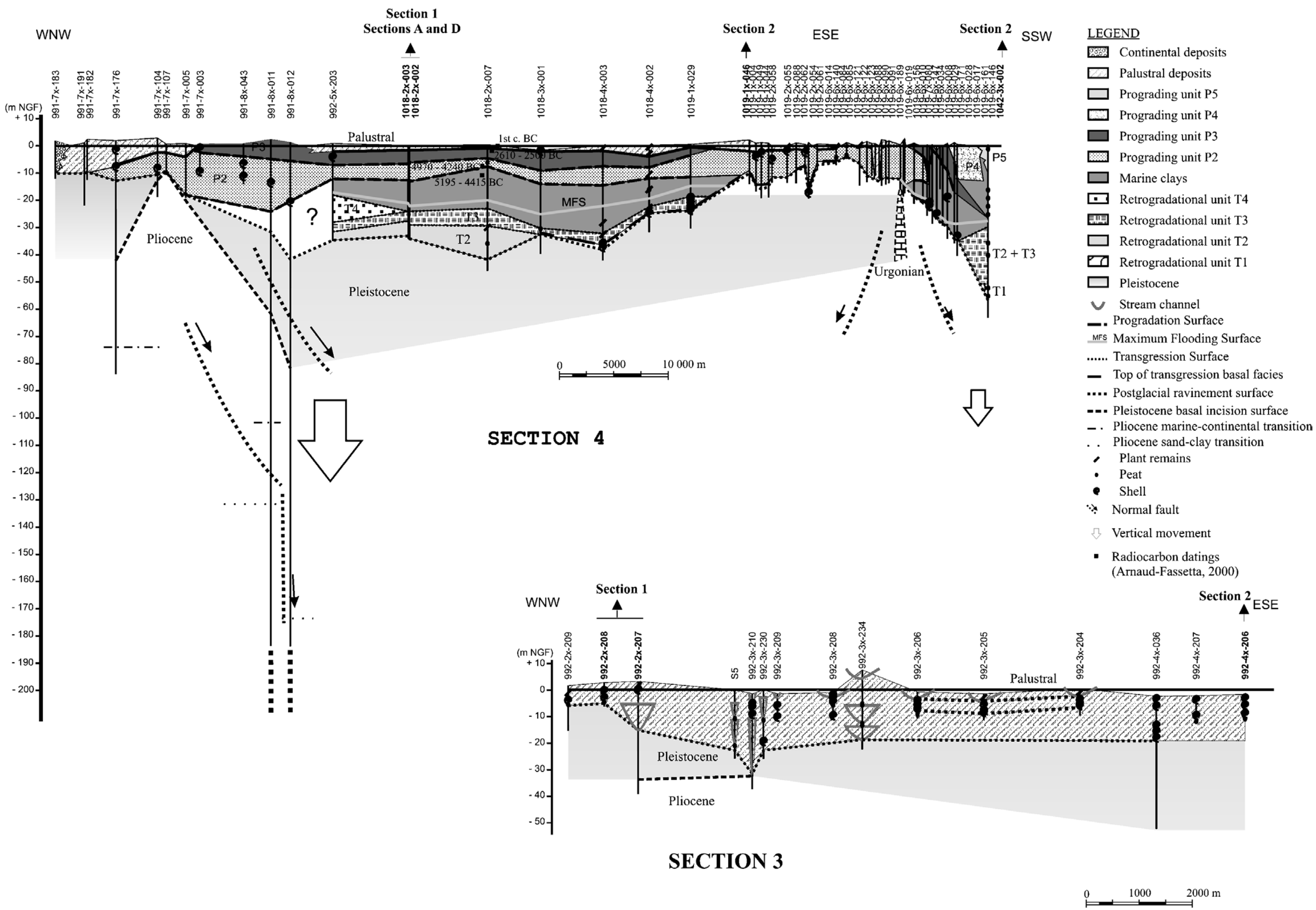

Fig. 9. East–West transverse sections through the upper delta plain (Section 3) and the lower delta plain (Section 4). See location on Fig. 1. On Section 3, from base to top, drillings cut across Pliocene deposits, Pleistocene gravel and Postglacial non marine deposits. Section 4 crosses the lower units T1–T4 and the upper units P2 and P3.

