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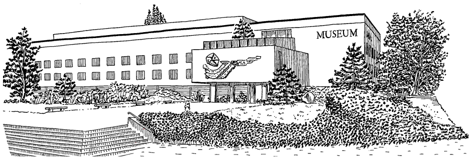

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Epi-bathyal ostracod assemblage in Holocene Rhone deltaic sediments (Gulf of Lions, NW Mediterranean) and their palaeoecological implications

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Abstract

Since the Last Glacial Maximum, the Rhone River, which is the most important source of freshwater and sediment to the western Mediterranean Sea, migrated in a north-westward direction during the rapid Deglacial and Early Holocene sea-level rise. During the phase of global high sea-level (Middle and Late Holocene), an overall eastward migration of the Rhone outlet, under natural and/or human influence, is recorded through several sediment accumulations confined along the inner shelf in the form of deltaic lobes. These lobes that make up the whole Rhone subaqueous delta represent very expanded sedimentary archives of the Rhone Holocene history.

In this paper, using three long piston cores retrieved from the most recent Bras de Fer (RHS-KS55) and Roustan (RHS-KS22 and RHS-KS57) deltaic lobes, at water depth ranging from 43 m to 79 m, we analyze the distribution of the Rhone ostracod assemblages during the Holocene. Our study highlighted the presence of epi-bathyal ostracods belonging to the genus *Argilloecia*, *Cytheropteron* and *Krithe* in shallow water deltaic sediments. Close to the Rhone River mouth, the presence of these full-marine ostracods is limited because of well-marked fluvial influence, whereas the occurrence of *Argilloecia* spp., *C. rotundatum*, *K. compressa* and *K. pernoides* increases with increasing distance from the river mouth. Thus, we hypothesize that *C. rotundatum*, *K. compressa*, and especially *Argilloecia* spp. might be more tolerant to higher fluvial influence than *K. pernoides*, which is only observed in the distal part of the Rhone River influence. Environment-related parameters (such as fresh-water and sediment input from the Rhone River, food supply, and dissolved oxygen) other than bathymetry are thought to have a major role in the development of these full-marine ostracods at the studied site.

Keywords

Ostracoda, subaqueous delta, palaeoecology, Holocene, western Mediterranean.

Résumé

Distribution des assemblages d'ostracodes appartenant au domaine épi-bathyal dans les sédiments holocènes deltaïques du Rhône (Golfe du Lion, NO de la Méditerranée) et leurs implications paléoécologiques.- Depuis le Dernier Maximum Glaciaire, le Rhône, qui représente la source la plus importante d'eau douce et de sédiments en Méditerranée occidentale, a migré progressivement vers le nord-ouest en réponse à la remontée rapide du niveau de la mer au cours de la déglaciation et de l'Holocène inférieur. Suite à la stabilisation du niveau de la mer et à l'établissement d'un haut niveau marin au cours de l'Holocène moyen et supérieur, la migration naturelle et/ou anthropique de l'embouchure du Rhône vers l'est a conduit à l'accumulation de plusieurs unités sédimentaires confinées au niveau de la plateforme interne sous la forme de lobes deltaïques. Ces lobes, constitutifs du delta sous-marin du Rhône, donnent accès à d'épaisses séries sédimentaires renfermant l'histoire holocène du Rhône.

A travers l'étude de trois carottes sédimentaires prélevées à des profondeurs d'eau comprises entre 43 m et 79 m au niveau des lobes deltaïques récents du Bras de Fer (RHS-KS55) et de Roustan (RHS-KS22 et RHS-KS57), nous analysons, dans ce papier, la distribution des assemblages d'ostracodes au cours de l'Holocène. Notre étude permet de mettre en avant la présence d'ostracodes caractéristiques du domaine épi-bathyal et appartenant aux genres *Argilloecia*, *Cytheropteron* et *Krithe* au sein de sédiments deltaïques peu profonds. A proximité de l'embouchure du Rhône, la présence de ces ostracodes de mer ouverte est restreinte par une influence fluviatile fortement marquée. En s'éloignant de l'embouchure du Rhône, nous notons l'apparition de *Argilloecia* spp., *C. rotundatum*, *K. compressa* et *K. pernoides*. Nous soulignons également que *C. rotundatum*, *K. compressa* et surtout *Argilloecia* spp. semblent tolérer une plus forte influence fluviatile que *K. pernoides* qui est uniquement rencontrée dans la partie distale de l'influence du Rhône. Ces différentes observations nous conduisent à émettre l'hypothèse que les paramètres environnementaux (tels que les apports d'eau douce et de sédiments par le Rhône, la nourriture disponible ou la teneur en oxygène dissous) autre que la bathymétrie jouent un rôle important dans le développement des ces ostracodes de mer ouverte au niveau de notre site d'étude.

Mots-clés

Ostracodes, delta sous-marin, paléoécologie, Holocène, Méditerranée occidentale.

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I. INTRODUCTION

Ostracods, one of the most diverse groups of living crustaceans (Horne *et al.*, 2002), are small organisms inhabiting a wide range of aquatic environment, from temporary ponds to deep oceans. They offer powerful potential as palaeoenvironmental proxies due to their sensitivity to a number of ecological factors (such as temperature, salinity, dissolved oxygen, and primary productivity), and their common fossil preservation in Quaternary sediments. During the past few decades, advances in understanding of the ecological sensitivity of individual species to environment- and climate-related parameters led to increase the number of palaeoenvironmental reconstructions at various time scales and latitudes (*e.g.* Babinot & El Khanchoufi, 2000; Brouwers *et al.*, 2000; Cronin *et al.*, 2002; Cronin *et al.*, 1999; Didié & Bauch, 2000; Dingle & Lord, 1990; Frenzel & Boomer, 2005; Ruiz *et al.*, 2005; Yamaguchi & Norris, 2012).

In the Gulf of Lions and the associated Rhone delta area, only few studies deal with ostracods and attempt to use them as monitoring modern and/or past environments (Bassetti *et al.*, 2010; Bruneton *et al.*, 2001; El Hmaidi *et al.*, 1998; El Hmaidi *et al.*, 1999; Fanget *et al.*, 2013; Kruit, 1955; Peypouquet & Nachite, 1984). In this paper, we present the distribution of genera *Argilloecia* (Sars, 1866), *Cytheropteron* (Sars, 1866) and *Krithe* (Brady, 1874), commonly considered as assemblage of deep-sea environments (*e.g.* Bonaduce *et al.*, 1975; Coles *et al.*, 1994; Cronin *et al.*, 1999; Didié *et al.*, 2002), in Holocene Rhone subaqueous (and shallow water) deltaic sediments. We focus on the spatial and temporal distribution of these elements through three studied cores located at different water depth within the Rhone prodeltaic lobes. We attempt to propose some hypothesis for explaining the presence of these ostracods in such shallow water site.

II. BACKGROUND

II.1. Geological setting

The Gulf of Lions (Fig. 1) is a siliciclastic passive and prograding margin located in the north-western sector of the Mediterranean Sea, and bounded to the west and to the east by Pyrenean and Alpine orogenic belts, respectively. It comprises a crescent-shaped continental shelf with a maximum width of 70 km in the central part. This shelf is relatively flat and dips gently seaward to the shelf break, located at a water depth between 120 m and 150 m. The continental slope is deeply incised by an intricate network of submarine canyons descending to the abyssal Algero-Balearic Basin (Berné & Gorini, 2005). The significant subsidence rate of the margin (250 m/Myr at the shelf edge; Rabineau *et al.*, 2005) creates a large amount of available space (*i.e.* accommodation) which is progressively infilling by a high sediment supply, mainly delivered by the Rhone River (80% of the total sediment load; Aloïsi *et al.*, 1977).

