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Deep-sea benthic foraminifera in an area around the Cassidaigne Canyon (NW Mediterranean) affected by bauxite discharges

C. Fontanier · L. Biscara · B. Mamo · E. Delord

Abstract During an environmental survey, living (stained) benthic foraminiferal faunas were investigated at 14 stations within the Cassidaigne Canyon (NW Mediterranean Sea) and the surrounding area. For many decades, industrial bauxite residues (namely red mud) have drained into this canyon via a submarine pipe. Stations investigated in this paper are located between water depths of 288 and 2,432 m from the shelf break to the deeper basin and at a distance ranging between ~5 and ~70 km from the pipe outlet. At almost every site, surface sediment is characterized by red mud deposits and their geochemical imprints. Our ecological observations show that foraminiferal standing stocks and simple diversity (S) decrease across the margin in response to the decreasing food input to the seafloor with increasing water depth. The foraminiferal composition echoes the overall meso-oligotrophic patterns of our study area. The contribution of opportunistic and stress-tolerant species, commonly identified as recolonizers of freshly disturbed areas, is minor at the 14 stations. This clearly shows that red mud dispersal in the Cassidaigne Canyon and the surrounding area has no major ecological impact on foraminiferal diversity.

Keywords Benthic foraminifera · Bauxite residues · Biomonitoring · Cassidaigne Canyon

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Introduction

Deep-sea foraminifera (Eukaryota, Rhizaria) are considered a major ecological group of benthic meiofauna (see the review by Gooday 2003). In natural settings, their faunal characteristics (standing stocks, diversity, microhabitat) are controlled by many physico-chemical parameters. Amongst these, organic matter flux reaching the sea floor is the most important ecological constraint in many settings (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 that pass down active submarine canyons can supply organic detritus and inorganic particles to the deep ocean. Foraminiferal faunas living in these disturbed habitats are characterized by either more or less advanced colonization stages 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, 2008b; 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 changes in the foraminiferal assemblage structure. Therefore, foraminifera make ideal candidates for the monitoring of environmental stress related to human activities (Schönfeld et al. 2012).

Since 1967, the Gardanne alumina refinery (France) has been disposing of bauxite residues (namely red mud) in the Cassidaigne Canyon (see review by Dauvin 2010). Bauxite red mud is drained away by a submarine pipe and discharged at a water depth of 320 m. This sedimentary material spreads along the axis of the Cassidaigne Canyon and on its lateral flanks at great depths (> 2,000 m) (Dauvin 2010; Fabri et al. 2014). 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 et al. 1993; Bourcier and Zibrowius 1973; Fabri et al. 2014; Vitiello and Vivier 1974; Vivier 1978a, 1978b). Close to the pipe outlet, hydro-sedimentary constraints related to the flooding of red muddy material (i.e., high sedimentation rate) preclude benthic meiofauna and macrofauna settlement along the canyon axis. In the surrounding areas, normal macrofauna with suspension and deposit feeders are able to thrive, despite the presence of in a thin layer of red mud.

Fontanier et al. (2012) conducted an ecological investigation of foraminiferal faunas from two stations located at water depths of 725 m and 1,528 m along the axis of the Cassidaigne Canyon (NW Mediterranean Sea) (Fig. 1). At both study 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 an unusual dominance of *Gyroidina umbonata* (Silvestri, 1898) and *Bulimina marginata* d'Orbigny, 1826. The physical disturbance related to red mud deposition is 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 have no obvious environmental impact on foraminiferal faunas.

Based on more extensive core collections and area coverage, here we investigate the potential impact of red mud dispersal on deep-sea foraminiferal faunas living in the Cassidaigne Canyon and its surroundings (Western Mediterranean Sea). In the framework of an environmental survey, foraminiferal communities were sampled at 14 stations located between water depths of 288 m and 2,432 m, with varying proximities to the pipe outlet (Fig. 1; Table 1). Most of these sites are located in a geographical zone where bauxite residues have been previously detected (Dauvin 2010). The main objective of our study was to assess the environmental impact of dumped red mud on benthic foraminiferal assemblage characteristics and composition during the sampling period (September 2012).