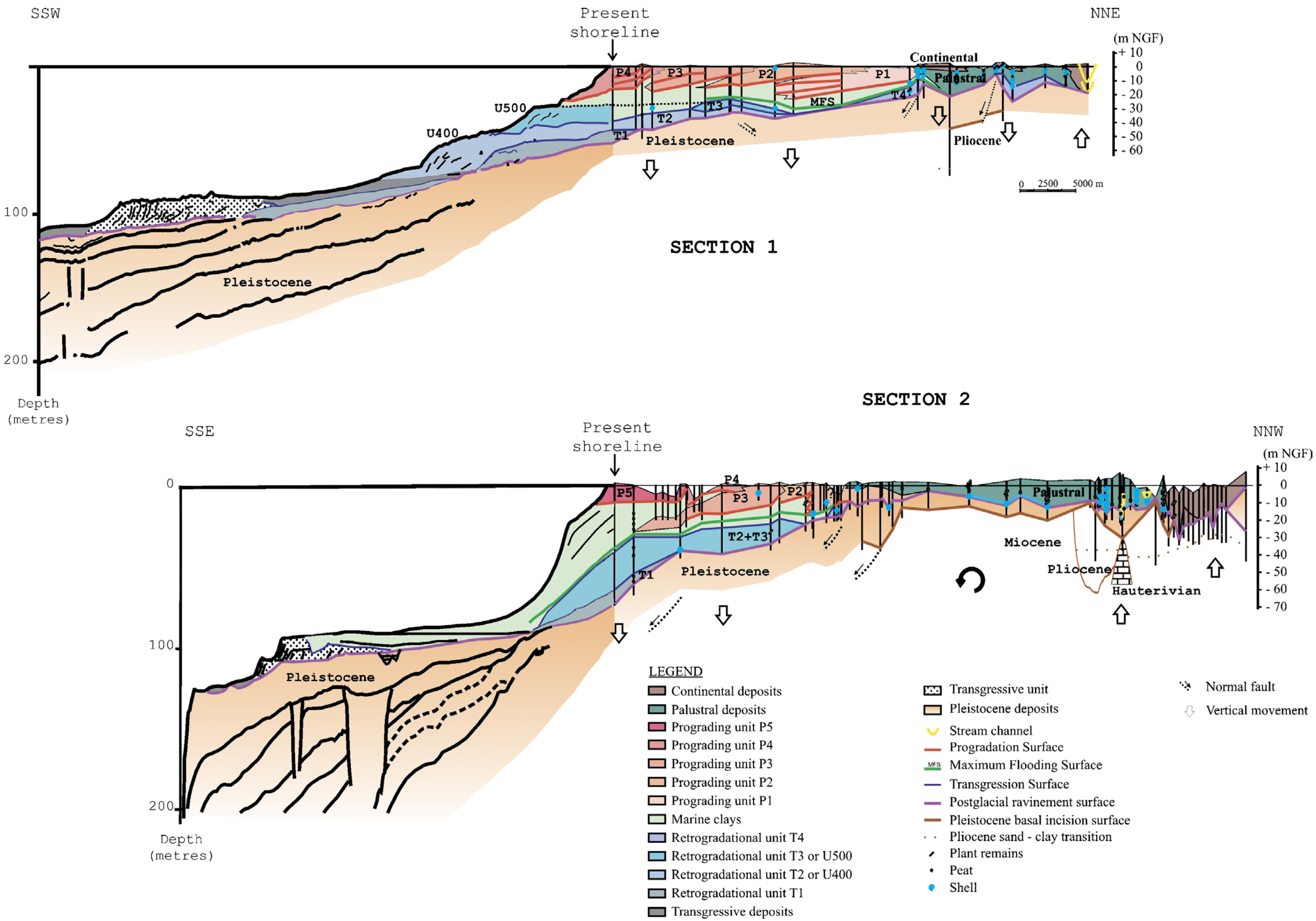

Fig. 10. Onshore–offshore correlations between two seismic lines orientated North–South cutting across the shelf and the two main delta plain Sections 1 and 2. The lower coastal plain deposits of the delta plain join up with units U400 and U500 identified on the shelf. The upper member of marine deposits and more precisely units P4 and P5 correlate with adjacent prograding units (U600 and U610, from Labaune et al., 2005) that develop off the present Rhône river mouth.

of the late transgressive parasequences. It marks the transition between the end of the Postglacial transgressive period and the beginning of a phase of general progradation.