Within the Middle and Late Quaternary, several prograding sequences were identified and related to Pleistocene forced regressions that formed during 100 kyr glacial/interglacial cycles (Aloïsi, 1986; Bassetti *et al.*, 2008; Jouet *et al.*, 2006; Rabineau *et al.*, 2005; Tesson *et al.*, 2000). These regressive deposits represent the majority of preserved sediments on the outer shelf. During the Last Glacial Maximum sea level fall (LGM, ca. 21 ka cal. BP; Mix *et al.*, 2001), the Rhone River was directly connected to the Petit Rhone canyon (Fig. 1) and fluvial sediments accumulated primarily at the Rhone deep-sea turbidite system (Bonnel *et al.*, 2005; Dennielou *et al.*, 2009; Droz & Bellaiche, 1985; Droz *et al.*, 2006; Jegou, 2008). The onset of the Deglacial sea-level rise led to the disconnection of the Rhone River and Petit Rhone canyon around 18.4 ka cal. BP (Bonnel *et al.*, 2005). The retreat of the Rhone outlet took place through the continental shelf following a north-westward direction during the rapid Deglacial sea level rise. It led to the deposition of several transgressive and backstepping parasequences across the shelf [the "shoal retreat Massif" of Swift *et al.* (1978)]. Thus, a deltaic complex, named as the Early Rhone Deltaic Complex, developed on the middle and inner shelf primarily during the Bølling-Allerød and the Younger Dryas (Berné *et al.*, 2007). Following the stabilization of global sea-level around 7 ka cal. BP, the Middle and Late Holocene Rhone outlet progressively shifted eastward, under natural and/or anthropogenic influence, and led to the development of several deltaic lobes (Fig. 1) identified onshore and offshore (Arnaud-Fassetta, 1998; Berné *et al.*, 2007; L'Homer *et al.*, 1981; Labaune *et al.*, 2005; Labaune *et al.*, 2008; Marsset & Bellec, 2002; Provansal *et al.*, 2003; Vella *et al.*, 2008; Vella *et al.*, 2005). With a beginning of progradation attested at ca. 7 ka cal. BP (L'Homer *et al.*, 1981), Saint Ferréol is the oldest and largest paleo-deltaic lobe, related to the "Rhône de Saint Ferréol" Channel. The Ulmet lobe, located eastward and related to the "Rhône d'Ulmet" Channel, is synchronous to the Saint Ferréol lobe, whereas the Peccais lobe, located west of Saint Ferréol lobe and related to the "Rhône de Peccais" Channel, appeared posterior to the erosion of the St Ferréol (Rey *et al.*, 2005; Vella *et al.*, 2005). The Bras de Fer lobe, related to the "Rhône de Bras de Fer" Channel, was built during the Little Ice Age, between 1587 and 1711 AD (Arnaud-Fassetta, 1998), a period characterized by increased amount of precipitation (Pichard, 1995). Until 1650 AD, the "Rhône de Bras de Fer" Channel is considered as synchronous to the "Rhône du Grand Passon" Channel (Arnaud-Fassetta, 1998). Following several intense floods in 1709-1711 AD, the "Rhône de Bras de Fer" Channel shifted to the east up to the Present-day position of the Grand Rhone River. Between 1711 and 1852 AD, the seaward termination of the "Grand Rhône" Channel displayed three mouths

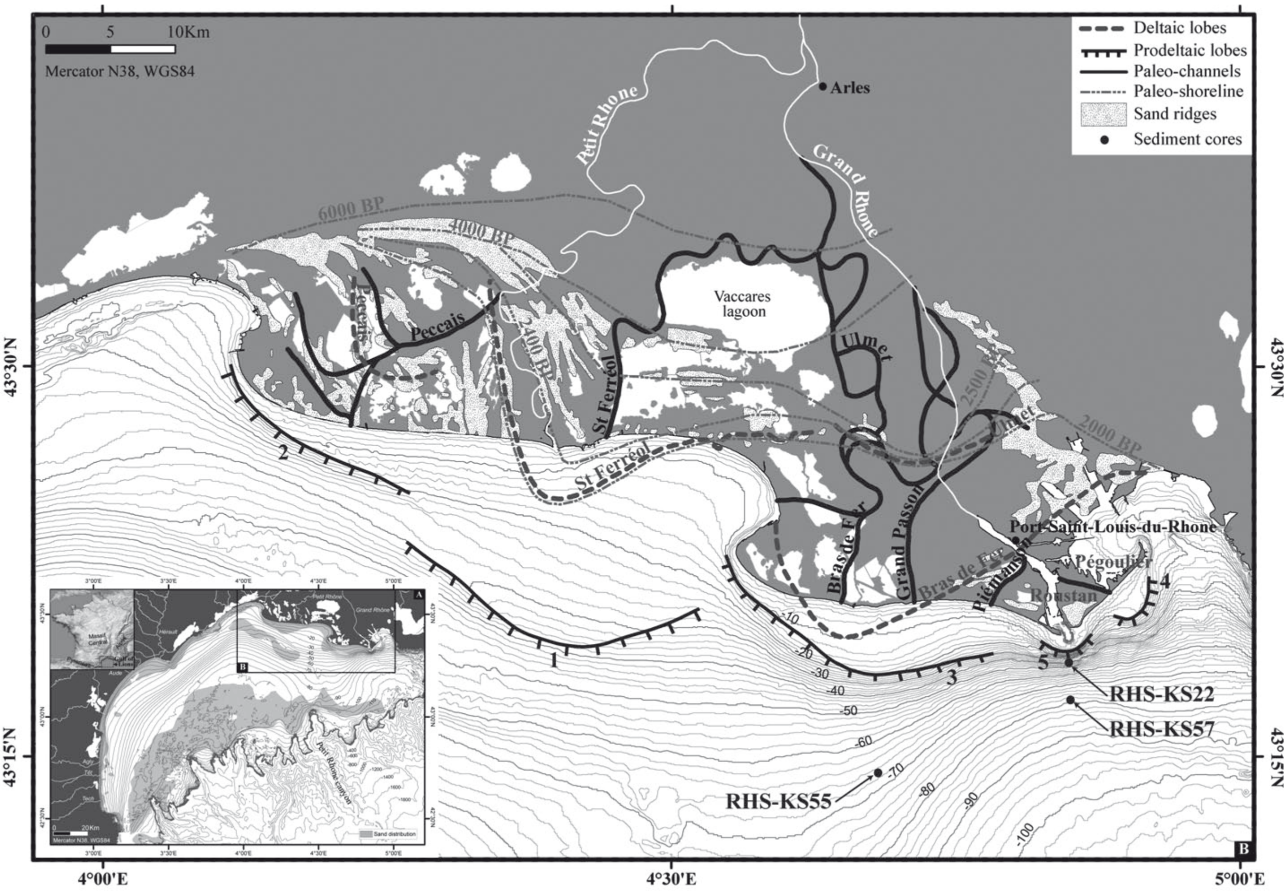

Fig. 1: A, Bathymetric map of the Gulf of Lions (based on Berné *et al.*, 2002) and B, detailed morphology of the Rhone subaqueous delta and main onshore morpho-sedimentary features (based on Berné *et al.*, 2007; Vella *et al.*, 2008). The distribution of sand is modified from Aloïsi (1986).The successive shifting of the Rhone distributaries under natural and/or anthropogenic influence during the Middle and Late Holocene led to several sediment accumulation along the coastal zone under the shape of prodeltaic lobes with 1: remnants of the Early Saint Ferréol delta front; 2: remnants of the Peccais (?) delta front; 3: remnants of the Bras de Fer delta front; 4: remnants of the Pégoulier delta front; 5: modern Roustan delta front. The evolution of the Rhone delta plain during the Holocene (paleo-shoreline, sand ridges and onshore deltaic lobes) are based on L'Homer *et al.* (1981), Arnaud-Fassetta (1998), Vella (1999) and Provansal *et al.* (2003). Black dots correspond to sediment cores presented in this study.

named (1) Piémanson to the west, (2) Roustan at the centre, and (3) Pégoulier to the east. Since 1855 AD, the Rhone River underwent anthropogenic influence by dyke constructions, which confined the flow into the "Rhône de Pégoulier" Channel between 1855 and 1892 AD. Then, since 1982 AD, the flow is constrained into the "Rhône de Roustan" Channel, the only exit of the Grand Rhone River into the Mediterranean.

II.2. Present dynamic context

With a mean annual water discharge of 1701 m^3 s^{-1} (Pont *et al.,* 2002), downstream the last confluence of the river, and a total suspended matter flux of 9.9±6.4 10^9 kg yr^{-1} (Sempéré *et al.*, 2000), the Rhone River is the main source of freshwater, nutrient and terrestrial organic matter for the Gulf of Lions (Durrieu De Madron *et al.*, 2000; Pont *et al.*, 2002; Sempéré *et al.*, 2000). A large amount of the fluvial discharge is constrained into the "Grand Rhône" Channel (90%), the main distributary of the Rhone River. The "Petit Rhône" Channel carries only 10% of the total water flux (Ibañez *et al.*, 1997). The hydrological regime of the Rhone River exhibits a strong inter-annual and seasonal variability with low water flux (<700 m^3 s^{-1}), essentially in summer, and high water flux (>3000 m^3 s^{-1}), primarily in spring and fall in response to snow melting and autumn rainfalls (Pont *et al.*, 2002). Present-day, the Rhone River supplies 7.4 10^6 t yr^{-1} of sediments to the Gulf of Lions, with high inter-annual variations (from 2 10^6 t yr^{-1} to 20 10^6 t yr^{-1}; Antonelli *et al.*, 2004; Ludwig *et al.*, 2003; Pont *et al.*, 2002; Sabatier *et al.*, 2006). A large amount of these sediments (80%) is transported during flood events, when water discharge exceeds 3000 m^{3}s^{-1} (Pont *et al.*, 2002), and exported seaward through (1) the river plume, (2) an intermediate nepheloid layer, formed during periods of water column stratification, and (3) a persistent bottom layer which plays a significant role in the budget of element transferred to the coastal area (Durrieu de Madron & Panouse, 1996) that decreases towards the sea (Aloïsi *et al.*, 1982; Aloïsi *et al.*, 1979; Naudin & Cauwet, 1997). The Rhone River plume forms a bulge generally deflected to the southwest, and that presents, in the absence of wind forcing, a strong density interfaces between fresh and saline waters. Its thickness (few meters), extension (~30 to 60 km from the river mouth; Broche *et al.*, 1998; Estournel *et al.*, 2003; Gatti *et al.*, 2006) and orientation are primarily controlled by interactions between the magnitude of river discharge, the strength of the Northern Current, and the wind conditions [*Mistral* (north winds), *Tramontane* (northwest winds), and *Marin* (east-southeast winds)] (Broche *et al.*, 1998; Demarcq & Wald, 1984; Estournel *et al.*, 2001; Estournel *et al.*, 1997; Naudin & Cauwet, 1997).

