Temporal variability of live (stained) benthic foraminiferal faunas in a river-dominated shelf – Faunal response to rapid changes of the river influence (Rhône prodelta, NW Mediterranean)

Response to the Anonymous Referee #1

We thank the Anonymous Referee#1 for his/her review and very interesting comments on our manuscript. We have taken into account those in order to improve our paper. Please find our answers to the review below (abbreviations are RC: referee comment; AC: author comment).

RC **(A1)** In the introduction chapter, the authors should clearly state how this manuscript differentiates from existing studies and manuscripts (specifically, Goineau et al., 2011a, b; Mojtahid et al., 2009, 2010). Inspection of the mentioned papers reveals significant overlap of the topic, scientific questions, results, and partly also figures. I regard this an important issue, which should be commented by the authors. What are the major new results and conclusions of the new study going significantly beyond the existing knowledge? Why is the new study necessary to understand the Rhone prodelta environmental variability?

AC The Reviewer 1 is right. We have reformulated some textual parts and added some sentences in our introduction (pages 9036-9037). Please see the bolded text below.

"*Benthic foraminiferal assemblages have also been analysed at a larger scale in the Rhône prodelta (15 to 100 m depth, 1 to 22.4 km off the mouth) during two sampling seasons (Mojtahid et al., 2009; Goineau et al., 2011).* ***Both studies permitted to get snapshots of foraminiferal faunas at the scale of the prodelta under two contrasted environmental conditions, eutrophic (i.e. late spring bloom, June 2005) and oligotrophic (i.e. late summer, September 2006) settings. Despite different conditions, foraminiferal communities show similar*** *bio-zonation depending on hydro-sedimentary processes and on the quality/quantity of sedimentary organic matter.* ***Nevertheless, some differences appear when comparing relative abundances of major species. Indeed, a strong contribution*** *of the most opportunistic species (e.g. Bulimina aculeata, Cassidulina carinata, Valvulineria bradyana) is noticed in June 2005. It might be related to a response to fresh phytodetritus input related to spring bloom conditions.* ***Unfortunately, the different locations of the study stations during both sampling periods and the lack of key environmental parameters such as chlorophyll-a content within the sediment precluded reliable and relevant interpretations concerning the temporal variability of foraminiferal communities in the Rhône prodelta. A temporal survey of both small- (63-150 µm) and large-sized foraminiferal faunas (>150 µm) supported by a complete characterisation of biotopes*** *would allow us to determine the impact of changing environmental conditions (e.g. hydro-sedimentary processes, quality/quantity of the organic matter) on the foraminiferal faunas in the Rhône prodelta. Furthermore, the dynamics of foraminiferal assemblages and associated time scales for ecosystem adaptation is needed to relate abrupt changes of river delivery (floods) to ecosystems dynamics.* ***Such a study has never been done until now.***
In this paper, we investigate the temporal variability of live (stained) benthic foraminiferal faunas from the Rhône prodelta at two sites sampled during four periods with contrasted environmental conditions. Sites A and N (24 and 67 m depth,

respectively) were both visited in April 2007, September 2007, May 2008 and December 2008, these sampling dates cover a wide range of environmental conditions from low to high discharge (flood), and from oligotrophic to spring bloom conditions. We have analysed both 63–150 µm and >150 µm size fractions of one core per site for each sampling period. These analyses are combined with numerous environmental measurements such as ***sedimentary features (granularity)****, sediment oxygenation (oxygen penetration depth, oxygen uptake) and sedimentary organic matter quantity (organic carbon content) and quality (Chl-a, amino acids and lipids contents, carbon and nitrogen stable isotopes). The aim of this study is to gain insight of the ecosystem dynamics with regards of changes in river input to the coastal zone. We describe the complex relationship between (1) changes in river discharge including extreme events (floods), (2) changes in environmental conditions in the water column and sediments and (3) the response of benthic foraminiferal faunas in the Rhône prodelta in terms of standing stocks, diversity and composition.*"

RC **(A2)** In this context, it should be considered that the cited study of Goineau et al. (submitted to J. Foramin. Res.) is not accessible yet. This paper should only remain cited in the final version of this paper if by then accepted.