–The progradational units (P1–P5) constitute a wedge of marine deposits thickening seaward and representing parasequences of the Highstand Systems Tracts which have prograded onto the late transgressive deposits (described above) since the period of reduced rate of sea level rise at the end of the Holocene.

The oldest units P1 and P2 are correlated with Saint-Ferréol lobe (see location on Fig. 4); the more recent ones which prograde in the eastern part of the delta plain are tentatively correlated with the Bras de Fer lobe (P4) and the presently active Roustan lobe (P5), and their marine correlative units U600 and U610 (Labaune et al., 2005).

This general scheme of stratigraphic organization is the same as the one of other Mediterranean deltas.

For example in the Po Plain (Amorosi et al., 2004), basal Postglacial deposits are characterized by a retrogradational stacking pattern of coastal plain and littoral facies (transgressive systems tract), reflecting invariably the landward migration of a barrier–lagoon–estuary system during the late transgressive phases (8800–6000 years BP) (Amorosi and Marchi, 1999). These retrogradational units are also observed in the Gulf of Cadiz continental shelf (Lobo et al., 2001), in the central Tyrrhenian continental shelf (Tortora, 1996) or in the Ebro delta (Somoza et al., 1998).

Above, in the Po Plain (Amorosi et al., 2004) or in the Ebro delta (Somoza et al., 1998), highstand deposition was characterized by extensive progradation of the delta and the strandplain from 6000 BP (Amorosi and Marchi, 1999).

The general stratigraphic organization is in the first place related to the glacio-eustatic changes that occurred at the end of the Holocene. Nevertheless, other factors may have interacted with eustasy and partly influenced the stacking pattern geometry and properties of Postglacial deposits parasequences.

5.2. Eustasy

The pattern of last deglaciation is characterized by steps with high rate of sea level rise corresponding to massive input of freshwater derived from melting continental ice (meltwater pulses) superimposed on sea level rise (Bard et al., 1996). The transgressive parasequences (U400/T2 and U500/T3), spreading on the inner shelf and on delta plain, are correlated with the intervals of slower eustatic rise (Fig. 3b) indicating that glacio-eustatic change is the main controlling factor for the preservation of the transgressive units deposits (Berné et al., 2003; Gensous and Tesson, 2003; Labaune et al., 2005).

Postglacial transgression ends at the Late Holocene with a final retreat of the shoreline up to 15 km landward of the present coastline up to the northern edge of the Vacarres lake (unit T4). Subsequently, occurred a period of reduced rate of relative sea level rise during which uppermost deposits of the Rhône delta plain have globally prograded seaward and built several major delta complexes (highstand parasequences P1–P5/U610).

However, the precise pattern of eustatic changes during this period is still in debate.

Lambeck and Bard (2000) joining observations with glacio-hydroisostatic models conclude that Holocene sea level along the Cote d'Azur and Golfe du Lion has never exceeded the present level.

But other studies from different areas of the western Mediterranean sea (Barra et al., 1999; Dalongeville et al., 1980; Dubar, 1987; Fuchey and Le Strat, 2001; Ozer, 1977; Pirazzoli, 1998) demonstrate a highstand sea level around 6000 BP, a sea level drop between 6000 and 4500 BP, then a constant sea level until today. This phenomenon has also been recorded and dated in the Atlantic ocean: we can quote the works of Decker et al. (2001) on the Rochefort marsh and the works of L'Homer et al. (1999) on the Mont Saint-Michel bay.

In the lower valley of the Herault river, west of Cap d'Agde, in a stable tectonic context, marine deposits (sands with marine shells) attributed to late Holocene highstand are found at an altitude of between 4 and 5 m (Fuchey and Le Strat, 2001). So, the general progradation, from 4500 BP (depositing of units P1–P5), would be caused by periods of sea level fall (from an altitude of 4 m to an altitude of 0 m).

5.3. Climate and sediment supply

The climate controls precipitation intensity and the nature of the vegetation cover thus it controls the river regime and the rate of sediment supply.

During the early Holocene period, the formation of transgressive units (T1–T4) may be related to short time scale climatic changes that caused at once periods of reduced rates of sea-level rise and high rates of terrigenous supply (Amorosi et al., 2004; Lobo et al., 2001). The most well-known example is the Younger Dryas period, correlated on shelf with unit U400 (Berné et al., 2003). Other similar events may have occurred during the Holocene like the 8200-year cold event (von Grafenstein et al., 1998).