A large amount of sediments delivered to the Gulf of Lions is primarily stored in the subaqueous delta (in the sense of Riboulot *et al.*, 2012) off the Rhone River mouth, which extends from the shoreline to around 80-90 m water depth. Sediments are initially deposited close to the river mouth, on the delta front (Maillet *et al.*, 2006), where high sedimentation rates (ranging from 20 to 50 cm yr $^{-1}$) are recorded (Beaudouin *et al.*, 2005; Calmet & Fernandez, 1990; Charmasson *et al.*, 1998; Radakovitch *et al.*, 1999). Accumulation rates decrease strongly seaward to ca. 0.2-0.6 cm yr $^{-1}$ at 20 km away (Miralles *et al.*, 2005).

The area surrounding the Rhone River mouth is also characterized by high organic carbon content (1-2% d.w.) with a strong terrestrial signature (Buscail *et al.*, 1995; Lansard *et al.*, 2009; Mojtahid *et al.*, 2009; Pastor *et al.*, 2011; Tesi *et al.*, 2007). Seaward, organic carbon presents a more marine signature, and oxygen penetration depths increase (Lansard *et al.*, 2009; Mojtahid *et al.*, 2009; Pastor *et al.*, 2011).

Sediment transport on the shelf of the Gulf of Lions, as well as water circulation, are also strongly controlled by wind-driven circulation and/or wave regime. The continental cold and dry winds from the N-NW (*Mistral* and *Tramontane*) have little influence on sediment transport since they generate small waves (significant wave height H_s<2 m, and peak period T_p<6 s; Sabatier, 2001) on the shelf due to a reduced fetch. During winter, these winds are responsible of the cooling and homogenization of the shelf water column, which facilitate dense water formation (Estournel *et al.*, 2003) and locally generate up-welling phenomena (Millot, 1990). Conversely, the episodic and intense winds originated from the E-SE (*Marin*) are associated with long fetch and induce large waves (Hs>7 m, and Tp up to 12 s; Guillén *et al.*, 2006; Palanques *et al.*, 2006). The storms generated by these winds have the most significant impact on sediment transport in the Rhone subaqueous delta since they induce intense wind-driven circulation able to transport sediment in an alongshore direction all over the inner shelf (Dufois *et al.*, 2008). E-SE winds induce also a rise in sea-level at the shore, and an overall intense cyclonic circulation on the shelf (Ulses *et al.*, 2008).

III. DATA AND METHODS

This study is based on the analysis of two Küllenberg piston cores (RHS-KS22 and RHS-KS57) retrieved in front of the Present-day "Grand Rhône" Channel, and one Küllenberg piston core (RHS-KS55) retrieved in front of the paleo-"Rhône du Bras de Fer" and "Rhône du Grand Passon" Channels. Cores RHS-KS22, RHS-KS57, and RHS-KS55 were collected during the RHOSOS cruise (September 2008) on board *R/V* "*Le Suroît*" at 43 m, 79 m, and 67 m water depth, respectively.

All the cores were split, photographed and visually described to identify sedimentological facies. Sedimentary cores were sampled for ostracods analyses. Three-cm thick slides were collected on the core RHS-KS57 and RHS-KS55, whereas five-cm thick slides were collected on the shallow water core RHS-KS22 because of the high dilution of microfauna content in front of the Present-day "Grand Rhône" mouth due to extremely high sedimentation rate. Analyses of ostracods were performed using a sampling step of 10 cm through the three cores. A total of 249 samples were washed over a 63 µm sieve and the residues were dried and dry-sieved again using a 125 µm mesh screen. All specimens of ostracods were hand-sorted from the >125 µm size fraction within the cores RHS-KS22 and RHS-KS55 to concentrate adult valves and avoid problematic taxonomic identification of juvenile ostracods. However, within the core RHS-KS57, all specimens of ostracods were hand-sorted from the >63 µm due to lower content of ostracods. In the core RHS-KS57, we did not increase the thickness of sampled sediment slabs despite the low abundance in ostracod assemblages to avoid the decrease in temporal resolution. Thus, to reach the minimum number of ostracods we have counted the fraction >63 µm instead of considering only the fraction >125 µm, as in cores RHS-KS22 and RHS-KS55. Ostracods were determined at genera and/or species-level in each sample on the basis of several reference works carried out in the Mediterranean Sea (Bonaduce *et al.*, 1975; El Hmaidi *et al.*, 1998; El Hmaidi *et al.*, 1999; El Hmaidi *et al.*, 2010; Peypouquet & Nachite, 1984). The relative abundance of each ostracods genera/species was calculated. Total abundance (values normalized for a 100 cm ^{3} volume) and species richness (S) were also computed in order to describe the vertical diversity of ostracods within the cores.

The chronological frameworks of the studied cores were established on the basis of (1) the decay of short-lived radio-elements (^{137}Cs) (cores RHS-KS22 and RHS-KS57), (2) the isotopic Pb ratio (^{206}Pb/ ^{207}Pb) (core RHS-KS57), and (3) Accelerator Mass Spectrometer (AMS) ^{14}C dates (cores RHS-KS57 and RHS-KS55). The detailed methodology of these techniques is given in Fanget *et al.* (2013).

IV. RESULTS

IV.1. Chronological frameworks

The age assessment for the core RHS-KS22 is based on the ^{137}Cs activity (Fig. 2). At the base of the core, ^{137}Cs activity yields a value reaching 59 Bq kg^{-1} dry weight. From 825 cm to 715 cm, ^{137}Cs profile shows a relatively constant activity with values ranging from ~15 to 28 Bq kg^{-1} dry weight. ^{137}Cs activity increases progressively from 705 cm to 565 cm with values bracketed between 44 and 104 Bq kg^{-1} dry weight. A peak of ^{137}Cs activity is observed between 535 cm and 445 cm, with values ranging from 69 to 167 Bq kg^{-1} dry weight. This peak is followed by a decrease of ^{137}Cs activity with values oscillating, up to 295 cm, between 15 and 45 Bq kg^{-1} dry weight. From 285 cm to the top of the core, ^{137}Cs activity decreases gradually. The detection of the ^{137}Cs at the base of the core indicates that the core RHS-KS22 corresponds to a time window younger than 1953 AD (date of the first releases of this nuclide into the environment). The peak found between 535 cm and 445 cm might conform to the Chernobyl nuclear accident in 1986 AD.

To summarize, the core RHS-KS22 records the recent history (Fig. 2), less than fifty years, of the Rhone subaqueous delta. During this time window, the flow of the Rhone was artificially constrained into the modern Roustan Channel (see Section 2.1).

The age model for the core RHS-KS57 is based on five chronological tie points determined through the core (Fig. 2) (Fanget *et al.*, 2013). The base of the core is constrained by one ^{14}C date obtained at 652 cm and giving an age of 1671 a cal. AD (*i.e.* 635±30 conventional ^{14}C yr BP) (Table 1). The Pb isotopic signature was studied in the core RHS-KS57 using the ^{206}Pb/^{207}Pb ratio, which

