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Deep-sea benthic foraminifera at a bauxite industrial waste site in the Cassidaigne Canyon (NW Mediterranean): Ten months after the cessation of red mud dumping

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Abstract. During an environmental survey performed in autumn 2016, living (stained) benthic foraminiferal faunas were investigated at 16 stations sampled within the Cassidaigne Canyon (NW Mediterranean Sea) and surrounding area and located between 265–2500 m water depth. For many decades, industrial bauxite residues of red mud have drained into the canyon via a submarine pipe, causing physical disturbance and chemical contamination. In January 2016, solid waste disposal ceased and was replaced with the dumping of a low-density liquid effluent. Our ecological observations at the 725 m-depth station closest to the Cassidaigne Canyon submarine pipe show the highest concentration of the opportunistic species, and a strongly altered benthic diversity. At the other fifteen stations, foraminiferal standing stocks and simple diversity decrease with decreasing food input to the seafloor and increasing water depth. There, foraminiferal composition with a minor contribution of stress-tolerant species echoes the overall meso-oligotrophic patterns of a relatively stable ecosystem.

Keywords. Benthic foraminifera, Bauxite residues, Cassidaigne Canyon, Opportunistic species.

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1. Introduction

Deep-sea foraminifera (Eukaryota, Rhizaria) are an important ecological group of benthic meiofauna (see the review by Gooday, 2003, Zeppilli et al., 2015). In natural settings, their faunal patterns (standing stocks, diversity, microhabitat) are controlled by many physico-chemical parameters. Organic-matter flux reaching the sea floor is one of their most important ecological constraints [Gooday, 2003]. The organic-matter flux acts indirectly as an ecological limiting factor when it induces either temporary or long-term hypoxia either in the sediment or in the bottom water Fontanier et al. [2014], Gooday et al. [2000], Kurbjeweit et al. [2000], Schumacher et al. [2007]. Sediment gravity flows passing down active submarine canyons can supply organic detritus and inorganic particles to the deep ocean. Foraminiferal faunas living in these naturally disturbed habitats are characterized either by various stages of colonization occurring after physical disturbance (e.g. turbidity flows), or by equilibrium phases related to the gradual accumulation of organic-matter (e.g. eutrophication) [Duros et al., 2011, 2013, Fontanier et al., 2008a,b, Hess and Jorissen, 2009, Hess et al., 2005, Koho et al., 2007, 2008]. Due to their relatively short life cycle, environmental change can be quickly recorded via foraminiferal assemblage change. Therefore, foraminifera make ideal candidates for the monitoring of environmental stress related to human activities Schönfeld et al. [2012], Zeppilli et al. [2015].

Between 1967 and 2015, bauxite residues (namely red mud) were dumped into the Cassidaigne Canyon by the Gardanne alumina refinery (South-East of France) (see review by Dauvin [2010]). Bauxite red mud (a combination of liquid effluent and residual solid) was drained away by a submarine pipe and discharged at a water depth of 320 m, about 8 km offshore the coast. This sedimentary material spread along the axis of the Cassidaigne Canyon and on its lateral flanks to great depths (>2000 m) [Dauvin, 2010, Fabri et al., 2013, Fontanier et al., 2012, 2015]. The total coverage of discharged red mud was estimated to be more than 900 km^2. In January 2016, red mud dispersal ceased and industrial wastes are now sieved and the solid fraction stored on land (see https://alteo-environnement-gardanne.fr/-Fabrication-et-stockage for further information). Since then, only residual liquid effluent has been released from the pipeline outlet into the Cassidaigne Canyon. This liquid, characterized by a density lower than the ambient sea water, is gradually diluted as it rises up the water column.

Environmental studies have been carried out for the last five decades in order to elucidate the impact of red mud on the deep-sea metazoan benthos [Bourcier, 1969, Bourcier and Zibrowius, 1973, Bourcier et al., 1993, Fabri et al., 2013, Vitiello and Vivier, 1974, Vivier, 1978a,b]. Those investigations proved that, close to the pipe outlet, the hydro-sedimentary contamination related to the flooding of red muddy material (i.e., high sedimentation rate) precluded benthic meiofauna and macrofauna settlement along the canyon axis. In the surrounding areas, normal macrofauna with suspension and deposit feeders were able to thrive, despite the presence of in a thin layer of red mud. Fontanier et al. [2012] conducted an ecological study of foraminiferal faunas from two stations located at 725 m and 1528 m along the axis of the Cassidaigne Canyon (NW Mediterranean Sea) (ESSROV cruise, October 2011). At both studied sites, sediments were highly contaminated by iron, titanium, vanadium and chromium compared to normal hemipelagic sediments. At the shallower station located close to the pipe outlet, the living benthic foraminiferal community was characterized by very low diversity (only three species) and by the unusual dominance of *Gyroidina umbonata* (Silvestri, 1898) and *Bulimina marginata* d'Orbigny, 1826. The physical disturbance related to red mud deposition was likely the major hydro-sedimentary parameter precluding the settlement of diverse fauna. Conversely, the living foraminiferal fauna from the deeper site was typical of oligo-mesotrophic conditions prevailing in natural environments. There, bauxite residues had no environmental impact on foraminiferal faunas. Nearly one year later (September 2012), fourteen stations located between 288–2432 m water depth at varying proximity to the pipe outlet were sampled [Fontanier et al., 2015]. Due to more extensive coring, Fontanier et al. [2015] evaluated the impact of red mud dispersal in the Cassidaigne Canyon, not along its axis but on its flanks, and its surrounding area (adjacent canyons and the deep basin). Deposits of red mud were observed in the Cassidaigne and Planier Canyons down to ~2000 m (coverage area ~900 km^2).

The diversity, composition and standing stock patterns for foraminiferal faunas in this area represented assemblages predominantly constrained by overall meso-oligotrophic conditions. The reduction of sedimentary organic detritus with varying water depth and the ecological constraint determined by bottom currents generated gradual changes in foraminiferal communities, regardless of red mud presence. Compared to the canyon axis studied by Fontanier et al. [2012], there was no obvious environmental impact of dispersed bauxite residues on benthic biodiversity at the sampling period (September 2012).

In September and October 2016, four years after the last foraminiferal investigation in the Cassidaigne canyon and its surrounding area (September 2012), and ten months after the cessation of red mud dumping (January 2016), more extensive core collections than those previously performed by Fontanier et al. [2012, 2015] were gathered in the frame of a statutory survey. Foraminiferal communities were sampled at 16 stations located between 265–2500 m with varying proximity to the pipe outlet (Figure 1; Table 1). Most of these sites are within the geographical zone where historical bauxite residues have been previously detected [Dauvin, 2010, Fontanier et al., 2012, 2015]. The main objective of our study is to determine the ecological patterns (diversity indices and faunal composition) of benthic environments some months after the cessation of solid waste dispersal in the Cassidaigne Canyon.

2. Study area

The Cassidaigne Canyon abuts the eastern Gulf of Lions and the Ligurian Sea (NW Mediterranean) (Figure 1 insert). The 200 m-deep canyon head borders the Cassis Bay at a distance of only 7 km from the coast and is characterized by a narrow canyon axis (1 km in width) (Figure 1).

The Northern Current (NC), which forms the northern branch of the cyclonic Liguro-Provençal Current (LPC), follows the continental margin from the Provence coast (France) to the coast of Catalonia (Spain) [Béthoux and Prieur, 1983, Millot, 1990]. The NC determines the general surface water circulation patterns. Below the surface waters (>200 m), spreads the modified Levantine Intermediate Water (LIW), which is characterized by a salinity maximum (~38.5) and a relative temperature maximum (>13 °C). The Western Mediterranean Deep Water (WMDW) occurs below the LIW with a diffusive boundary at 500–800 m [Béthoux and Prieur, 1983, Béthoux et al., 2002]. It is generally characterized by a rather homogeneous temperature (~13 °C) and salinity (38.40–38.45) [Béthoux and Prieur, 1983, Béthoux et al., 2002].