Study area

The Cassidaigne Canyon (also called Cassis Canyon) is situated at the frontier between the eastern Gulf of Lions and the

Fig. 1 Bathymetry, study area and location of the 14 stations sampled during the ALPEJAN 01 cruise. *Triangles* correspond to stations also investigated by Fontanier et al. (2012)
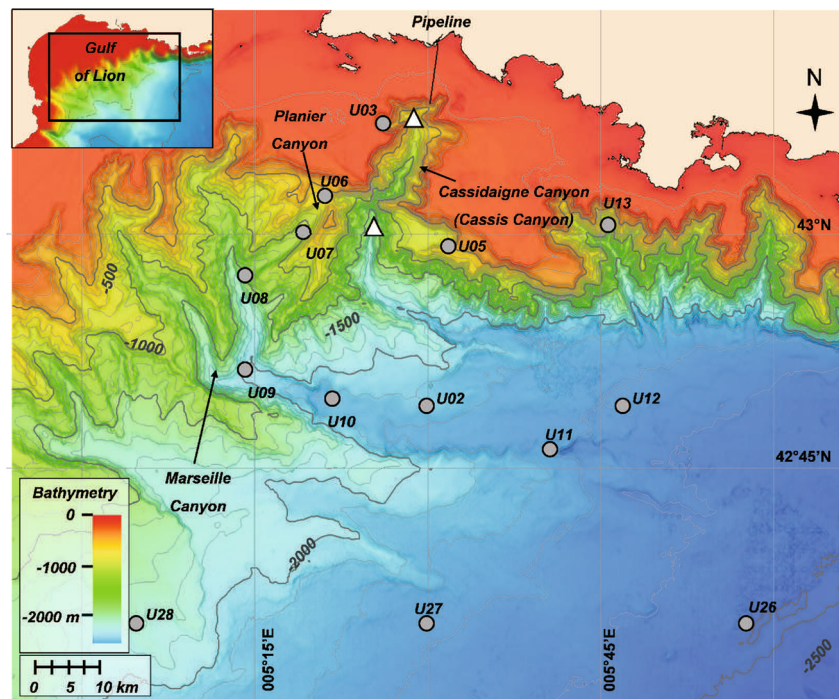
Table 1 Water depth, coordinates and physiographic settings of all stations sampled during the 'ALPEJAN 01' cruise (September 2012)

Station	Latitude	Longitude	Depth (m)	Settings	Horizontal distance from the pipeline outlet (km)	Visual detection of red mud deposits
U03	43°07.05′N	05°26.11′E	288	Head of the Cassidaigne Canyon	6	Reddish brown surface layer (several cm)
U05	42°59.39′N	05°31.85′E	745	Eastern flank of the Cassidaigne Canyon	16.5	No
U13	43°00.78′N	05°45.45′E	958	Western Branch of the Cap-Sicié Canyon	24.9	No
U06	43°02.40′N	05°21.00′E	598	Head of the eastern branch of the Planier Canyon	16.5	Reddish brown surface layer (several cm)
U07	43°00.10′N	05°19.20′E	1,050	Eastern branch of the Planier Canyon	21.2	Reddish brown surface layer (several cm)
U08	42°57.43′N	05°14.04′E	1,547	Axis of the Planier Canyon	29.7	Reddish brown surface layer (several cm)
U09	42°51.15′N	05°14.53′E	1,968	Axis of the Planier Canyon	38.1	Reddish brown surface layer (several cm)
U10	42°49.22′N	05°21.95′E	2,126	Connection between both Marseille and Planier Canyons	37	Reddish brown patches at the sediment surface
U02	42°48.83′N	05°29.96′E	2,104	Connection between both Marseille and Planier Canyons	36	Reddish brown patches at the sediment surface
U11	42°46.22′N	05°40.80′E	2,222	Connection between Marseille/Planier and Cassidaigne Canyons	43.3	Reddish brown surface layer (cm)
U12	42°49.01′N	05°46.98′E	2,290	Connection between Marseille/Planier and Cassidaigne Canyons	42.3	Reddish brown patches at the sediment surface
U28	42°35.00′N	05°05.00′E	1,758	Lower slope between both Petit Rhône and Grand Rhône Canyons	70.5	Rare reddish brown patches at the sediment surface
U27	42°35.00′N	05°30.00′E	2,250	Deep Basin	61.6	Rare reddish brown patches at the sediment surface
U26	42°35.00′N	05°57.50′E	2,432	Deep Basin	71.9	Rare reddish brown patches at the sediment surface

Ligurian Sea (NW Mediterranean). The canyon head, located at a water depth of 200 m, borders the Cassis Bay at a distance of only 7 km away from the coast. The Cassidaigne Canyon is characterized by a narrow canyon axis (1 km in width).