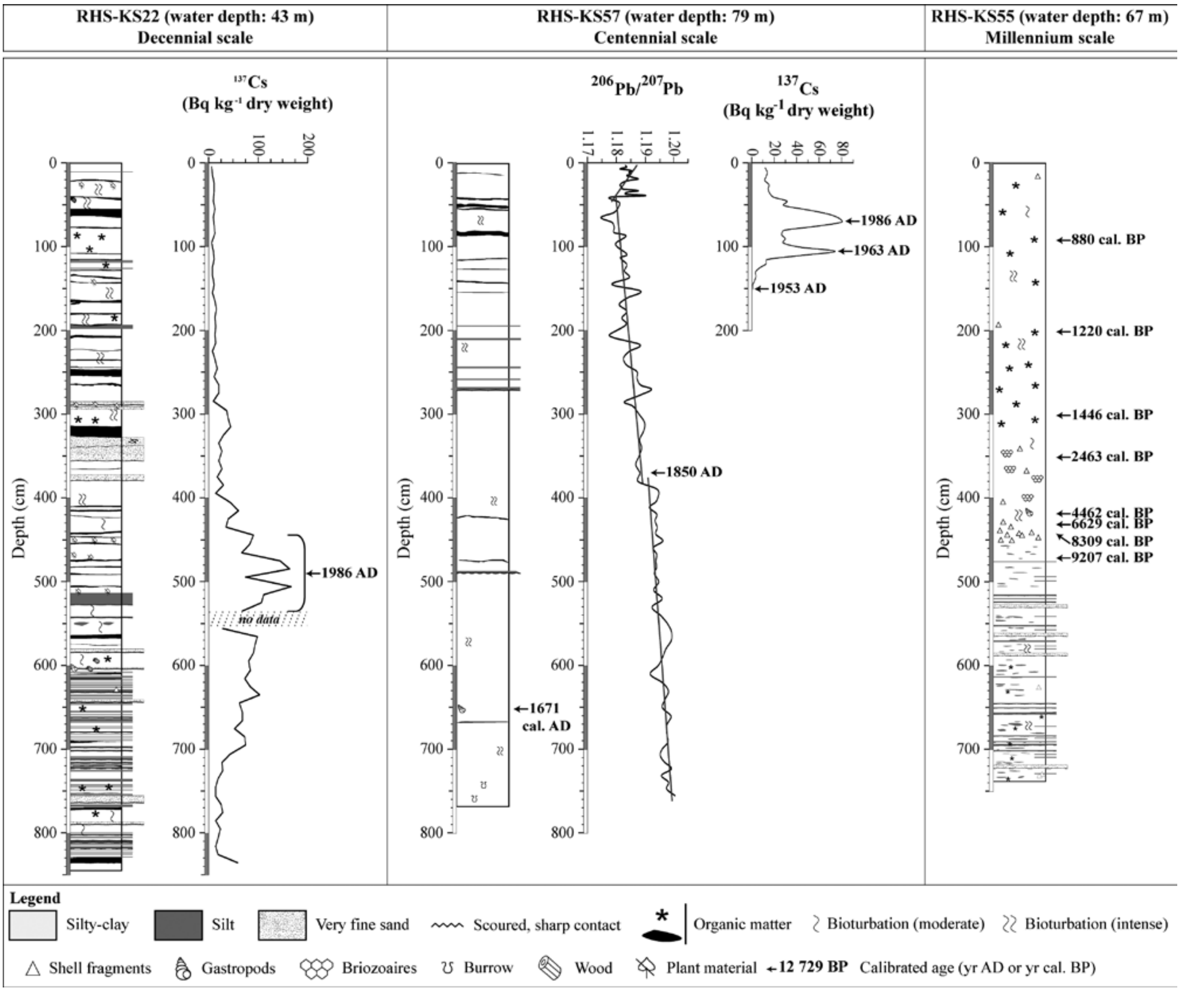

Fig. 2: Lithology and age model of the three studied cores. The chronology was established 1: in the core RHS-KS22 on the basis of short-lived radionuclides (^{137}Cs activity), 2: in the core RHS-KS57 on the basis of ^{137}Cs profiles, isotopic Pb ratio and on one ^{14}C date, and 3: in the core RHS-KS55 on eight ^{14}C dates.

Table 1: Summary of the dated samples used for this study. Absolute dates were obtained with accelerator mass spectrometer (AMS) ^{14}C on well-preserved mollusk shells and benthic foraminifera at *Laboratoire de Mesure 14C* (LMC14) at *Commissariat à l'Energie Atomique* (CEA, Saclay) and at Poznan Radiocarbon Laboratory (PRL). The ages reported herein are delta ^{13}C-normalised conventional ^{14}C years, corrected for an assumed air-sea reservoir effect of 400 years. Calendar ages were calculated using the Calib 6.0.1 version and the Marine 09 calibration curve (Reimer *et al.*, 2009). The ages are given with 1 sigma error.

Depth (cm)	Material	Sample weight (mg)	Sample number	Conventional ^{14}C age (yr BP)	1 Sigma calibrated age (yr cal. BP)	Probability distribution
			RHS-KS57			
652	*Turritella* sp.	980	SacA 15957	635 ± 30	253-306	1.000000
			RHS-KS55			
90-93	Benthic foraminifera	9,5	SacA 27201	1335 ± 30	839-921	1.000000
200-203	Benthic foraminifera	10,6	SacA 23205	1655 ± 30	1184-1256	1.000000
300-303	Benthic foraminifera + *Turritella* sp.	10,9	SacA 23206	1900 ± 30	1400-1492	1.000000
350-353	Benthic foraminifera	11,3	SacA 27203	2760 ± 35	2376-2549	1.000000
417-420	*Turritella* sp.	896	Poz-35061	4335 ± 35	4415-4508	1.000000
430-433	Benthic foraminifera	10,5	SacA 27204	6190 ± 40	6571-6687	1.000000
440-443	*Nucula* sp.	11,2	SacA 27205	7830 ± 40	8259-8358	1.000000
470-473	Benthic foraminifera	10,2	SacA 23208	8565 ± 35	9140-9273	1.000000

allows detecting periods of Pb pollution (Elbaz-Poulichet *et al.*, 2011; Komárek *et al.*, 2008; Thevenon *et al.*, 2010). The sudden decrease of $^{206}Pb/^{207}Pb$ ratio recorded at 350 cm reflects the increase in atmospheric Pb pollution at the beginning of the Industrial Revolution, *i.e.* at ca. 1850 AD. For the uppermost part of the core RHS-KS57, chronological tie points are determined thanks to the vertical distribution of the ^{137}Cs. The end of the ^{137}Cs activity, recorded at 150 cm, indicates the first year of introduction of the ^{137}Cs into the environment in 1953 AD. The first peak of ^{137}Cs activity (74 Bq kg^{-1} dry weight), found at 105 cm, might correspond to maximum of radioactive particles fall-out in 1963 AD related to the military atmospheric nuclear tests. The second peak (80 Bq kg^{-1} dry weight), observed at 70 cm, matches the Chernobyl event in 1986 AD [more details are given in Fanget *et al.* (2013)].

To summarize, the core RHS-KS57 records the last four centuries (Fig. 2), a period characterized by the successive displacement of the Rhone distributaries under natural or human influence (Fanget *et al.*, 2013)(see Section 2.1).

The age model for the core RHS-KS55 is based on eight valid ^{14}C dates (Fig. 2 and Table 1). From the bottom of the core down to 472 cm, ^{14}C dates indicate a deposition between ca. 10,500 a cal. BP [age of the underlying deposits of the Early Rhone Deltaic Complex in this area (Berné *et al.*, 2007)] and 9200 a cal. BP, *i.e.* during a transgressive interval. From 442 cm to 419 cm, ^{14}C dates are bracketed between ca. 8300 a cal. BP and 4450 a cal. BP. This interval corresponds to a condensed interval that forms during the stabilization of the sea-level and the maximum landward shift of the shoreline. The last 4000 a cal. BP, which corresponds to the highstand deposits, are recorded between 400 cm and the top of the core.

To summarize, the sediment intervals identified in the core RHS-KS55 encompass, at different resolution, the Holocene epochs (Fig. 2), a period marked by sea-level variations as well as several migrations of the Rhone distributaries (see Section 2.1).

IV.2. Sediment characteristics

On the basis of lithofacies, sedimentary structures, bioturbation, and color, five sedimentary facies are identified.

Facies 1 is made of numerous silt or rarely very fine to fine sand laminae interbedded with grayish silty clay. These thin laminae (mm to cm thick) display erosional bases and few parallel or undulated stratifications are also distinguished. Bioturbation, which hide sometimes the primary structures, are observed within facies 1. This facies is interpreted as sediment deposited by storm currents (*i.e.* tempestite). As storm events from the E-SE are often associated with floods in the Gulf of Lions, it is possible that flood and storm deposits are mixed in facies 1.

Facies 2 consists of abundant shells and shells debris in a grayish silty clay matrix. Biogenic material is mainly made of *Turritella* sp. and a number of bivalves (*e.g. Acanthocardia echinata*, *Arca tetragona*, *Nucula* sp.). Facies 2 corresponds to a condensed interval (3,840 yr cal. BP deposits in 30 cm).

Facies 3 is characterized by beige silty clay, with some diffuse yellowish veneers and oxidized spots of hydrotroilite (hydrous ferrous sulfide). This facies yields an intense bioturbation. Sparse *Turritella* sp., bivalves, and scattered bryozoans debris are also observed.

Facies 4 is made of grayish and beige silty clay. This facies is characterized by abundant bioturbation and hydrotroilites.

Facies 5 consists of silty clay, with abundant color banding. Few silt laminae or few silt or very fine sand beds are also observed within this facies. These laminae or beds often display erosional bases.