Our present study is based on sediment cores collected aboard the R/V *FéliX* during the monitoring oceanographic cruise, which took place in September and October 2016. Sixteen stations were sampled within and around the Cassidaigne Canyon (Table 1; Figure 1). Fourteen of these stations, starting with “U”, have already been studied by Fontanier et al. [2015] and the remaining two stations, SR1 and SR2, correspond approximately to sampling sites investigated in Fontanier et al. [2012]. Stations U03 (292 m) and U05 (751 m) are located at the head and on the eastern flank of the Cassidaigne Canyon. Stations SR2 (747 m) and SR1 (1553 m) are situated along the Cassidaigne Canyon axis. Stations U06–U09 are along the Planier Canyon between ~600–2000 m water depth. Both stations U02 and U10 are located along the deep valley where both the Marseille and Planier tributary canyons converge (>1800 m). U11 and U12 (>2200 m) are under the influence of the Marseille/Planier/Cassidaigne Canyon system. U28, U27 and U26 represent a bathymetric transect of the interfluve between the Petit Rhône and Grand Rhône Canyons (~1750 m) to the deep basin (~2400 m). Station U13 is located in the western branch of the Cap-Sicié Canyon (France), less than 7 km from the coast and around 25 km south-east of the pipe outlet.

In accordance with previous studies by Fontanier et al. [2012, 2015], reddish brown surface sediment was observed at most stations providing (with other physicochemical proves) qualitative evidence regarding the geographical and historical dispersal of bauxite residues (Table 1; CREOCEAN, 2018). Only stations U05 (725 m), U13 (958 m), U28 (1758 m), U27 (2250 m) and U26 (2432 m) were not contaminated by red mud deposits. Surface sediment (0–4 cm interval) Titanium (Ti) content, considered a geochemical proxy of red mud dispersal [Dauvin, 2010], matches relatively well with visual observations of sediment-water interface (Figure 2). Extraor-

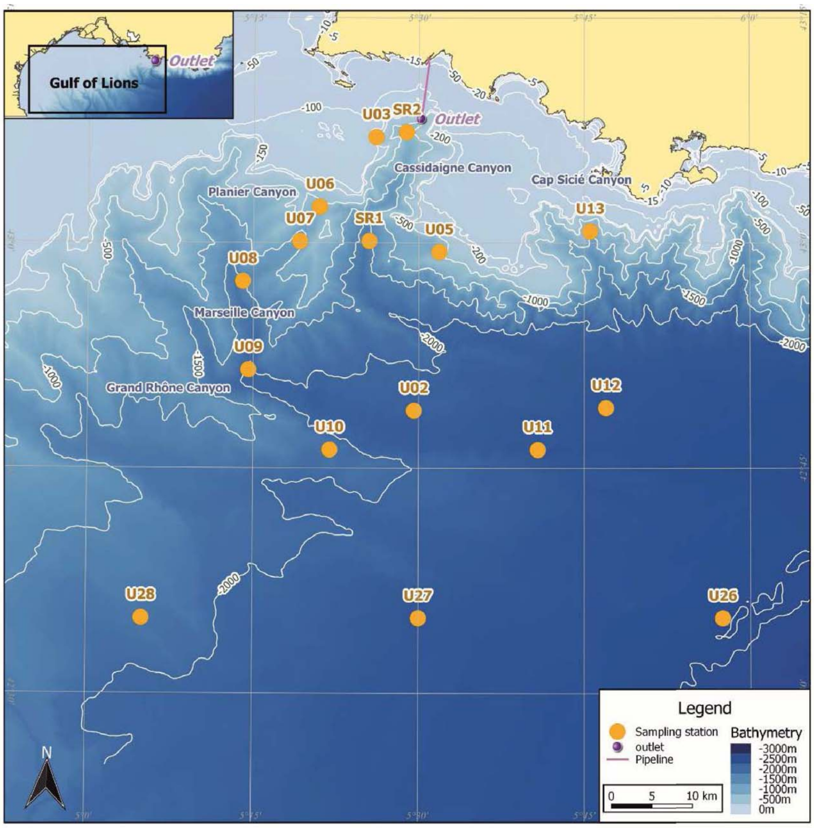

Figure 1. Bathymetry, study area and location of the 16 stations sampled during the 2016 oceanographic cruise (autumn 2016).

dinarily high Ti values were recorded at station SR2 (~32,000 $\mu g \cdot g^{-1}$ DW) and to a lesser degree, station SR1 (~20,500 $\mu g \cdot g^{-1}$ DW) confirming that bauxite residues accumulated preferentially along the Cassidaigne Canyon axis. For comparison, the Ti content of the pipeline dispersed red mud before January 2016 was ~70,000 $\mu g \cdot g^{-1}$ DW [SAFEGE, 2011]. Nepheloid layers and sediment gravity flows are considered the main hydro-sedimentary processes responsible for transferring the bauxite-derived material from the pipeline outlet along the Cassidaigne Canyon axis [Dauvin, 2010, Fabri et al., 2013, Fontanier et al., 2012, 2015]. Moderate to high Ti values were recorded at most of the other stations in adjacent canyons (between 3300 and 4400 $\mu g \cdot g^{-1}$ DW) even at great depths (~5100 $\mu g \cdot g^{-1}$ DW at station U10, 1800 m). As suggested by Fontanier et al. [2015], the region's episodically strong up- and down-welling currents coupled with efficient sediment transfer by both gravity and suspension flows could trigger the large spatial coverage of the natural and Ti-laden seafloor sediments. In contrast, samples from station U05 (725 m) and U13 (958 m) yielded relatively low Ti content (respectively ~3400 and ~3100 $\mu g \cdot g^{-1}$ DW) (Figure 2) [Fontanier et al., 2012, 2015]. As already discussed in Fontanier et al. [2015], both stations U05 and U13 are located in canyon areas not accessible by the bauxite residue (Figure 2). Stations U11 (2222 m), U12 (2290 m) and U02 (2100 m) located at the deeper connections between the Marseille, Planier and Cassidaigne Canyons, also exhibit low Ti content (between 2700 and 3100 $\mu g \cdot g^{-1}$ DW). Sites U28, U27 and U26, located more than 60 km away from pipeline outlet at depths greater than 1700 m, logically present Ti content close to natural background levels (<2400 $\mu g \cdot g^{-1}$ DW), an order of magnitude lower than the highly contaminated station SR2.

Table 1. Water depth, coordinates and physiographic settings of all stations sampled during the 2016 oceanographic cruise (autumn 2016)