AC We have submitted a revised version of this paper to the Journal of Foraminiferal Research on 10th November 2011. Nevertheless, if we do not get its final acceptance before submitting a revised version of the present study in Biogeosciences, we will follow the Reviewer 1's suggestion. In that case, we would refer to "Unpublished data" instead of "submitted". In addition, we propose the following modifications in the text:

1. To remove from the introduction the textual part referring to the above-mentioned submitted paper (page 9036, lines 17-23);
2. To reformulate the introductive part of the discussion (page 9048, lines 10-17).

"*Foraminiferal datasets from ecological studies are usually established on the basis of one sample (i.e., core) per investigated station. Only few studies dealing with shelf environments (Buzas, 1968; Hohenegger et al., 1989, 1993; Buzas and Gibson, 1990; Silva et al., 1996; Swallow, 2000; Buzas et al., 2002; Morvan et al., 2006) have investigated the spatial dynamics of benthic foraminifera at a small spatial scale (<1 km). In these papers, small-scale (decimetric to decametric) spatial variability of benthic foraminiferal faunas exists and is generally explained by a patchy distribution of organic detritus at the seafloor. In our study area, unpublished data show that absolute abundances of major foraminiferal taxa at a single site may present a significantly patchy distribution at a decimetric scale. However, the variability of foraminiferal percentages (i.e. relative abundances) is not significant. Since our temporal survey of benthic foraminiferal faunas was performed with only one core per investigated site and per sampling period, the following discussion is based on percentage data of the major species.*"

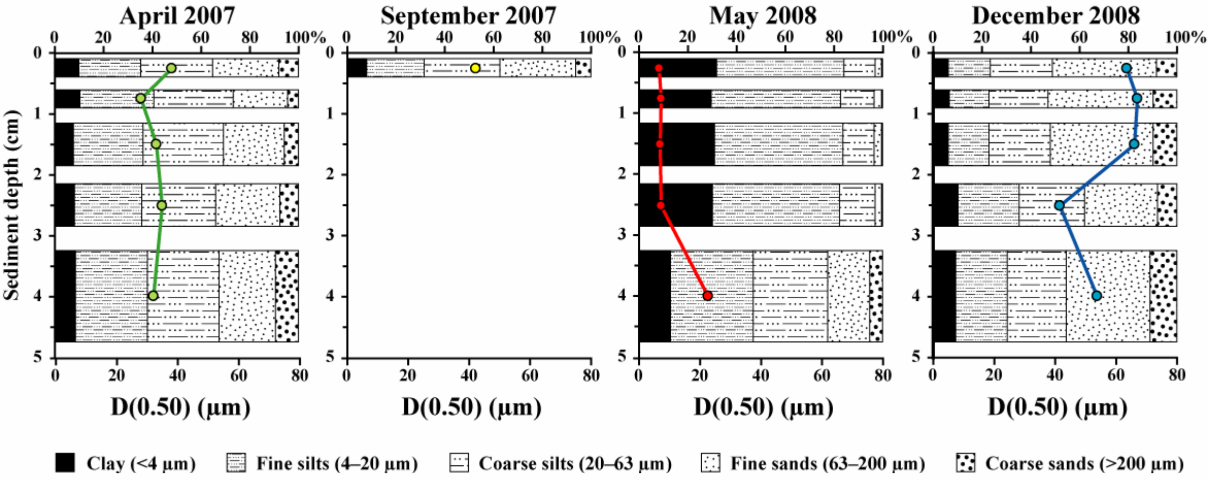
3. To reformulate the text on page 9055 between lines 10 and 13.

"*It is assumed that, in shelf environments, local accumulation of food particles in decimetric depressions can favour the growth of the most opportunistic taxa (e.g. N. turgida) by enhanced reproduction and growth (Buzas, 1968; Hohenegger et al., 1989, 1993; Buzas and Gibson, 1990; Silva et al., 1996; Swallow, 2000; Buzas et al., 2002; Morvan et al., 2006)*".

RC **(B)** The author put quite some efforts on the characterization of food sources and biogeochemical processes at the sea floor. Without any doubt, this information is crucial for the understanding of faunal composition and environmental variability. However, additional information on the detrital components of the substrate, particularly grain size composition, appears also important since substrate changes commonly influence biogeochemical processes in the surface sediment. In this context, presentation and discussion of any available granulometric data would be useful. Since the authors studied the 63-150 µm and >150 µm fraction, they should at least be able to provide information on the sand versus pelite content.