Facies 3, 4, and 5 are typical facies association observed in prodeltaic settings of the Rhone (Aloïsi & Monaco, 1980; Chassefiere, 1990; Touzani, 1998), and indicate shallow water environment with occasional fluvial influence.

The vertical successions of the sedimentary facies previously described through the cores RHS-KS22, RHS-KS57, and RHS-KS55 are illustrated in Table 2.

IV.3. Ostracods distribution

A high diversity of ostracods is observed through the studied cores (Figs. 3, 4, and 5), with ostracods assigned to a large variety of environments, ranging from freshwater to epi-bathyal settings. A large amount of ostracods encountered are genera and species expected in a shallow water prodeltaic environment under river influence. Among those, freshwater species [(*e.g. Cyprinotus* spp., *Ilyocypris* sp., *Darwinula stevensoni* (Brady & Robertson, 1885)], due to the proximity of the Rhone outlet(s), are found together with infra-littoral species [*e.g. Semicytherura* spp., *Carinocythereis carinata* (Roemer, 1838), *Loxoconcha* spp.]. Nevertheless, the relative abundance of seven genera/species, that we consider as unusual in such shallow water setting, has attracted our attention. This unusual assemblage is composed by *Argilloecia* spp. [mainly represented by *Argilloecia acuminata* (Müller, 1894)], *Cytheropteron alatum* (Sars, 1866), *Cytheropteron monoceros* (Bonaduce *et al.*, 1975), *Cytheropteron rotundatum* (Müller, 1894), *Krithe compressa* (Seguenza, 1980) [*Krithe* sp. C (large vestibulum) of Peypouquet (1977)], *Krithe pernoides* (Bonermann, 1855) [*Krithe* sp. A (small vestibulum) of Peypouquet (1977)], and juvenile *Krithe*. These species are essentially described as common element in deep waters (epi-bathyal species, *e.g.* Cronin *et al.*, 1999; Didié *et al.*, 2002). In this paper, due to the

Table 2: Sedimentary features of the studied cores.

Core (depth in cm)	Sedimentary Facies Feature	Environment
	Facies 1	
RHS-KS22 (845-600) RHS-KS55 (738-460)	Silt or sand beds intercalated (with rare parallel or undulated stratifications) in fine-grained sediments	Storm-influenced environment
	Facies 2	
RHS-KS55 (460-430)	Silty clay matrix with heterolithic contents (*Turritella* sp., bivalves)	Condensed interval
	Facies 3	
RHS-KS55 (430-320)	Structureless silty clay sediments with biogenic contents (bryozoans debris, shells fragments, *Turritella* sp. and bivalves) and abundant bioturbation	Prodeltaic environment (shallow water setting with occasional fluvial influence)
	Facies 4	
RHS-KS57 (760-500; 420-280) RHS-KS55 (320-0)	Structureless silty clay sediments with abundant hydrotroilites and bioturbation	Prodeltaic environment (shallow water setting with occasional fluvial influence)
	Facies 5	
RHS-KS22 (600-0) RHS-KS57 (771-760; 500-420; 280-0	Silty clay sediments with abundant colour banding, few silt laminae, and moderate bioturbation	Prodeltaic environment (shallow water setting with occasional fluvial influence)

high abundance of these unusual elements through our shallow water cores, we choose to focus our attention only on the seven species mentioned above. In order to highlight the contribution of these unusual species, we show their abundance in single curves and grouped all the others in a cumulative plot (Figs. 3, 4, and 5) without discussing them.

In core RHS-KS22, the number of ostracods per sample varies greatly from 0 to 451 ind./100 cm^3 (Fig. 3). The number of counted specimens between the bottom of the core and 653 cm is moderate and is comprising between 1 and 95 ind./100 cm^3. Density increases between 643 cm and 583 cm with values reaching up to 248 ind./100 cm^3 at 603 cm. From 573 cm and 543 cm, a decrease is observed with 11 ind./100 cm^3 recorded at 563 cm. The number of ostracods increases again between 533 and 513 cm with 217 counted specimens/100 cm^3 at 523 cm. A constant decrease is observed from 503 cm to 383 cm, with 35 ind./100 cm^3 and 9 ind./100 cm^3, respectively. Highest ostracod abundances are recorded between 373 cm and 283 cm, with values reaching up to 451 counted specimens/100 cm^3 at 333 cm. Along the uppermost 323 cm of the core, the number of ostracods per sample decreases progressively. The lowest density is recorded between 153 cm and the top of the core where values drop to 0 ind./100 cm^3.

Diversity, which is comprised between 0 and 25 genera/species/sample, follows approximately the same trend (Fig. 3). Highest diversity is recorded when ostracods abundances are maximal, *i.e.* between 373 and 283 cm.

In core RHS-KS22 (Fig. 3), juvenile *Krithe* are only recorded in one sample, at 673 cm (~8.5%). *C. rotundatum* is also very scarce and only found at 533 cm, 333 cm, and 293 cm. In these three samples, *C. rotundatum* presents very low abundances (<1%). *Argilloecia* spp. are locally encountered through the core RHS-KS22. These species are observed with low abundances (ranging from ~0.2 to 3%) between 773 and 583 cm, 483 and 453 cm, 373 and 283 cm, and 213 and 173 cm. The abundance of *Argilloecia* spp. reaches a peak of 11% at 123 cm, and disappears on the uppermost 113 cm. *C. alatum*, *C. monoceros*, *K. compressa*, and *K. pernoides* are not recorded in the core RHS-KS22.

In core RHS-KS57, the number of ostracods in each sample varies greatly from 1 to 454 ind./100 cm^3 (Fig. 4). Highest ostracod abundances are recorded between the bottom of the core and 590 cm, with values bracketed between 14 and 454 ind./100 cm^3. The maximum of density is observed at 709 cm and 699 cm, with 282 and 454 counted specimens/100 cm^3, respectively. From 587 cm to 359 cm, density drops with values ranging between 1 and 22 ind./100 cm^3. From 349 cm to 279 cm, the number of ostracods increases again with two peaks of 76 and 82 counted specimens/100 cm^3 at 349 cm and 329 cm, respectively. Along the uppermost 269 cm of the core, relatively low densities are observed (from 1 to 24 ind./100 cm^3).

Diversity varies between 1 and 17 genera/species per sample (Fig. 4). Diversity follows also the same trend that the density, with minima recorded between 587 cm and 359 cm and along the top 269 cm. The maximum of diversity is recorded at 699 cm with 17 genera/species.

In core RHS-KS57 (Fig. 4), juvenile *Krithe* as well as *K. compressa* are essentially found at the bottom of the core, between 767 cm and 603 cm. Relative abundances of juvenile *Krithe* ranging between ~10 and 45%, whereas relative abundances of *K. compressa* oscillating between 0 and ~8% through this interval. Juvenile *Krithe* are also observed at 487 cm, and between 339 cm and 310 cm, and *K. compressa* at 441 cm and 349 cm. A relatively high contribution (up to ~55%) of *C. rotundatum* is recorded between the bottom of the core and 502 cm. From 491 cm to 359 cm, the presence of *C. rotundatum* is more scattered. High abundance (up to ~60%) of this species is again observed within the interval reaching from 359 cm to 230 cm. Along the topmost 219 cm of the core, *C. rotundatum* is very scarce. *Argilloecia* spp. are primarily found between 767 cm and 614 cm, and between 390 cm and 269 cm. Within the rest of the core, *Argilloecia* spp. appear only at discrete levels. *C. alatum*, *C. monoceros*, and *K. pernoides* are not found in the core RHS-KS57.

In core RHS-KS55, the number of ostracods per sample varies from 68 to 12,821 ind./100 cm^3 (Fig. 5). From the bottom of the core to 482 cm, the number of counted specimens oscillates between 68 and 1266 ind./100 cm^3. The lowest values are recorded at 642 cm and 632 cm, whereas four peaks of 1141 ind./100 cm^3, 1243 ind./100 cm^3, 1006 ind./100 cm^3, and 1266 ind./100 cm^3 are observed at 702 cm, 622 cm, 571 cm, and 541 cm, respectively. From 471 cm to 352 cm, density increases strongly with values reaching up to 12,821 ind./100 cm^3 at 432 cm, and up to 10 539 ind./100 cm^3 at 412 cm. Density drops to 222 ind./100 cm^3 at 332 cm, and oscillates between 305 and 1182 ind./100 cm^3 between 322 cm and 162 cm. The number of ostracods per sample decreases from 152 cm to 82 cm, where a value of 90 ind./100 cm^3 is observed. Along the uppermost 82 cm of the core, density increases progressively, and reaches a value of 616 ind/100 cm^3 at the top of the core.

Diversity is comprised between 7 and 31 genera/species per sample (Fig. 5). The lowest diversity is recorded between the bottom of the core and 632 cm, with values comprised between 8 and 18 genera/species by sample. From 622 cm to 442 cm, diversity increases, and the maximum is recorded at 462 cm with 31 genera/species. Diversity decreases again from 432 cm to 82 cm, to reach a minimum of 7 genera/species. Diversity follows the same trend that the density through the uppermost 72 cm of the core.