Station	Sampling date	Latitude	Longitude	Depth (m)	Settings	Distance from the pipeline outlet (km)	Visual detection of red mud deposits
U03	31/08/2016	43° 07.05′ N	05° 26.11′ E	292	Head of the Cassidaigne Canyon	5.9	Reddish brown surface layer (several cm)
SR2	02/09/2016	43° 07.31′ N	05° 28.88′ E	747	Axis of the Cassidaigne Canyon	2.4	Reddish brown sediment
U05	03/09/2016	42° 59.40′ N	05° 31.85′ E	751	Eastern flank of the Cassidaigne Canyon	17.3	No
SR1	02/09/2016	43° 00.13′ N	05° 25.49′ E	1553	Axis of the Cassidaigne Canyon	16.3	Reddish brown surface layer (several cm)
U13	22/09/2016	43° 00.78′ N	05° 45.54′ E	952	Western Branch of the Cap-Sicié Canyon	25	No
U06	01/09/2016	43° 02.34′ N	05° 21.00′ E	605	Head of the eastern branch of the Planier Canyon	16.6	Reddish brown surface layer (several cm)
U07	01/09/2016	43° 00.09′ N	05° 19.21′ E	1056	Eastern branch of the Planier Canyon	21.2	Reddish brown surface layer (several cm)
U08	02/10/2016	42° 57.43′ N	05° 14.04′ E	1530	Axis of the Planier Canyon	29.7	Reddish brown surface layer (several cm)
U09	01/10/2016	42° 51.53′ N	05° 14.58′ E	1968	Axis of the Planier Canyon	37.5	Reddish brown surface layer (several cm)
U10	30/09/2016	42° 49.22′ N	05° 21.95′ E	1800	Connexion between both Marseille and Planier Canyons	42.3	Reddish brown patches at the sediment surface
U02	30/09/2016	42° 48.83′ N	05° 29.58′ E	2100	Connexion between both Marseille and Planier Canyons	36	Reddish brown patches at the sediment surface
U11	03/09/2016	42° 46.22′ N	05° 40.80′ E	2222	Connection between Marseille/Planier and Cassidaigne Canyons	43.3	Reddish brown surface layer (cm)
U12	07/10/2016	42° 49.01′ N	05° 46.97′ E	2290	Connection between Marseille/Planier and Cassidaigne Canyons	42.3	Reddish brown patches at the sediment surface
U28	04/10/2016	42° 35.00′ N	05° 05.00′ E	1758	Lower slope between Petit Rhône and Grand Rhô Canyons	72	No
U27	02/10/2016	42° 35.00′ N	05° 30.00′ E	2250	Deep Basin	61.6	No
U26	07/10/2016	42° 35.00′ N	05° 57.50′ E	2432	Deep Basin	72	No

3. Material and methods

This study constitutes a snapshot of ecological conditions prevailing during September/October 2016 in the Cassidaigne Canyon and surrounding area. Many works on living foraminifera were performed in the Gulf of Lions and in the Ligurian Sea before our present study [Bizon and Bizon, 1984, Contreras-Rosales et al., 2012, De Rijk et al., 2000, Fontanier et al., 2008a,b, 2015, Goineau et al., 2012, 2011, Schmiedl et al., 2000]. They provide reliable information concerning what we might expect in terms of natural foraminiferal abundance and distribution in the region. Furthermore, a foraminiferal response to red mud pollution in the axis of the Cassidaigne Canyon has already been documented by Fontanier et al. [2012]. This work and other recent papers regarding foraminiferal recolonization in canyon settings [Duros et al., 2011, 2013, Hess and Jorissen, 2009, Hess et al., 2005] provide a reliable basis on which to assess the potential impact of red mud dispersal on foraminiferal biodiversity and its potential

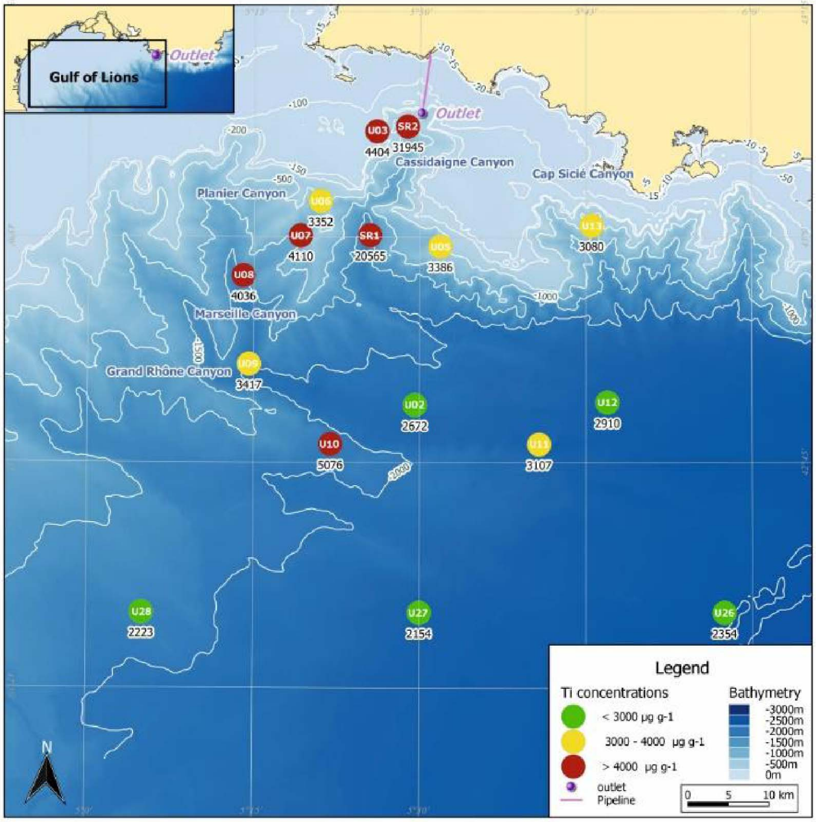

Figure 2. Titanium (Ti) content in surface sediments (0–4 cm interval) collected at 16 stations (2016 oceanographic cruise, autumn 2016). The Ti content is indicated using a 3-class color code). This data was taken from the survey report by CREOCEAN (CREOCEAN, 2018).

resilience since January 2016, when red mud dispersal ceased).

3.1. *Samplings*

Sediment samples were collected with a Barnett-type multiple corer equipped with Plexiglas tubes (9.3 mm internal diameter, surface area of 68 cm^2) [Barnett et al., 1984]. The multi-corer allowed sampling of the uppermost centimeters of the sediment column, the overlying bottom waters, and a comparatively undisturbed sediment-water interface. It was deployed once at each station. One core from each site was used for this foraminiferal study. The cores were sliced horizontally every 0.5 cm from the sediment-water interface (SWI) down to 2 cm. Because of meteorological constraints (strong swell), the multicorer could not be deployed at stations U13 (952 m), U12 (2290 m) and U26 (2432 m). There, sediment samples were collected with an USNEL box corer (surface area of 2500 cm^2). A Plexiglas tube (internal diameter 9.3 cm, surface area of 68 cm^2) was used to subsample a sediment core. The uppermost 2 cm were similarly sliced to the Barnett cores for foraminiferal analyses. All potential methodological biases related to foraminiferal sampling with a box corer have been discussed previously by Fontanier et al. [2015]. To understand overall ecosystem variability, triplicates are recommended at each sampling site [Schönfeld et al., 2012]. Despite this, most ecological papers studying deep-sea living (stained) foraminiferal communities use only one core per site. To facilitate effective comparisons between previous work of this kind, we have also only used one core per site. Nevertheless, readers should consider our observations and interpretations with care as they may be

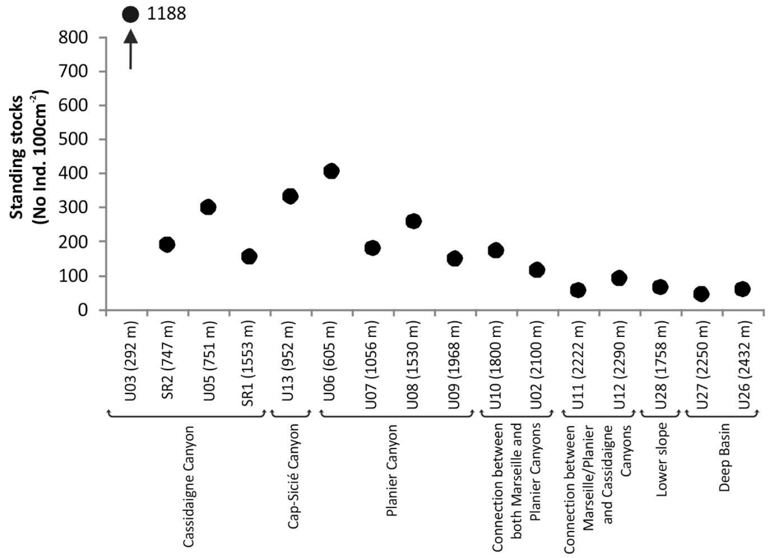

Figure 3. Standing stocks (No. Ind. 100 cm^{-2}) of living (stained) foraminiferal faunas at the 16 investigated stations. Stations are arranged by both physiographic setting and increasing depth.

biased by potential spatial (cm to m scale) variability that we cannot fully account for with our data sets.