AC We agree with this suggestion. Grain size analyses were performed at both stations in the top 5 cm of sediment for April 2007, May 2008 and December 2008. However, only the top half-centimetre was analysed for September 2007 (see Figure 1). Nevertheless, supplementary analyses will be performed to get the complete grain size profile down to 5 cm depth at both stations for this sampling period.

(a) Station A



(b) Station N

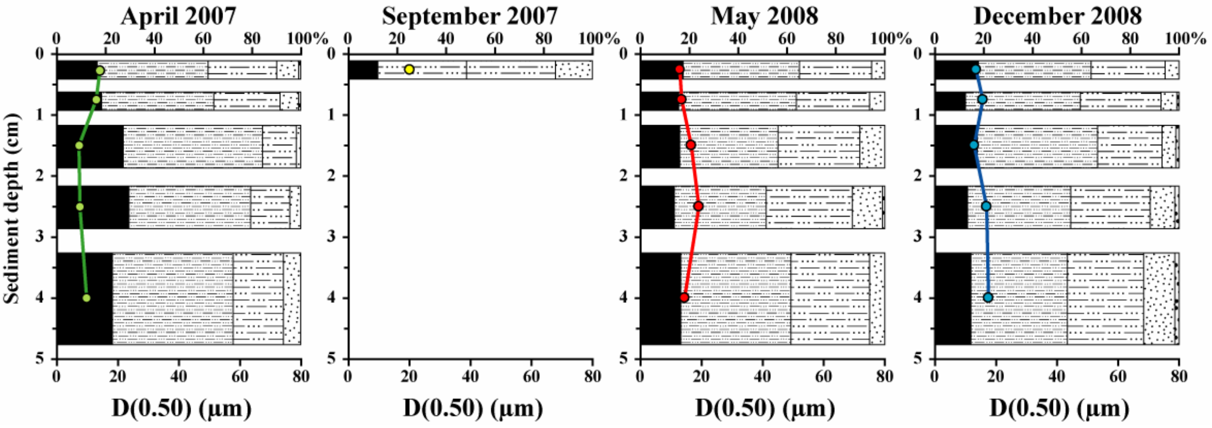


Figure 1: Sediment composition along the top 5 cm of the cores at both Stations A (a) and N (b). Horizontal bars represent clay, fine silts, coarse silts, fine sands and coarse sands contributions. Curves correspond to sediment median diameter D(0.50) for each sediment interval.

Compared to station N, Station A displays important changes of grain-size distribution. (D(0.50) = 6.7–67.1 µm). At this site, largest differences are observed between May and December 2008, when both samplings were performed few days to weeks after major floods. In May, the top 3 cm of sediment are composed of 82–84% of clay and fine silts (<20 µm); this layer corresponds to the "*flood deposit constituted by very light liquid mud*" already discussed in the paper (page 9050, lines 27-28). Below, clay and fine silts contribution decreases down to 47%.

In December 2008, we observe 51–53% of sand (>63 µm) in the top 2 cm of the core. This coarse layer was also noticed in the discussion and will now be referred as "*an approximately 2 cm-thick surficial deposit of sandy sediments*" (page 9052, lines 3-4). This coarse sediment is likely related to strong reworking processes (winnowing of fine sediments, deposition of coarse particles) induced by flood and/or wave-induced bottom currents. Despite significant sedimentary differences between May and December 2008, organic carbon and labile organic compounds show quite similar contents in the top half-centimetre of both periods. Similarly, when considering the two other sampling periods (April and September 2007), very close dissolved oxygen uptake values are recorded in the silty (D(0.50) = 38.5 µm) and in the sandy sediments (D(0.50) = 63.7 µm) of April 2007 and December 2008, respectively. On the contrary, sediments with similar grain size characteristics (i.e., April and September 2007: D(0.50) = 38.5–42.1 µm) present quite different DOU. Therefore, no clear correlation exists between sediment grain size, organic matter content and bio-geochemical processes related to its mineralisation. It seems "logical" when you consider that most geochemical processes occur in unsteady states in such river-dominated environment.

RC **(C)** The authors demonstrate that the ecosystems of the shallow site (Station A, 24 m water depth) are strongly impacted by flood events of the Rhone River. Because of its shallow water depth, this site will be also influenced by wave and current action, particularly during the stormy winter season. As far as I know, storm wave base is well below 24 m water depth. The potential impact of wave action is neglected in the discussion of faunal results although it likely influences the stability/variability of the shallow water benthic ecosystem. In the revised version, the authors should therefore address this issue.