This hypothesis is confirmed by onshore studies of the palaeohydrological records (Magny et al., 2002), in the western Mediterranean region, indicating that the period from 12000 to 6500 years BP was punctuated by detritic crises related to climate deterioration and marked by major sediment accumulation in valley floors and major sediment supply.

On the other hand, during periods of accelerated sea-level rise, flooding and/or transgressive surfaces were preferentially developed.

Regarding the late Holocene, because of the reduced rate of sea level rise, the variations of sediment supply have a prevailing effect on sedimentary evolution. Studies of the paleohydrology of the Rhône delta (Arnaud-Fassetta, 2000, 2002; Arnaud-Fassetta and Provansal, 1999; Vella et al., this volume) indicate that a total of four major hydrologic phases occurred between 5800 and 3800 years BP, between 2500 and 2400 years BP, between 1st century BC and 2nd century AD (beginning of the Roman Antiquity) and during the little Ice Age (second part of the 17th and beginning of the 18th centuries). They were characterized by abundant water and sediment discharge, aggradation of the floodplain, development of the deltaic lobes and progradation of the coastline. The two first hydrological changes are correlated with the progradation of the lobe of Saint Ferréol (units P1 and P2). The Rhône d'Ulmet (unit P3) prograded during the Roman period (between 5780 ± 40 BP and the medieval period when it is closed artificially in 1440; Rossiaud, 1994) and the Rhône du Bras de Fer (unit P4) during the Little Ice Age (between 1587 and 1711; Colomb et al., 1975; Rossiaud, 1994). This latter event is also recorded in the Ebro delta (Somoza et al., 1998) and particularly in the Po delta (Cattaneo et al., 2003) where a major phase of progradation is recorded during the Little Ice Age.

During the last 150 years, the changes in the paleohydrology of the Rhône river have been induced by climatic changes but have been intensified by human disturbances at the Rhône catchment scale (Arnaud-Fassetta, 2002). The main disturbances are the channel sediment mining and dredging, and the construction of numerous dams (19 on the Rhône river) that severely reduced the sediment load downstream. Moreover, the Rhône channelization facilitated sediment transport to the coastal system and causes a bypass phenomenon on the alluvial plain (Roveri et al., 2001). Most of the sediment eroded downstream of the dams made its way down to the prodelta (no-mobility zone), and increased a sedimentary deficit in the coastline. The consequences of anthropic activities are, on the one hand, the chronic deficit of river drifts and on the other hand a proportion of fine particles more and more important in these deposits.

The influence of sediment supply in the building of a delta appears at other deltas scale like the Ganges-Brahmaputra delta (Goodbred et al., 2003). In this delta, sediment supply is a major control on deltaic processes. Variation in the timing or magnitude of that sediment pulse, relative to sea-level rise, led to considerable changes in the subaerial extent of the delta and the proportional dominance of alluvial and marine facies within the sequence.

5.4. Subsidence

The subsidence in the western part of the Golfe du Lion is estimated at a rate of 250 m/My during the Pleistocene period on the center of the continental shelf (Rabineau, 2001) and is active since the lower Pliocene with an increase during the upper Pliocene–lower Pleistocene period (Duvail et al., 2002, 2005).

The comparison of sea level changes (based on dating of peat beds) between the eastern part of the Rhône delta plain and the rocky coast to the east of Marseille indicates a negative difference of between 1.5 and 0.5 m, then a rapid adjustment after 2120 BP (Vella and Provansal, 2000). The authors suggest that tecto-subsident movements account for these differences, as well as the rapid rise in relative sea-level during the subsequent period between 2120 and 1200 BP. This is compatible with the network of post-Miocene faults that account for the differences in altitude of the Roman quarries carved-out from the Miocene layers (Vella and Provansal, 2000).

From archeological data (Arnaud-Fassetta, 2000; Vella and Provansal, 2000; Vella et al., 1998) and long range tide recording (Emery et al., 1988; Suanez et al., 1997), subsidence rates in the Rhône delta plain (between 0.1 and 1.4 mm/year) are lower than rates of other Mediterranean deltas: 7.3 mm/year for the Pô delta (Bondesan et al., 1995b), 4.8 mm/year for the Nile delta (Stanley, 1990).