3.2. *Benthic foraminiferal analysis*

Whilst on board, sediment samples dedicated to foraminiferal study were transferred to 250 cm^3 bottles filled with 95% ethanol containing 2 $g{\cdot}L^{-1}$ Rose Bengal stain, commonly used to identify live foraminifera [Murray and Bowser, 2000, Walton, 1952]. All samples were gently shaken for several minutes to obtain a homogeneous mixture. One month after the cruise they were sieved through a 125 µm screen and the sieve residues were stored in 95% ethanol. Well-stained foraminifera (all chambers excluding the final stained bright pink) were sorted in wet samples and stored in Plummer slides. Strict staining criteria were applied and doubtful individuals without perfectly stained tests were not included. Non-transparent agglutinated and miliolid taxa were broken on many occasions for inspection of the interior of the test. Most live foraminifera were identified to species level. All data generated or analysed during this study are included in this published article (See Supplementary material). At each station, we calculated diversity indices including simple diversity S (representing the number of species), Shannon index H' (log base e), Rarefied Species Richness $E(S_{35})$ and Dominance index D [Hayek and Buzas, 1997, Murray, 2006]. These indices were based on counts of stained specimens from the four depth horizons analysed in each core. Census data are available on request to the first author of this publication.

4. Results

4.1. *Foraminiferal standing stocks and diversity*

Foraminiferal standing stocks ranged between ~50 (U27, 2250 m) and ~1190 (U03, 265 m) individuals 100 cm^{-2} (Figure 2). Values were lower (<100 individuals 100 cm^{-2}) at depths greater than 2200 m compared to shallower stations. Simple diversity (S) varied between 7 (U26, 2500 m) and 61 (U03, 265 m) species (Figure 3). Diversity generally decreased with increasing water depth, with S values lower than 12 species below 2200 m. The only exceptions were recorded at stations SR2 (747 m) and SR1 (1553 m) located along the Cassidaigne Canyon axis where only 13 and 11 taxa were identified respectively. Shannon index H' and Rarefied Species Richness $E(S_{30})$ followed the same trend (Figure 3) as values were low at stations deeper than 2200 m compared to more shallow sites. Once again, stations SR2 and SR1 were exceptions with low H′ (<1.8) and $E(S_{30})$ (<7) values corresponding to the very low simple diversity and strong dominance. Dominance index D and Shannon index values were inversely related.

4.2. *Faunal composition*

At the head of the Cassidaigne Canyon (station U03, 292 m), *Melonis barleeanus* (Williamson, 1858) (32%) and *Valvulineria bradyana* (Fornasini, 1900) (18%) dominated the living fauna (Figure 4). Along the axis of the Cassidaigne Canyon (station SR2, 747 m), *Bulimina marginata* d'Orbigny, 1826 (50%) and *Gyroidina altiformis* Stewart & Stewart, 1930 (27%) were dominant. At the same depth on the eastern flank of the Cassidaigne Canyon (station U05, 751 m), *Bigenerina nodosaria* d'Orbigny, 1826 (16%) and *Rosalina bradyi* (Cushman, 1915) (16%) were the most abundant living fauna. At station SR1 (1553 m) located along the Cassidaigne Canyon axis, foraminiferal fauna were dominated by *Uvigerina mediterranea* Hofker, 1932 (43%), *Uvigerina peregrina* Cushman, 1923 (19%) and *Hoeglundina elegans* (d'Orbigny, 1826) (15%). In the Sicié Canyon, and along the Planier Canyon axis (<2000 m water depth), *M. barleeanus* was dominant with a relative contribution ranging between 10% and 30% at both stations U08 (1530 m) and U13 (952 m) respectively. *Globobulimina affinis* (d'Orbigny, 1839) was abundant (16%) in the Sicié Canyon (station U13, 952 m). *Uvigerina mediterranea* Hofker, 1932 and *Uvigerina peregrina* Cushman, 1923 were both substantial components (>10%) at stations U06, U07 U08 and U10 (ranging between 605–1800 m). Deeper than ~2000 m, *Nodellum membranaceum* (Brady, 1879) was the dominant species with percentages between 11% (U09, 1968 m) and 83% (U26, 2432 m) (Figure 4) and agglutinated *Lagenammina calcarea* (Cushman, 1947) and *Thurammina albicans* (Brady, 1879) were secondary taxa.

5. Discussion

5.1. *Natural trophic control on foraminiferal faunas in the Cassidaigne Canyon surrounding (Figure 5)*

As already discussed by Fontanier et al. [2015], based on samples collected in September 2012, all stations except SR2 and SR1 located in the Cassidaigne Canyon axis, present a decrease in both foraminiferal density and diversity (S) with water depth (Figures 3 and 4). Low-diversity foraminiferal faunas are documented in the deeper basin and on the distal lower slope compared to more diverse communities from other shallower stations. This trend is likely related to the natural scarcity of food (i.e. sedimentary organic matter) at varying depths, which echoes (1) the natural decrease of exported primary productivity (i.e. fresh phytodetritus) with increasing water depth and (2) the naturally diminishing lateral advection of degraded organic compounds from neritic areas to deep-basin stations [Fontanier et al., 2015].

The faunal composition of the isolated foraminiferal communities confirms the major role of organic matter supply on the ecological status of benthic ecosystems. For instance, *Melonis barleeanus* is a major species at stations between ~290–2000 m where the overall sedimentary input of organic matter is considered relatively high [Fontanier et al., 2015]. Accordingly, this taxon is abundant in mesotrophic and well-oxygenated environments [Caralp, 1989a,b, Duros et al., 2011, 2013, Fontanier et al., 2002, 2003, 2005, 2008a,b, Koho et al., 2007, Kurbjeweit et al., 2000, Licari et al., 2003, Schmiedl et al., 2000]. In both open slope and canyon settings, *M. barleeanus* thrives generally in deep microhabitats below the sediment-water interface where it feeds on degraded organic matter. This supports the assumption that most of the bathyal stations are characterized by the input of low-quality organic compounds, likely transported laterally by along-slope currents. Furthermore, the co-occurrence of *U. mediterranea* and *U. peregrina* is in agreement with bathyal faunas described in the western Mediterranean Sea. These uvigerinids are generally described as shallow infaunal species able to feed on relatively fresh organic detritus in mesotrophic ecosystems [Contreras-Rosales et al., 2012, De Rijk et al., 2000, Duros et al., 2011, 2013, Eberwein and Mackensen, 2006, Fontanier et al., 2002, 2003, 2006, 2008b, Koho et al., 2007, 2008, Schmiedl et al., 2000]. *Uvigerina peregrina* is considered an opportunistic species feeding on freshly exported phytodetritus in canyon and slope environments whereas *U. mediterranea* is a reactive taxon able to grow and reproduce when food is available in the surface sediment [Duros et al., 2011, 2013, Fontanier et al., 2003]. To summarize, the fact that the *M. barleeanus*