In core RHS-KS55 (Fig. 5), juvenile *Krithe*, *K. pernoides*, and *C. rotundatum* exhibit a very low contribution (<10%) between the bottom of the core and 362 cm. Relative abundances of these three species increase

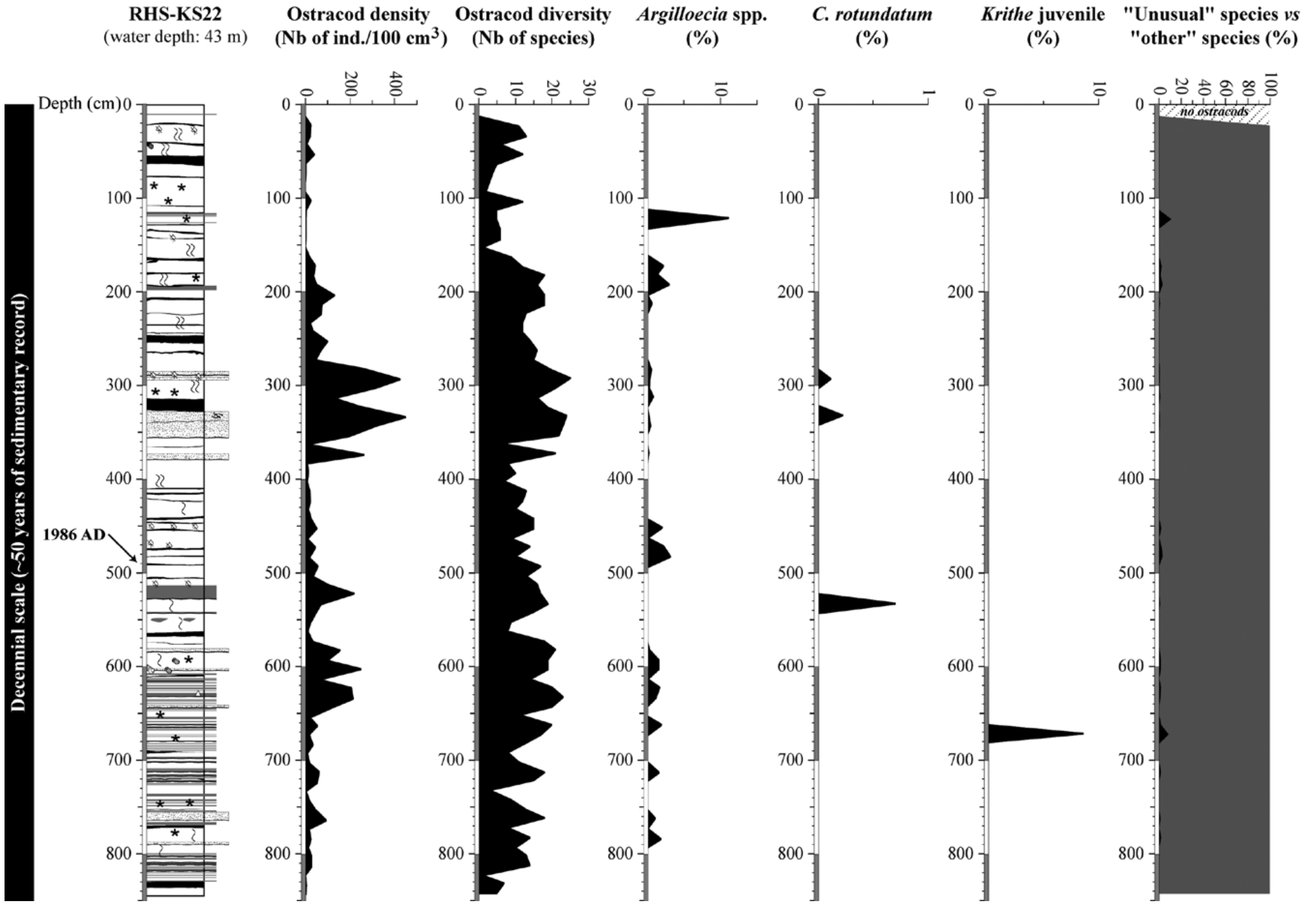

Fig. 3: Density and diversity of the ostracod population along the core RHS-KS22, and vertical distribution of each epi-bathyal ostracods (*i.e. Argilloecia* spp., *C. rotundatum*, juvenile *Krithe*) in core RHS-KS22.

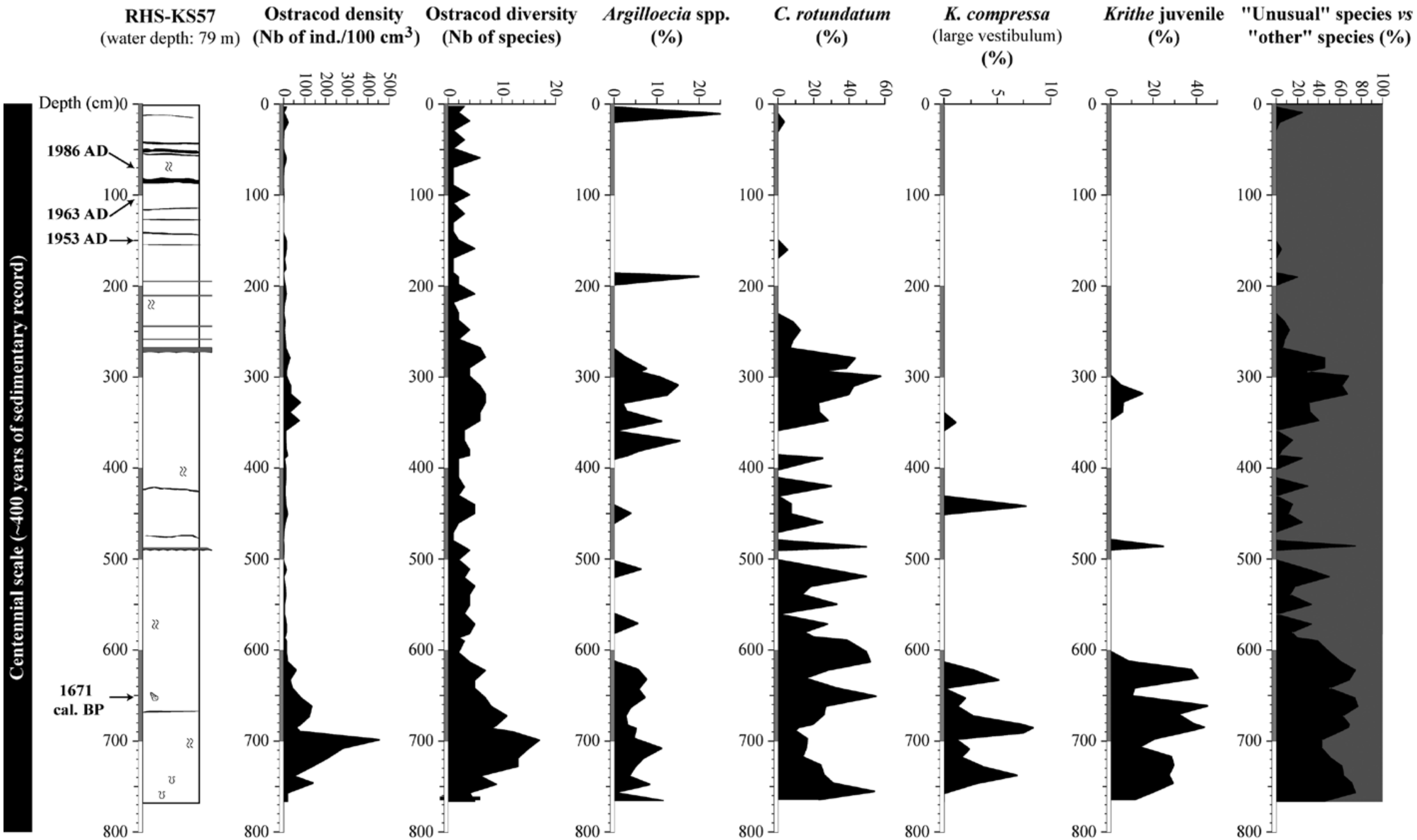

Fig. 4: Density and diversity of the ostracod population along the core RHS-KS57, and vertical distribution of each epi-bathyal ostracods (*i.e. Argilloecia* spp., *C. rotundatum*, *K. compressa*, and juvenile *Krithe*) in core RHS-KS57.