Locally, the morphology of units and key surfaces, deduced from well log data, suggests the possibility that subsidence took place:

– On section A (Fig. 6), transgressive surfaces 3 and 4 (TS3 and TS4) disappear upstream (towards the North–East), where they are truncated by a more recent transgressive surface (TS5). This may be a first indication of the delta tilting which is in accordance with the global trend of tilting observed during the Pleistocene time scale (Tesson and Allen, 1995).
– In the area of Saint Ferréol, well log data indicate that the maximum flooding surface is a composite surface. On section D (Fig. 7), according to the wells, the maximum flooding surface corresponds to the surfaces FS1, FS2, FS3, FS4 or FS5, indicating a lateral migration of the depocenters (deltaic lobes) controlled by local subsidence.
– On section C (Fig. 7), progradation surfaces PS3 and PS4 are only preserved in distal area (towards the South–West). They are eroded in proximal area. This may imply a seaward subsidence of the studied domain.

At the delta plain scale, evidence of subsidence is also observed on the four long profiles:

– On Section 1 (Fig. 8), the unit P1 which is 15 m thick between wells 992-6x-008 and 992-6x-007 shows at once aggradation and progradation. This pattern of the sedimentary record is the result of the local increase of available space thanks to differential subsidence movements. At the same place, transgressive units T3 and T4 are tilted northward and southward respectively as the transgressive surfaces deepen. These movements are still attributed to differential subsidence.
– On Section 4 (Fig. 9), the deformation of key surfaces (Pliocene marine–continental transition, Pliocene sand–clay transition) is also attributed to differential subsidence.

5.5. To sum up

Today, all these parameters work in a negative way for the coastline. Indeed, subsidence is still recorded, sediment supply is very low, climate shows a global warming so sea level rises. The natural parameters couldn't induce such disturbances because they evolve at the geological speed following well known terrestrial cycles. It's only because of the phenomena acceleration caused by anthropism that we attend this evolution. Thus, the natural millennial global signal is progradation, but the anthropic century-old signal is retrogradation. The maximal prograding evolution before the anthropic retrograding evolution until today is recorded by barriers beach, next to Montpellier (Ambert, 2004) which had a more distal position in 1780 than today, or in front of the Saint Ferréol lobe (Vella et al., this volume) which had a more distal position in 2000 BP than today.

This subject here is approached in an original way, thanks to the use of onshore well logging sections, in Postglacial prisms. The analysis, using sequence and genetic stratigraphy, of these well logs permits to decompose a part of the sedimentary message. The approach by well logging measurements on the Postglacial prism is the only one which permits the elaboration of a quantified genetic model. This genetic model, with a very fine mesh, is the first stone to extrapolate the correlations at the Rhône delta subsurface scale. It is also important in the analysis of onshore–offshore correlations where it brings a naturalistic calibration.

6. Conclusions

Postglacial deposits of the Rhône delta plain have been studied thanks to well logging of the French BRGM subsurface data bank, calibrated by lithologic data.

The analysis of sections at the whole delta scale permits to distinguish, from base to top, a retrogradational stacking pattern, materialized by four transgressive units, and a prograding stacking pattern constituted in distal position by five deltaic lobes and in proximal position, by an alternance of incision periods and of aggradation of palustral and continental deposits periods. These two stacking patterns are the onshore extension of those already observed offshore on seismic profiles.

This stratigraphic organization results of the interaction between global eustatic variations and sediment supply, both under control of climatic changes. During the late Holocene, because of the reduced rate of sea level variations, sediment supply has a prevailing effect on sedimentary evolution. From 150 years, the changes in the paleohydrology of the Rhône river have been intensified by anthropic activities.

Another important controlling factor is subsidence. It is expressed on well logging sections by the geographic variation of depocenters, and on long profiles by the aggradation of globally prograding units, by the tilting of transgressive units, and by the deformation of Pliocene key surfaces. These movements are in agreement with the continental margin tilting already observed in other areas of the Golfe du Lion.

Acknowledgements

This work is a contribution to the French National GDR Marges program, workshop Gulf of Lion. We thank the Eurodelta Concerted Action for their invitation.

We wish to thank M. E. Field and S. L. Kuehl for their review and comments, which greatly improved the manuscript, and M. Rabineau for her advices.

Thanks are extended to BRGM, at Montpellier and Orléans (this work is part of the BRGM geological referential program) and the BDSI (Perpignan) for the putting in common of their data and their savoir-faire in sedimentology of coastal domains, deltas and onshore–offshore transitions. This work is an example of collaboration between organizations, on onshore–offshore transitions in recent deposits.

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