AC The Reviewer 1 is right. It is assumed that storm waves can rework sediments down to 30 m depth (e.g., LCHF, 1976; Migniot and Viguier, 1980). We propose to assess this issue in the discussion paragraph about December 2008 sampling period (see below our response to comment D).

RC **(D)** The authors sliced the upper 5 cm of the cores providing the option for microhabitat studies. It is a pity that no data on the down-core distribution of the taxa are presented. Such information would have been particularly interesting to further characterize the differences between sites and seasons, and, specifically, to explain the mono-specific or low-diverse faunas after the major flood events. In December 2008, Station A was sampled only two days after a major flood event associated with a 3 cm thick silty layer that contains a monospecific assemblage of *L. scottii*. The authors speculate that the individuals of *L. scottii* may have been transported with the flood event and originate from shallower environments in the river mouth which may well be correct. Below the suspension layer, the former surface layer should be still present, if not eroded by the flood event. If not eroded, I would expect the 3-5 cm layer to contain quite some stainable foraminifers of the pre-event fauna, because they are either still alive or have only recently died due to burial. On the other hand, absence of stained individuals of the pre-event fauna in the 3-5 cm level would suggest either that sediment was eroded by the flood event or that disturbance was not solely caused by the river flood but may have been preceded by other disturbances, such as wave action during winter storms or other flood events. Therefore, I strongly recommend that in the revised version, the authors will add data on the down-core distribution of at least the major taxa in order to check for the presence and diversity of the pre-flood event fauna. This would add important data on the general variability of this site.

AC We think that the Reviewer 1 made some confusion between May and December 2008 data. Nevertheless, his/her comments on the vertical distribution of the faunas remain very relevant for the discussion. Also, following Reviewer 1's suggestions, we have represented on figure 2 the vertical distribution of the living faunas in May 2008 and in December 2008.

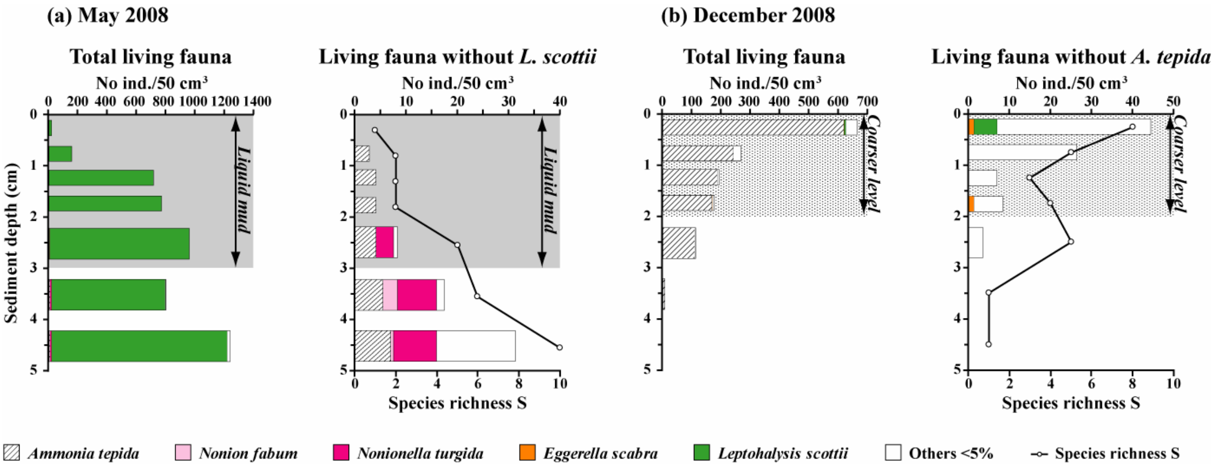


Figure 2: Vertical distribution of the major taxa at Station A in May 2008 (a) and December 2008 (b). On the right are represented the faunas without dominant taxa, i.e. without Leptohalysis scottii in May 2008 and without Ammonia tepida in December 2008.