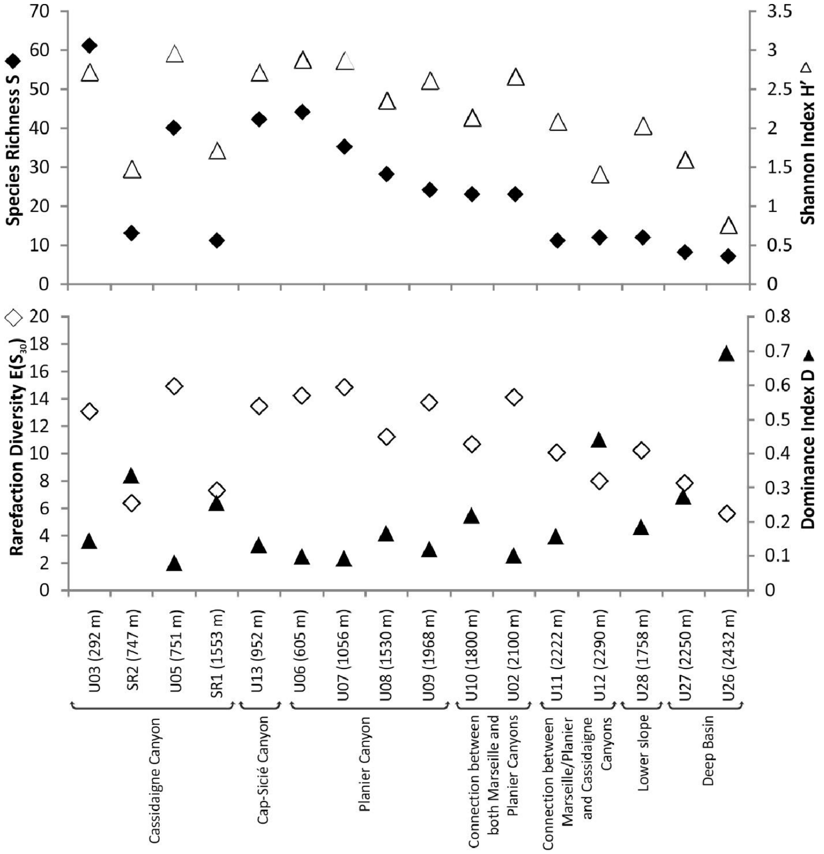

Figure 4. Simple diversity S, Shannon diversity index H′, Rarefied Species Richness E(S_{30}) and Dominance index D of living (stained) foraminiferal faunas at the 16 investigated stations. Stations are arranged by both physiographic setting and increasing depth.

and uvigerinid faunal association originally found in the autumn 2012 biomonitoring [Fontanier et al., 2015], still prevails in autumn 2016, shows that the mesotrophic conditions within the canyon systems adjacent to the Cassidaigne Canyon are independent of bauxite residues. Furthermore, the dominance of the outer-shelf/upper-bathyal species *V. bradyana* with *M. barleeanus* at the shallowest station U03 (292 m) indicates an ecosystem enriched in organic detritus [Fontanier et al., 2002, Goineau et al., 2011, Hess and Jorissen, 2009, Langezaal et al., 2006]. It is a common species in rich and diverse faunal assemblages encountered in canyon-head environments where there is no sediment redeposition [Hess and Jorissen, 2009]. The co-occurrence of *M. barleeanus* and *V. bradyana* suggests that meso-eutrophic conditions prevail at the shallowest station. The remarkable presence of *R. bradyi* at stations U05 (751 m), U13 (952 m) and U06 (U06) is questionable. This euryhaline taxon is abundant in neritic areas with a preference for an epiphytic and/or epilithic life habit in inner shelf environments [Fontanier et al., 2008a]. Whilst attached to vegetation, individuals of this species can be transported by bottom currents into canyons [Fontanier et al., 2008a]. Therefore, the occurrence of *R. bradyi* at our sample sites further underlines a natural source-to-sink connection in terms of organic supply and sediment transfer between upper-slope environments and deeper adjacent shelves. In autumn 2012, the dominance of *Globobulimina* spp. and a relatively high organic content (1.4% DW) suggested a preferential focusing of organic compounds at station U13 [Fontanier et al., 2015], a site located in the western branch of

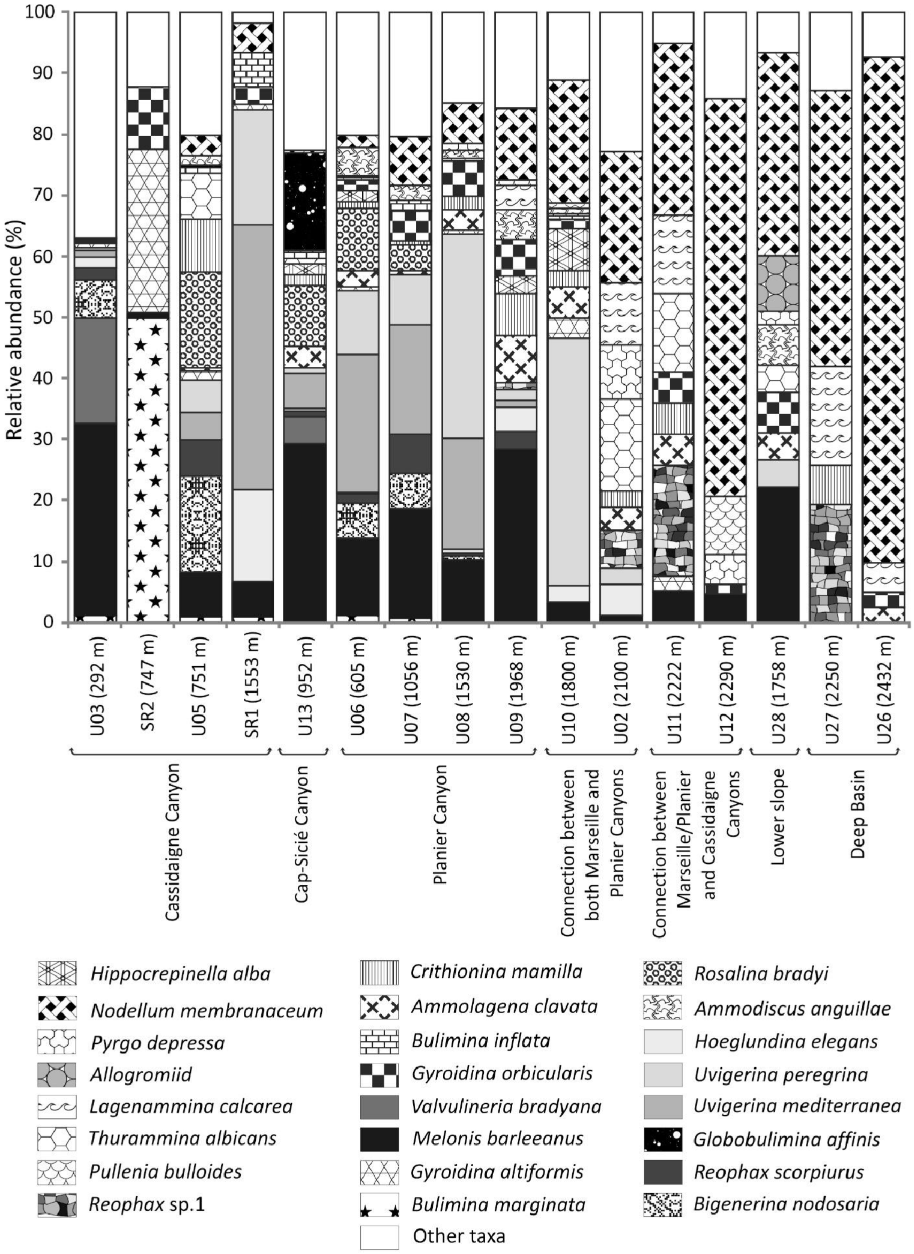

Figure 5. Composition of benthic live (stained) foraminiferal faunas at the 16 investigated stations. Only major species (at least >5% at one site) are illustrated. Stations are arranged by both physiographic setting and increasing depth.

the Cap Sicié Canyon only 7 km from the coast. In autumn 2016, *Globobulimina* spp. remains a substantial component (20%) of the living faunal assemblage after *M. barleeanus*. This genus is considered a highly specialized taxon able to feed on low-quality organic detritus that collects within eutrophicated canyon depressions [Fontanier et al., 2005, 2008a]. Below 2000 m, the foraminiferal community is dominated by *N. membranaceum, P. depressa, L. calcarea, Thurammina albicans* Brady, 1879 and *Pullenia* *bulloides* (d'Orbigny, 1846). Similarly, these observations coincide with the autumn 2012 faunal patterns and surface sediment organic carbon content [Fontanier et al., 2015]. All above-mentioned taxa are typical of oligotrophic basins from the western Mediterranean Sea [Bizon and Bizon, 1984, De Rijk et al., 2000, Fontanier et al., 2008b, 2012, 2015]. This suggests that our deeper sample sites (>2000 m) are affected by a limited input of organic compounds, likely related to either exported primary productivity or lateral advection of reworked phytal remains.