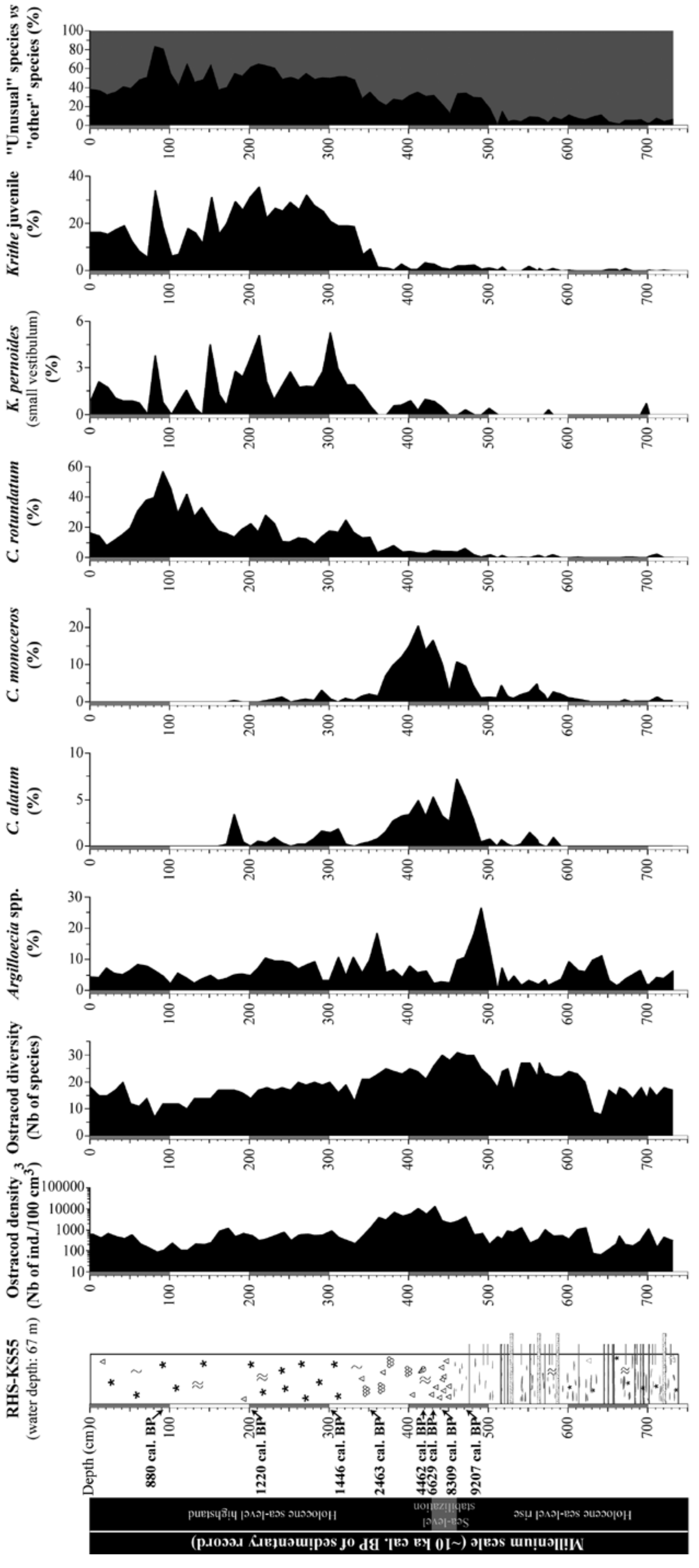

Fig. 5: Density and diversity of the ostracod population along the core RHS-KS55, and vertical distribution of each epi-bathyal ostracods (*i.e. Argilloecia* spp., *C. alatum*, *C. monoceros*, *C. rotundatum*, *K. pernoides*, and juvenile *Krithe*) in core RHS-KS55.

within the uppermost 352 cm of the core. It is particularly notices for juvenile *Krithe* and *C. rotundatum* with abundances reaching up to ~35 and 57%, respectively. *C. monoceros* is very scarce (from 0 to 5%) between the bottom of the core and 492 cm, and between 362 cm and 182 cm. Relative abundances of this species increase between 492 cm and 362 cm, to reach a maximum of ~20% at 412 cm. *C. monoceros* disappears through the uppermost 172 cm of the core. *C. alatum* correlates with *C. monoceros*. It presents a low contribution (<4%) between 592 cm and 492 cm, and between 332 cm and 162 cm. Highest abundances are encountered between 492 cm and 332 cm, with a maximum of ~7% at 462 cm. *C. alatum* is not found between the bottom of the core and 592 cm, and along the uppermost 162 cm of the core RHS-KS55. *Argilloecia* spp. are relatively constant through the core, with abundances generally oscillating between ~2 and 10%. Two peaks of ~25% and ~20% are observed at 492 cm and 362 cm, respectively. *K. compressa* is not found in the core RHS-KS55.

V. DISCUSSION

Despite the fact that species of *Argilloecia*, *Cytheropteron* and *Krithe* generally increase rapidly in abundance with depth (*e.g.* Cronin *et al.*, 1999; Didié & Bauch, 2000; Didié *et al.*, 2002; Machain-Castillo *et al.*, 1990; Rodriguez-Lazaro & Cronin, 1999), they are relatively abundant in shallow water studied cores (Figs. 3, 4, and 5). These genera were observed occurring sporadically in the Rhone subaqueous delta by Peypouquet & Nachite (1984), as possibly resulting from up-welling phenomena in the coastal area of the Gulf of Lions caused by continental cold and dry winds (*Mistral* and *Tramontane*) (Millot, 1990). The influence of up-welling processes on the ostracod fauna, marked by the presence of epi-bathyal and meso-bathyal ostracods in a shallow water domain, is also put forward by Pascual *et al.* (2008) in the study of the Basque continental shelf sediments.

In this study, we believe that the local and occasional up-welling phenomena could not be the only factor governing the distribution of these elements and explaining their abundance (up to 65%) in total ostracod assemblages. The hypothesis is that environmental parameters other than bathymetry (*e.g.* food supply or dissolved oxygen) have a major role in the development *in situ* of the above described assemblage.

The genus *Cytheropteron*, a worldwide marine genus inhabiting mostly epi-bathyal and meso-bathyal environments, yields the highest abundances. In the Mediterranean Sea, the modern distribution of the species belonging to the genus *Cytheropteron* is well known (Bonaduce *et al.*, 1975). *C. rotundatum* is generally observed at water depth greater than 50 m, and the maximum number of specimens is essentially observed between 170 m and 210 m (Bonaduce *et al.*, 1975). Within Rhone deltaic sediments, the highest abundances of *C. rotundatum* are found through the cores RHS-KS57 and RHS-KS55 (Figs. 4 and 5). *C. rotundatum* appear significantly only after the Holocene sea-level stabilization (*i.e.* after ca. 7 ka cal. BP) and is mostly recorded during periods of low to moderate fluvial influence (Fig. 4) (Fanget *et al.*, 2013). On the other hand, the shallowest site (RHS-KS22 core) seems to be not suitable for this species.

The distribution of *C. rotundatum* generally correlates with the genus *Krithe* (Figs. 3, 4, and 5). *Krithe* is known as a cosmopolitan infaunal-living genus that is common in deep-sea sediments (Coles *et al.*, 1994). Since the postulate of Peypouquet (1975) that variation in the anterior vestibule morphology in *Krithe* can be used for estimating past oxygen conditions, the significance of the genus *Krithe* has been roundly debated (*e.g.* McKenzie *et al.*, 1989; Van Harten, 1995; Whatley & Zhao, 1993; Zhao & Whatley, 1997; Zhou & Ikeya, 1992). The Peypouquet's hypothesis, which suggests an inverse relationship between the size of the vestibule and the oxygen content of the sea water (*i.e.* small and narrow vestibule means high oxygen content, whereas large vestibule corresponds to low oxygen content), remains controversial because any study on living ostracods exist. The hypothesis proposed by Peypouquet (1975) has been rejected by several authors (Van Harten, 1995; Whatley & Zhao, 1993; Zhao & Whatley, 1997), whereas others found a fairly good correspondence between the size of the vestibule of *Krithe* species and oxygen content of bottom waters (Bassetti *et al.*, 2010; McKenzie *et al.*, 1989). Thus, the Peypouquet's hypothesis should be used with caution, in particular due to the complex influence of environmental parameters on *Krithe* morphology. In our studied cores, a large part of *Krithe* is made of juvenile specimens but within the adult specimens, two species are encountered: *K. pernoides* [*Krithe* sp. A of Peypouquet (1977)], which is characterized by small/medium vestibule, and *K. compressa* [*Krithe* sp. C of Peypouquet (1977)], which is distinguished by large vestibule.