In May 2008, the faunas were sampled 2 days after a flood. At Station A, we observed a ~4 cm-thick layer of liquid mud (Cathalot et al., 2010). Despite its very liquid nature, we found living individuals of *Leptohalysis scottii*. Unfortunately, we have no idea about the foraminiferal community living in the river mouth even if *L. scottii* might be adapted to dominate river-mouth environments. Indeed, its flexible and micaceous test might be an ecomorphological adaptation to colonise and thrive in high-energy (i.e. high-turbidity) environments. A close inspection of foraminiferal census data reveals relatively high species richness under the flood deposit, i.e., under the former sediment-water interface, with few individuals of *Nonion fabum*, *Nonionella turgida*, *Nonionella stella* and 8 other additional taxa (Figure 1). The association of *N. fabum*, *N. turgida* and *N. stella* was already observed in April 2007, constituting ~20% of the small-sized faunas and ~31% of the >150 size fraction. Therefore, these 3 taxa likely belong to the pre-flood faunas and, as suggested by the Reviewer 1, the sediment has not been eroded by the flood. At a farther and deeper site (45 m depth), the flood deposit was ~30 cm-thick ten days after sampling and was not eroded at least until October 2008 (Cathalot et al., 2010).

In December 2008, only ~20 cm of this soft mud from the May 2008 flood remains. A newly deposited sediment layer was visible over the softy mud, likely due to a flood 3 weeks before sampling (Cathalot et al., 2010). At our Station A, this sediment layer consists in a ~3-cm-thick silty deposit (see above, Comment B). Therefore, living foraminiferal faunas (and fine sediments) may have been removed when the November 2008 flood occurred. In December 2008, pioneer species have colonised the newly deposited OM-enriched sediment down to, at least, 4 cm depth (Figure 1b). This observation traduces the dynamic and unstable conditions prevailing at this shallow site at this sampling period. However, wave-generated currents may redistribute longshore sediments from the river mouth to the eastern coast, notably during the autumn and winter seasons when onshore winds generate high-energy waves (Suanez, 1997; Sabatier and Suanez, 2003). Therefore, in our study, the sediment erosion/deposition assumed at the shallowest station A close to the river mouth in December 2008 can be due either to flood- or to wind/wave-related bottom currents.

RC **(E)** The authors may also consider adding a short paragraph or subchapter on the fossilization potential of the Rhone prodelta faunas. Fossil assemblages should present an integration over various seasons and years. In this context, it would be interesting to discuss if information on the seasonal variability and impact of abrupt events were still traceable in the fauna, e.g. by appearance of opportunistic taxa. Such knowledge would be particularly useful for the interpretation of fossil assemblages from comparable shallow-water environments.

AC A paper focussing on fossilising faunas from the Rhône prodelta is in preparation. This study aims to calibrate the present-day distribution of sub-fossil foraminiferal faunas to make them a reliable tool for paleo-environmental reconstructions in the Rhône prodelta. In order to do so, we compare the living and dead foraminiferal faunas (>150 µm) from 39 stations sampled in June 2005 and September 2006 between 15 and 100 m depth. This comparison highlights that both physico-chemical (transport, fragmentation/dissolution) and biological processes modify the composition of the sub-fossil faunas in the Rhône prodelta. For instance, high production rates may explain higher relative abundances of opportunistic species in the dead fauna such as, e.g., *Bulimina marginata, Cassidulina carinata, Nonionella turgida, Valvulineria bradyana*. Thereafter, cluster analyses based on dead foraminiferal assemblages divide our study area into four main thanatofacies directly related to precise environmental conditions: “River mouth”, i.e., highest riverine influence (bottom currents, organic and inorganic material input); “Coastal area”, i.e., relict deltaic lobe west of the river mouth (silty-sandy sediments, strong longshore currents); “River plume”; “Outer shelf”, i.e., the deep southern to south-eastern prodeltaic area (more stable conditions, foraminiferal species able to feed on fresh phytodetritus). Then, we illustrate our conclusions with a multiproxy study on a 400-year-long sediment core recovered by 79 m depth in the Rhône prodelta (Fanget et al., Submitted to Marine Geology). A succession of foraminiferal faunas from outer shelf to river plume thanatofacies highlights the gradual increasing riverine influence at our study site induced by the successive migrations of the Rhône channels over the last 400 years. Finally, this study puts into evidence minor variations between the living and the dead faunas, and improves the use of benthic foraminiferal faunas to investigate the paleo-Rhône prodelta through the study of fossil foraminiferal archives. Unfortunately, no clear foraminiferal assemblage appears indicative of abrupt events (e.g., major floods) in the present sub-fossil faunas. Nevertheless, in the fossil archive, violent events such as Rhône channel migrations are marked by the occurrence of species from shallow areas as far as ~4 km away from the mouth.