5.2. *Questionable ecological resilience along the Cassidaigne Canyon axis*

In autumn 2012, a 725 m-deep sample site was characterised by a very low-diversity fauna ($S = 3$ and $H' = 0.76$) and dominated by the opportunistic and stress-tolerant species *Gyroidina umbonata* and *Bulimina marginata* [Fontanier et al., 2012]. Considered pioneer taxa, the species found at this site indicate intense hydro-sedimentary pollution due to the red mud deposition along the axis of the Cassidaigne Canyon. Our results from autumn 2016 at site SR2 (747 m), located very close to the autumn 2012 site, show that diversity has increased ($S = 13$; $H' = 1.67$). *Bulimina marginata* dominates, contributing 50% of the living fauna. This taxon is documented as an opportunistic species living in outer-shelf and upper-slope environments, at both early and advanced stages of recolonization in active canyons (e.g. Fontanier et al., 2003, Goineau et al., 2011, Hess and Jorissen, 2009, Hess et al., 2005, Langezaal et al., 2006. *Gyroidina altiformis* constitutes 27% of the living community and is generally a very low contributor (<1%) to bathyal foraminiferal faunas in the Western Mediterranean al., 2013; Sea and the North-east Atlantic Ocean (e.g., Duros et al., 2011, 2013, Fontanier et al., 2002, 2008a,b, 2015). Its dominance with *B. marginata* at station SR2 may underline its exceptional ability as a pioneer species in a first step of sediment recolonization after extended extreme environmental stress. As described by Anschutz et al. [2002] and Hess et al. [2005] in Cap Breton canyon (NE Atlantic), the overall biotic recovery of foraminiferal fauna was uncompleted two years after recent turbidite deposition. Therefore, in our study area, only 10 months after a historical change in the nature of discharged industrial waste in the region (from the dumping of dense red mud to liquid effluent release), it is fairly natural to document at station SR2 an ongoing recolonization characterized by a low diversity fauna. In Figure 6, we illustrate the proportion of opportunistic, stress-tolerant foraminiferal taxa which were documented as potential recolonizers of freshly disturbed areas (*Psammosphaera* spp., *Saccammina* spp., *Technitella* spp., *R. scorpiurus, Quinqueloculina seminula* (Linneaus, 1758), *G. umbonata, B. marginata)* [Fontanier et al., 2012, 2013, Hess and Jorissen, 2009, Hess and Kuhnt, 1996, Hess et al., 2005, Kaminski, 1985]. We added *G. altiformis* to this group as a potential stress-tolerant taxon. At station SR2, opportunistic and pioneer taxa constitute more than 80% of the fauna, indicating a stressed community is recovering from ecosystem upheaval. Yet at all stations except SR2, opportunistic recolonizers account for less than 5% of the living faunas (Figure 6) where benthic foraminifera thrive in relatively stable ecosystems and natural trophic conditions control diversity, density and composition.

6. Conclusions

In autumn 2016, ten months after red mud dispersal ceased in the Cassidaigne Canyon, foraminiferal communities were sampled at 16 stations located between 265–2500 m water depth at varying proximity to the pipe outlet. Our ecological observations at the 725 m station (station SR2) located closest to the submarine pipe along the Cassidaigne Canyon axis show the highest concentration of the opportunistic and stress-tolerant species *Bulimina marginata*, commonly identified as a recolonizer of disturbed areas. At the other fifteen stations, foraminiferal standing stocks and simple diversity (S) decrease with increasing water depth and decreasing food input to the seafloor. There, the foraminiferal composition is characterized by a minor contribution of stress-tolerant species, echoing the overall meso-oligotrophic patterns of relatively stable ecosystems. Our study clearly shows that foraminiferal diversity close to pipe outlet in the Cassidaigne Canyon remains altered.

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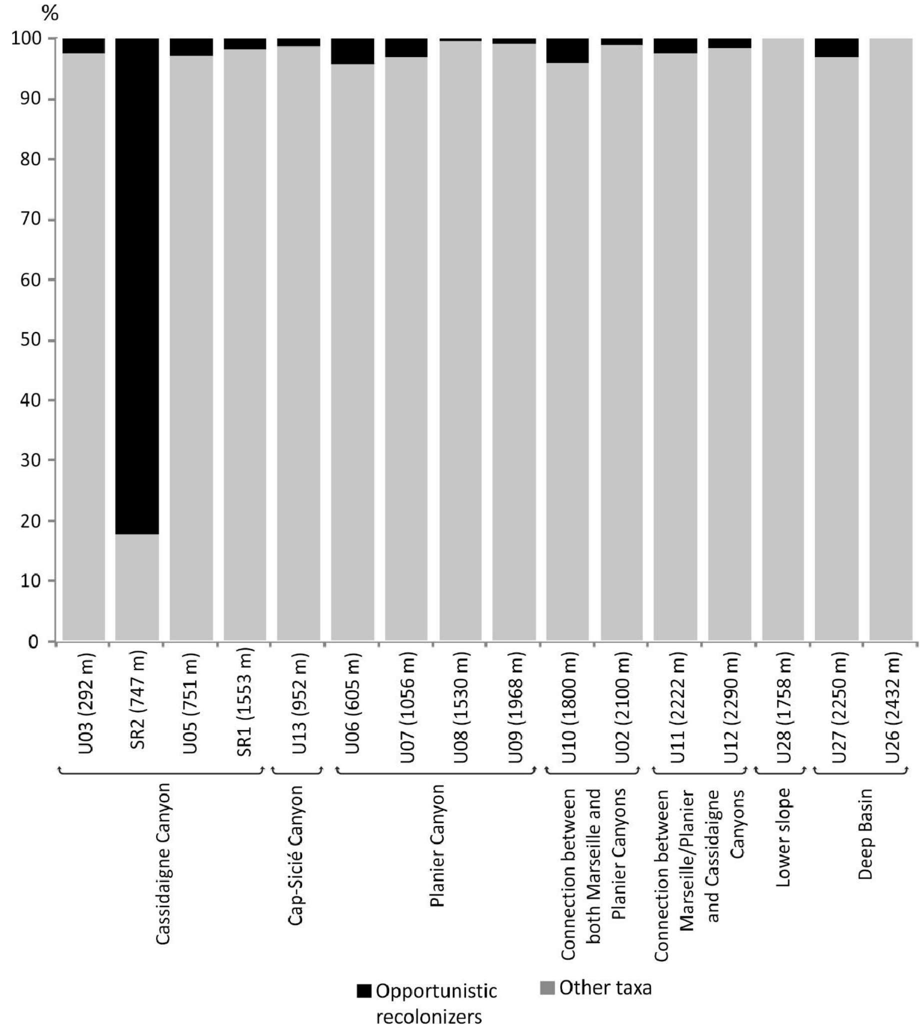

Figure 6. Relative abundance (%) of opportunistic and stress-tolerant foraminiferal taxa that are considered potential recolonizers of freshly disturbed areas (*Psammosphaera* spp., *Saccammina* spp., *Technitella* spp., *Quinqueloculina seminula*, *Gyroidina umbonata*, *Gyroidina altiformis*, *Bulimina marginata*).

graphic cruise. C.F. (first author of this paper) and P.D. performed foraminiferal analyses in the framework of an industrial contract linking financially the FORAM Research Group (http://www.foram.eu.com) and CREOCEAN (http://www.creocean.fr) to ALTEO. In summer 2018, ALTEO allowed C.F. to use foraminiferal data for this publication. The Titanium dataset generated during the current study are not publicly available due contractual constraints linking CREOCEAN to ALTEO ALUMINA but are available from the corresponding author and the co-authors working in CREOCEAN on reasonable request. Finally, we want to thank both reviewers for their comments on the first manuscript.