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 patterns of surface water circulation. 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 to 800 m (Béthoux et al. 2002; Béthoux and Prieur 1983). It is generally characterized by a rather homogeneous temperature (~13 °C) and salinity (38.40–38.45) (Béthoux et al. 2002; Béthoux and Prieur 1983).

Our present study is based on sediment cores collected during the monitoring cruise "ALPEJAN 01", which took place in September 2012. We sampled 14 stations in the surroundings of the Cassidaigne Canyon (Table 1; Fig. 1).

Stations U03 (288 m) and U05 (750 m) are located at the head and on the eastern flank of the Cassidaigne Canyon. Stations U06, U07, U08 and U09 are situated along the Planier Canyon between water depths of 600 and 2,000 m. Both stations U02 and U10 are located along the deep valley where both the Marseille and Planier tributary canyons converge (> 2,100 m). U11 and U12 (> 2,200 m) are under the influence of the Marseille/Planier/Cassidaigne Canyon system. U28, U27 and U26 represent a bathymetric transect from the interfluve between the Petit Rhône and Grand Rhône Canyons (~1,750 m) to the deep basin (~2,400 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.

Material and methods

Samplings

Sediment samples were collected with a box corer (surface area of 2,500 cm^2). Two deployments were conducted at almost all sites (Fig. 1; Table 1). In the first box core, two

sectors with equal surfaces (1,250 cm^2) were defined with a plastic plate (Fig. 2). One sector was subsampled with a Plexiglas tube (internal diameter 9.3 cm, surface area of 68 cm^2). The uppermost 2 cm of this sediment core was sliced in half-centimeter intervals and dedicated to foraminiferal analyses.

Benthic foraminiferal analysis

On board, sediment samples dedicated for foraminiferal study were transferred into 250 cm^3 bottles, which were filled with 95 % ethanol containing 2 g/L 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. Fourteen days 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 except the last one 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. The highest number of stained specimens (285 individuals) was recorded in the 0–0.5 cm interval at station U03 (288 m, Fig. 1). The absence of stained individuals was noted only once, in the 1.5–2 cm sample from station U26

Fig. 2 Photographs of surface sediments at the 14 stations (first box corer deployment). Methods of sediment sampling for different analyses are illustrated for station U03
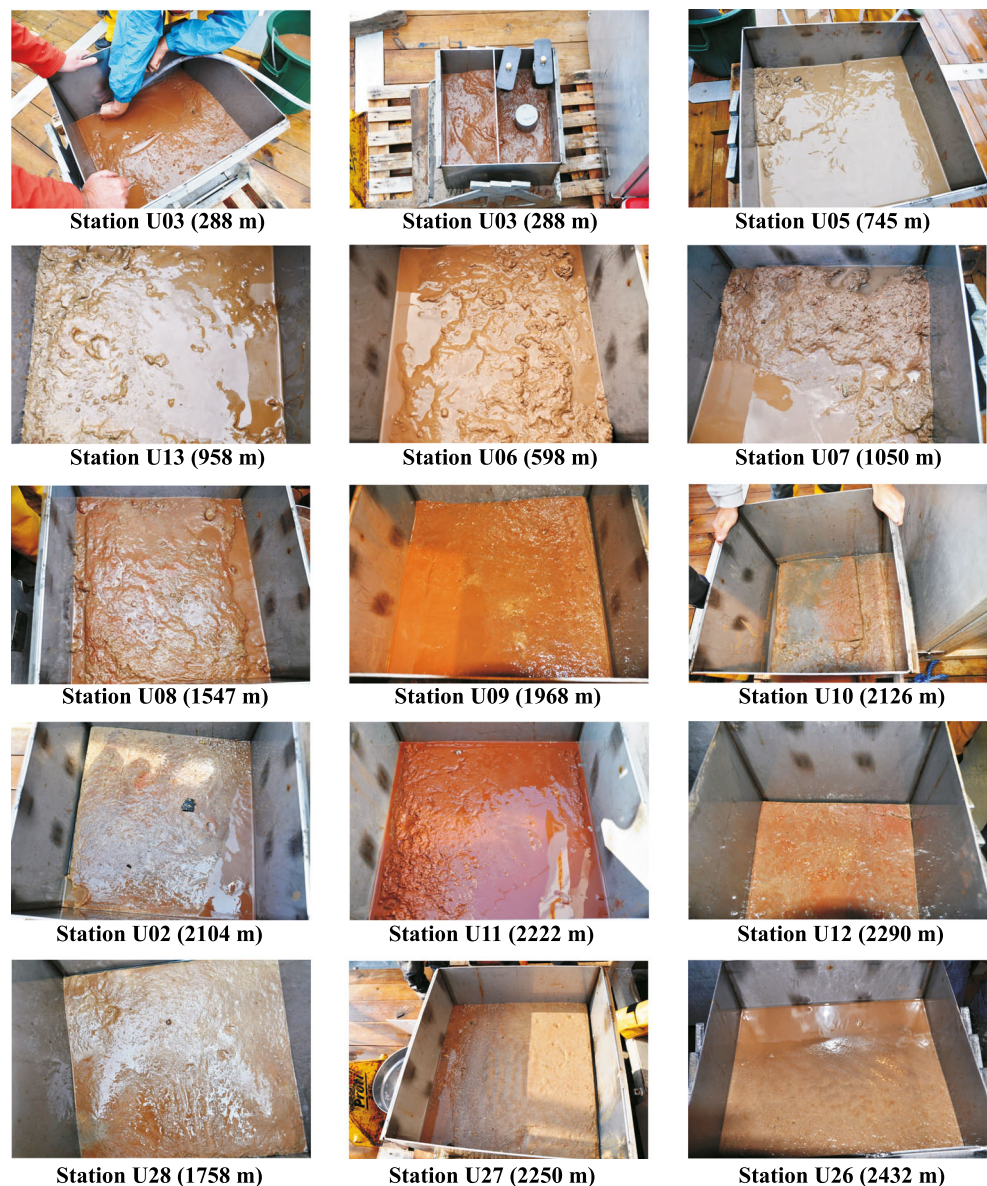
(2,432 m, Fig. 1). Most live foraminifera were identified at the species level (see Appendix A). At each station, we calculated diversity indices, including simple diversity S (representing the number of species), Shannon index H' (log base e), Rarefied Species Richness $E(S_{35})$ and Dominance index D (Hayek and Buzas 1997; Murray 2006). These indices were based on counts of stained specimens from the four depth horizons that were analyzed in each core. In order to investigate the spatial variability of live (stained) foraminiferal faunas in our study area, cluster analysis (Ward's method) was applied for the 14 cores. We used arcsin values for the square root of "pi" for all taxa recorded in each core. The "pi" value is the relative abundance (%) of one species divided by 100. A cluster diagram was constructed (Ward's method) based on the squared Euclidean distances between all cores.