In the present paper submitted in Biogeosciences, we propose to present issues concerning foraminiferal fossilisation in the conclusion as an important work (draft to be submitted in Marine Micropaleontology). As far as it would be too long, we don’t want to add our fossil data in the present draft.

References

Buzas, M. A.: On the spatial distribution of foraminifera, Contribution from the Cushman Foundation for Foraminiferal Research, 19, 1-11, 1968.

Buzas, M. A., and Gibson, T. G.: Spatial distribution of Miocene foraminifera at Calvert Cliffs, Maryland, Smithsonian Contributions to Paleobiology, 68, 1-35, 1990.

Buzas, M. A., Hayek, L. A. C., Reed, S. A., and Jett, J. A.: Foraminiferal densities over five years in the Indian River Lagoon, Florida: A model of pulsating patches, J. Foramin. Res., 32, 68-93, 2002.

Cathalot, C., Rabouille, C., Pastor, L., Deflandre, B., Viollier, E., Buscail, R., Grémare, A., Treignier, C., and Pruski, A.: Temporal variability of carbon recycling in coastal sediments influenced by rivers: assessing the impact of flood inputs in the Rhône River prodelta, Biogeosciences, 7, 1187-1205, 2010.

Fanget, A. S., Bassetti, M. A., Arnaud, M., Chiffoleau, J. F., Cossa, D., Goineau, A., Fontanier, C., Buscail, R., Jouet, G., Maillet, G., Negri, A., Dennielou, B., and Berné, S.: Historical evolution and extreme climate events during the last 400 years on the Rhône prodelta (NW Mediterranean), Mar. Geol., Submitted.

Goineau, A., Fontanier, C., Jorissen, F. J., Lansard, B., Buscail, R., Mouret, A., Kerhervé, P., Zaragosi, S., Ernoult, E., Artéro, C., Anschutz, P., Metzger, E., and Rabouille, C.: Live (stained) benthic foraminifera from the Rhône prodelta (Gulf of Lion, NW Mediterranean): Environmental controls on a river-dominated shelf, J. Sea Res., 65, 58-75, 2011.

Hohenegger, J., Piller, W., and Baal, C.: Reasons for spatial microdistributions of foraminifers in an intertidal pool (northern Adriatic Sea), Marine Ecology, 10, 43-78, 1989.

Hohenegger, J., Piller, W. E., and Baal, C.: Horizontal and vertical spatial microdistribution of foraminifers in the shallow subtidal Gulf of Trieste, northern Adriatic Sea, J. Foramin. Res., 23, 79-101, 1993.

LCHF: Action de la houle sur les sédiments, étude réalisée par le Centre National pour l'EXploitation des Océans (CNEXO), Tomes 1 et 2, 200 pp., 1976.

Migniot, C., and Viguier, J.: Influence de l'extraction des granulats en mer sur l'équilibre du littoral, La Houille Blanche, 3-1980, 177-193, 1980.

Mojtahid, M., Jorissen, F., Lansard, B., Fontanier, C., Bombled, B., and Rabouille, C.: Spatial distribution of live benthic foraminifera in the Rhône prodelta: Faunal response to a continental-marine organic matter gradient, Mar. Micropaleontol., 70, 177-200, 2009.

Morvan, J., Debenay, J.-P., Jorissen, F., Redois, F., Bénéteau, E., Delplancke, M., and Amato, A.-S.: Patchiness and life cycle of intertidal foraminifera: Implication for environmental and paleoenvironmental interpretation, Mar. Micropaleontol., 61, 131-154, 2006.

Sabatier, F., and Suanez, S.: Evolution of the Rhône delta coast since the end of the 19th century, Géomoprhologie: Relief, Processus, Environnement, 47, 283-300, 2003.

Silva, K. A., Corliss, B. H., Rathburn, A. E., and Thunell, R. C.: Seasonality of living benthic foraminifera from the San Pedro Basin, California Borderland, J. Foramin. Res., 26, 71-93, 1996.

Suanez, S.: Dynamiques sédimentaires actuelles et récentes de la frange littorale orientale du delta du Rhône, PhD Thesis, Université d’Aix Marseille I, 1997.

Swallow, J. E.: Intra-annual variability and patchiness in living assemblages of salt-marsh foraminifera from Mill Rythe Creek, Chichester Harbour, England, Journal of Micropalaeontology, 19, 9-22, 2000.