Supplementary data

Supporting information for this article is available on the journal's website under https://doi.org/10.5802/crgeos.5 or from the author.

References

Anschutz, P., Jorissen, F. J., Chaillou, G., Abu-Zied, R., and Fontanier, C. (2002). Recent turbidite deposition in the eastern Atlantic: early diagenesis and biotic recovery. *J. Mar. Res.*, 60:835–854.

Barnett, P. R. O., Watson, J., and Connely, D. (1984). A multiple corer for taking virtually undisturbed sample from shelf, bathyal and abyssal sediments. *Oceanol. Acta*, 7:399–408.

Béthoux, J.-P., Durrieu de Madron, X., Nyffeler, F., and Tailliez, D. D. (2002). Deep water in the western Mediterranean: peculiar 1999 and 2000 characteristics, shelf formation hypothesis, variability since 1970 and geochemical inferences. *J. Mar. Syst.*, 33–34:117–131.

Béthoux, J.-P. and Prieur, L. (1983). Hydrologie et circulation en Méditerranée Nord-Occidentale. *Petrole et techniques*, 229:25–34.

Bizon, G. and Bizon, J. J. (1984). Les foraminifères des sédiments profonds. In Bizon, J. J. and Burollet, P. F., editors, *Ecologie des microorganismes en Méditerranée occidentale 'ECOMED': Ecologie des foraminifères en Méditerranée nord-occidentale*, pages 103–139. Association Française des Techniciens du Pétrole, Paris.

Bourcier, M. (1969). Ecoulement des boues rouges dans le canyon de la Cassidaigne (décembre 1968). *Tethys*, 1:79–782.

Bourcier, M., Stora, G., and Gerino, M. (1993). Réponse du macrobenthos d'un canyon sous-marin méditerranéen à des apports particulaires telluriques et anthropiques. *C. R. Acad. Sci. Paris III*, 316:191–196.

Bourcier, M. and Zibrowius, H. (1973). Les boues rouges déversées dans le canyon de la cassidaigne (région de marseille). Observations en soucoupe plongeante SP350 (juin 1971) et résultats de dragages. *Tethys*, 4:811–842.

Caralp, H. M. (1989a). Abundance of *Bulimina exilis* and *Melonis barleeanum*: relationship to the quality of marine organic matter. *Geo-Mar. Lett.*, 9:37–43.

Caralp, H. M. (1989b). Size and morphology of benthic foraminifer Melonis barleeanum: relationships with marine organic matter. *J. Foraminifer. Res.*, 19:235–245.

Contreras-Rosales, L. A., Kohoa, K. A., Duijnsteea, I. A. P., de Stigter, H. C., García, R., Koning, E., and Epping, E. (2012). Living deep-sea benthic foraminifera from the Cap de Creus Canyon (western Mediterranean): Faunal–geochemical interactions. *Deep-Sea Res. I*, 64:22–42.

CREOCEAN (2018). *Usine d'alumine de Gardanne, Etude et suivi de l'impact des rejets sur le milieu marin*. Synthèse globale, Suivi 2016–2017, 28 p.

Dauvin, J. C. (2010). Towards an impact assessment of bauxite red mud waste on the knowledge of the structure and functions of bathyal ecosystems: the example of the Cassidaigne Canyon (northwestern Mediterreanean Sea). *Mar. Pollut. Bull.*, 60:197–206.

De Rijk, S., Jorissen, F. J., Rohling, E. J., and Troelstra, S. R. (2000). Organic flux control on bathymetric zonation of Mediterranean benthic foraminifera Mar. *Micropaleontology*, 40:151–166.

Duros, P., Fontanier, C., Metzger, E., Cesbron, F., Deflandre, B., Schmidt, S., Buscail, R., Zaragosi, S., Kerhervé, P., Rigaud, S., and Jorissen, F. J. (2013). Live (stained) benthic foraminifera from the Cap-Ferret Canyon (Bay of Biscay, NE Atlantic): a comparison between the canyon axis and the surrounding areas. *Deep-Sea Res. I*, 74:98–114.

Duros, P., Fontanier, C., Metzger, E., Pusceddu, A., Cesbron, F., de Stigter, H. C., Bianchelli, S., Danovaro, R., and Jorissen, F. J. (2011). Live (stained) benthic foraminifera in the Whittard Canyon, Celtic margin (NE Atlantic). *Deep-Sea Res. I*, 58:128–146.

Eberwein, A. and Mackensen, A. (2006). Regional primary productivity differences off Morocco (NW-Africa) recorded by modern benthic foraminifera and their stable carbon isotopic composition. *Deep-Sea Res. I*, 53:1379–1405.

Fabri, M.-C., Pedel, L., Beuck, L., Galgani, F., Hebbeln, D., and Freiwald, A. (2013). Megafauna of vulnerable marine ecosystems in French mediterranean submarine canyons: spatial distribution and anthropogenic impacts. *Deep-Sea Res. II*, 104:184–207.

Fontanier, C., Biscara, L., Mamo, B., and Delord, E. (2015). Deep-sea benthic foraminifera in an area around the Cassidaigne Canyon (NW Mediterranean) affected by bauxite discharges. *Mar. Biodiv.*, 45:371–382.

Fontanier, C., Duros, P., Toyofuku, T., Oguri, K., Koho, K. A., Buscail, R., Grémare, A., Radakovitch, O., Deflandre, B., De Nooijer, L. J., Bichon, S., Goubet, S., Ivanovsky, I., Chabaud, G., Menniti, C., Reichart, G. J., and Kitazato, H. (2014). Living (stained) deep-sea foraminifera off Hachinohe (NE Japan, Western Pacific): environmental interplay in oxygen-depleted ecosystems. *J. Foraminifer. Res.*, 44:281–299.

Fontanier, C., Fabri, M.-C., Buscail, R., Biscara, L., Koho, K., Reichart, G. J., Cossa, D., Galaup, S., Chabaud, G., and Pigot, L. (2012). Deep-sea foraminifera from the Cassidaigne Canyon (NW Mediterranean): assessing the environmental impact of bauxite red mud disposal. *Mar. Pollut. Bull.*, 64:1895–1910.

Fontanier, C., Jorissen, F. J., Anschutz, P., and Chaillou, G. (2006). Seasonal variability of foraminiferal faunas at 1000 m depth in the Bay of Biscay. *J. Foraminifer. Res.*, 36:61–76.

Fontanier, C., Jorissen, F. J., Chaillou, G., Anschutz, P., and Griveaud, C. (2005). Live foraminiferal faunas from a 2800 m deep lower canyon station from the Bay of Biscay: faunal response to focusing of refractory organic matter. *Deep-Sea Res. I*, 52:1189–1227.

Fontanier, C., Jorissen, F. J., Chaillou, G., David, C., Anschutz, P., and Lafon, V. (2003). Seasonal and interannual variability of benthic foraminiferal faunas at 550 m depth in the Bay of Biscay. *Deep-Sea Res. I*, 50:457–494.

Fontanier, C., Jorissen, F. J., Geslin, E., Zaragosi, S., Duchemin, S., Laversin, M., and Gaultier, M. (2008a). Live dead foraminiferal faunas from the Saint-Tropez Canyon (Bay of Fréjus): observations based on in situ and incubated cores. *J. Foraminifer. Res.*, 38:137–156.