K. pernoides is only found in the core RHS-KS55. This species appears essentially after 7 ka cal. BP, within the prodeltaic sedimentary facies which are associated to the development of the several Rhone deltaic lobes, after the stabilization of the global sea-level. *K. compressa* is only observed in the core RHS-KS57 occurring during periods of low fluvial influence (Fanget *et al.*, 2013). Within the core RHS-KS22, the presence of the genus *Krithe* is very low. We observe that *K. pernoides* and *K. compressa* never cohabite in our studied cores, and seem to be adapted to slightly different environments. Mojtahid *et al.* (2009) and Goineau *et al.* (2011) studies based on benthic foraminifera, emphasize stress-environmental conditions in front of the Rhone River (close to the RHS-KS22 and RHS-KS57 cores site). They are essentially expressed by high organic matter input of terrestrial provenance and limited oxygen penetration depth into the sediment (Goineau *et al.*, 2011; Mojtahid *et al.*, 2009). With increasing distance from the river mouth, more stable environmental conditions are observed, characterized by increased marine-derived organic matter supplies and better oxygen penetration in the sediment. In the Rhone subaqueous delta setting (this work), *K. compressa* appears in shallow water sediments under stressful conditions (core RHS-KS57), whereas *K. pernoides* occurs in more stable shallow water conditions (core RHS-KS55) (Fig. 6). This observation might be correlated to the correspondence between dissolved oxygen content and vestibule size as proposed by Peypouquet (1975). Small vestibule *Krithe* should be related to higher oxygenated environment and large vestibule *Krithe* to lower oxygen conditions. Bassetti *et al.* (2010) have already notice this phenomenon in the sediments of the Gulf of Lions, but no further evidence can be provided to proof the exactness of this assumption. Close to the Rhone river mouth (core RHS-KS22), environmental conditions appear clearly not suitable (shallow water environment and too high fresh-water input from river) to record species belonging to the genus *Krithe* and *Cytheropteron* (Fig. 6).

The genus *Argilloecia* is often associated with *Cytheropteron* and *Krithe* (Alvarez Zarikian *et al.*, 2009; Cronin *et al.*, 1999; Didié *et al.*, 2002; Yamaguchi & Norris, 2012). *Argilloecia* is a worldwide infaunal genus mostly observed in deep-sea sediments (Van Morkhoven, 1963; Whatley & Coles, 1987), and is an indicator of organic rich sediments (Alvarez Zarikian *et al.*, 2009). In the Mediterranean Sea, *Argilloecia* is observed at water depths exceeding 70 m, and the maximum number of elements increased with depth (Bonaduce *et al.*, 1975). *Argilloecia* is observed through all studied cores (Figs. 3, 4, and 5). The distribution of *Argilloecia* within the Rhone subaqueous deltaic sediments seems to be lesser governed by water depths (Fig. 6). Thus, we hypothesize that *Argilloecia* in the Rhone shallow water sediments might be linked to organic matter inputs.

The remaining two unusual elements found in our studied

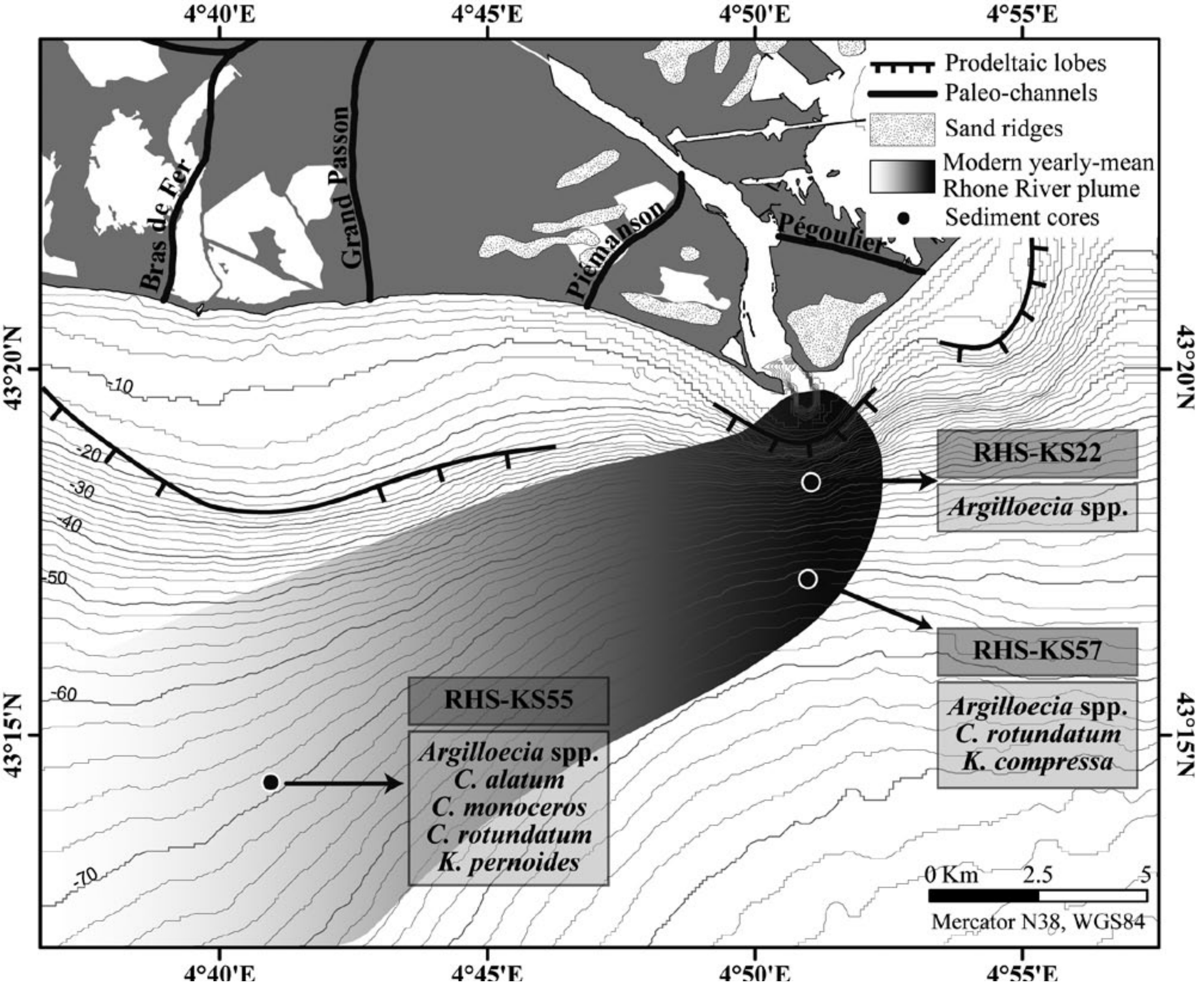

Fig. 6: Synthetic map summing up the distribution of epi-bathyal ostracods in the shallow water Rhone deltaic sediments.

cores, *C. alatum* and *C. monoceros*, do not show any correlation with the distribution of the species mentioned above. In the Mediterranean Sea, *C. monoceros* is widely distributed at water depth beyond 70 m whereas *C. alatum* is essentially observed at water depths of ca. 200 m (Bonaduce *et al.*, 1975). These two species are only observed through the core RHS-KS55 (Fig. 5), and the highest abundance of these species is recorded within a short condensed interval made of abundant shells and shells debris in a silty clay matrix (Facies 2). *C. alatum* and *C. monoceros* are related to a very specific time interval, formed between ca. 8300 a cal. BP and 4450 a cal. BP and corresponding to a coarse-grained level. In addition, the organic matter flux during this interval was probably of low quality (refractory) at the RHS-KS55 site, because the fluvial input is located far away landwards. We cannot completely exclude the possibility of reworking processes, but the carapaces are generally well-preserved. The ecology of these two species is poorly known, we might put forward the hypothesis that *C. alatum* and *C. monoceros* can adapt to live in a relatively coarse-grained substrate and with poor organic matter input.

VI. CONCLUSION

The Rhone subaqueous deltaic setting is characterized by a high diversity of the ostracods fauna, with species assigned to a large variety of environments. Among this fauna, seven species, belonging to the genus *Argilloecia*, *Cytheropteron*, and *Krithe*, are observed in a relatively high abundance within our shallow water sediments. These species are known as common assemblage of deep-sea environments and increase in abundance with depth. Nonetheless, we have found them in high abundance in a shallow water setting and we put forward the hypothesis that their occurrence should not be only controlled by water depth. Obviously, they are full marine species, thus their occurrences are essentially found after the establishment of modern conditions in terms of sea-level. Nonetheless, we believe that environmental parameters (such as fresh-water and sediment input from river, food supply, and dissolved oxygen) must play an important role. Close to the Rhone River mouth, the strong fluvial influence restricts the presence of epi-bathyal ostracods but with increasing distance from the river mouth, these ostracods are found in high abundance. We observed that *C. rotundatum* and *K. compressa* occur under higher fluvial influence than *K. pernoides*, which is only encountered in the distal part of the Rhone River influence. We also notice that *Argilloecia* is tolerant to variable environmental conditions.

In this work, we are not able to better define which are exactly the parameters controlling the distribution of the above mentioned species, since a more detailed studied on living ostracods would be necessary but we consider this contribution important to the knowledge of the ostracod ecology.

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