Fontanier, C., Jorissen, F. J., Lansard, B., Mouret, A., Buscail, R., Schmidt, S., Kerhervé, P., Buron, F., Zaragosi, S., Hunault, G., Ernoult, E., Artero, C., Anschutz, P., and Rabouille, C. (2008b). Live (stained) foraminiferal faunas from open slope environments separating submarine canyons in the Gulf of Lions (NW Mediterranean): diversity, density and microhabitats. *Deep-Sea Res. I*, 55:1532–1553.

Fontanier, C., Jorissen, F. J., Licari, L., Alexandre, A., Anschutz, P., and Carbonel, P. (2002). Live benthic foraminiferal faunas from the Bay of Biscay: faunal density, composition, and microhabitats. *Deep-Sea Res. I*, 49:751–785.

Fontanier, C., Metzger, E., Deflandre, B., Waelbroeck, C., Jouffreau, M., Leflock, N., Jorissen, F. J., Etcheber, H., Bichon, S., Chabaud, G., Poirier, D., and Grémare, A. A. (2013). Live (stained) benthic foraminifera off Walvis Bay (Namibia): a deep-sea ecosystem under the influence of benthic nepheloid layer. *J. Foraminifer. Res.*, 43:50–66.

Goineau, A., Fontanier, C., Jorissen, F., Buscail, R., Kerhervé, P., Cathalot, C., Pruski, A. M., Lantoine, F., Bourgeois, S., Metzger, E., and Legrand, E. C. R. (2012). 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). *Biogeosci. Disc.*, 8:9033–9086.

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. (2011). Live (stained) benthic foraminifera from the Rhône prodelta (Gulf of Lions, NW Mediterrenean): environmental controls on a river-dominated shelf. *J. Sea Res.*, 65:58–75.

Gooday, A. J. (2003). Benthic Foraminifera (Protista) as Tools in Deep-water Palaeoceanography: Environmental Influences on Faunal Characteristics. *Adv. Mar. Biol.*, 46:1–90.

Gooday, A. J., Bernhard, J. M., Levin, L. A., and Suhr, S. B. (2000). Foraminifera in the Arabian Sea oxygen minimum zone and other oxygen-deficient settings: taxonomic composition, diversity, and relation to metazoan faunas. *Deep-Sea Res. II*, 47:24–54.

Hayek, L. E. C. and Buzas, M. A. (1997). *Surveying Natural Populations.* Columbia University Press, New York.

Hess, S. and Jorissen, F. J. (2009). Distribution patterns of living benthic foraminifera from Cap Breton canyon, Bay of Biscay: faunal response to sediment instability. *Deep-Sea Res. I*, 56:1555–1578.

Hess, S., Jorissen, F. J., Venet, V., and Abu-Zied, R. (2005). Benthic foraminiferal recovery after recent turbidite deposition in Cap Breton Canyon (Bay of Biscay). *J. Foraminifer. Res.*, 35:114–129.

Hess, S. and Kuhnt, W. (1996). Deep-sea benthic foraminiferal recolonization of the 1991 Mt. Pinatubo ash layer in the South China Sea. *Mar. Micropaleontol.*, 28:171–197.

Kaminski, M. A. (1985). Evidence for control of abyssal agglutinated foraminiferal community structure by substrate disturbance. *Mar. Geol.*, 66:113–131.

Koho, K. A., García, R., de Stigter, H. C., Epping, E., Koning, E., Kouwenhoven, T. J., and van der Zwaan, G. J. (2008). Sedimentary labile organic carbon and pore water redox control on species distribution of benthic for.aminifera: a case study from Lisbon-Setúbal canyon (southern Portugal). *Prog. Oceanogr.*, 79:55–82.

Koho, K. A., Kouwenhoven, T. J., de Stigter, H. C., and van der Zwaan, G. (2007). Benthic foraminifera in the Nazaré canyon, Portuguese continental margin: sedimentary environments and disturbance. *Mar. Micropaleontol.*, 66:27–51.

Kurbjeweit, F., Schmiedl, G., Schiebel, R., Hemleben, C., Pfannkuche, O., Wallman, K., and Schäfer, P. (2000). Distribution biomass and diversity of benthic foraminifera in relation to sediment geochemistry in the Arabian Sea. *Deep-Sea Res. II*, 47:2913–2955.

Langezaal, A. M., Jorissen, F. J., Braun, B., Chaillou, G., Fontanier, C., Anschutz, P., and van der Zwaan, G. J. (2006). The influence of seasonal processes on geochemical profiles and foraminiferal assemblages on the outer shelf of the Bay of Biscay. *Cont. Shelf Res.*, 26:1730–1755.

Licari, L. N., Schumacher, S., Wenzhöfer, F., Zabel, M., and Mackensen, A. (2003). Communities and microhabitats of living benthic foraminifera from the tropical east Atlantic: impact of different productivity regimes. *J. Foraminifer. Res.*, 33:10–31.

Millot, C. (1990). The Gulf of Lions' hydrodynamics. *Cont. Shelf Res.*, 10:884–895.

Murray, J. W. (2006). *Ecology and Applications of Benthic Foraminifera.* Cambridge University Press, New York.

Murray, J. W. and Bowser, S. S. (2000). Mortality, protoplasm decay rate, and reliability of staining techniques to recognise 'living' foraminifera: a review. *J. Foraminifer. Res.*, 30:66–70.

SAFEGE (2011). Rejets en mer des effluents du centre de production d'alumine de Gardanne. Synthèse et analyse bibliographique.

Schmiedl, G., de Bovée, F., Buscail, R., Charrière, B., Hemleben, C., Medernach, L., and Picon, P. (2000). Trophic control of benthic foraminiferal abundance and microhabitat in the bathyal Gulf of Lions, western Mediterranean Sea. *Mar. Micropaleontol.*, 40:167–188.

Schönfeld, J., Alve, E., Geslin, E., Jorissen, F., Korsun, S., and Spezzaferri, S. (2012). The FOBIMO (FOraminiferal BIo-MOnitoring) initiative–Towards a standardised protocol for soft-bottom benthic foraminiferal monitoring studies. *Mar. Micropaleontol.*, 94–95:1–13. group motF.

Schumacher, S., Jorissen, F. J., Dissard, D., Larkin, K. E. E., and Gooday, A. J. (2007). Live (Rose Bengal stained) and dead benthic foraminifera from the oxygen minimum zone of the Pakistan continental margin (Arabian Sea). *Mar. Micropaleontol.*, 62:45–73.

Vitiello, P. and Vivier, M. H. (1974). Données quantitatives sur la méiofaune d'une zone profonde de déversements industriels. *Bulletin de l'Union des Océanographes de France*, 6:13–16.

Vivier, M. H. (1978a). Conséquences d'un déversement de boue rouge d'alumine sur le méiobenthos profond (can.yon de Cassidaigne, Méditerranée). *Tethys*, 8:249–262.

Vivier, M. H. (1978b). Influence d'un déversement industriel profond sur la nématofaune (canyon de Cassidaigne, Méditerranée). *Tethys*, 8:307–321.

Walton, W. R. (1952). Techniques for recognition of living foraminifera. *Contrib. Cushman Lab. Forum Res.*, 3:56–60.

Zeppilli, D., Sarrazin, J., Leduc, D., Martinez Arbizu, P., Fontaneto, D., Fontanier, C., Gooday, A. J., Kristensen, R. M., Ivanenko, V. N., Sørensen, M. V., Vanreusel, A., Thébault, J., Mea, M., Allio, N., Andro, T., Arvigo, A., Castrec, J., Danielo, M., Foulon, V., Fumeron, R., Hermabessiere, L., Hulot, V., James, T., Langonne-Augen, R., Le Bot, T., Long, M., Mahabror, D., Morel, Q., Pantalos, M., Pouplard, E., Raimondeau, L., Rio-Cabello, A., Seite, S., Traisnel, G., Urvoy, K., Van Der Stegen, T., Weyand, M., and Fernandes, D. (2015). Is the meiofauna a good indicator for climate change and anthropogenic impacts? *Mar. Biodiv.*, 45:505–535.