Results

Visual observations of surface sediments

The surface sediment collected at 12 of the 14 stations included reddish brown deposits (Fig. 2; Table 1). Along the Planier, the Marseille and the Cassidaigne Canyons, this material formed either a centimeter-thick surface layer or patches at the sediment–water interface (Fig. 2). No evidence was found for the deposition of abnormal (bauxite-derived) sediment at stations U05 (745 m water depth) and U13 (958 m water depth). Sieve residues (> 125 μm) were characterized by

biogenic particles (mainly dead foraminifera and pteropods) and terrigeneous minerals (mainly quartz and micas).

Foraminiferal faunas

Standing stocks and diversity

Foraminiferal standing stocks ranged between ~50 (U02, 2,104 m) and ~950 (U03, 288 m) individuals/100 cm² (Fig. 3). Values were lower (< 100 individuals/100 cm²) at depths greater than 2,000 m compared to shallower stations. Simple diversity (S) varied between eight (U26, 2,432 m) and 68 (U03, 288 m) species (Fig. 4). Diversity decreased with increasing water depth, with S values lower than 20 species below 2,000 m. The only exception was recorded at station U13 (958 m), where only 19 taxa were identified. Shannon index H' and Rarefied Species Richness $E(S_{35})$ followed the same trend (Fig. 4), as values were low at stations deeper than 2,000 m compared to more shallow sites. Once again, station U13 was an exception, with low H' (~1.8) and $E(S_{35})$ (~11) values corresponding to the very low simple diversity and a dominance of *Globobulimina* spp. Dominance index D and Shannon index values were inversely related.

Faunal composition

At the head of the Cassidaigne Canyon (station U03, 288 m), *Melonis barleeanus* (Williamson, 1858) (29 %), *Reophax scorpiurus* de Montfort, 1808 (23 %) and *Valvulineria bradyana* (Fornasini, 1900) (8 %) dominated the living fauna (Fig. 5). In the Sicié Canyon, on the eastern flank of the Cassidaigne Canyon and along the Planier Canyon axis (<

Fig. 3 Standing stocks (No. Ind./100 cm²) of living (stained) foraminiferal faunas at the 14 investigated stations. Stations are organized by both physiographic setting and increasing depth
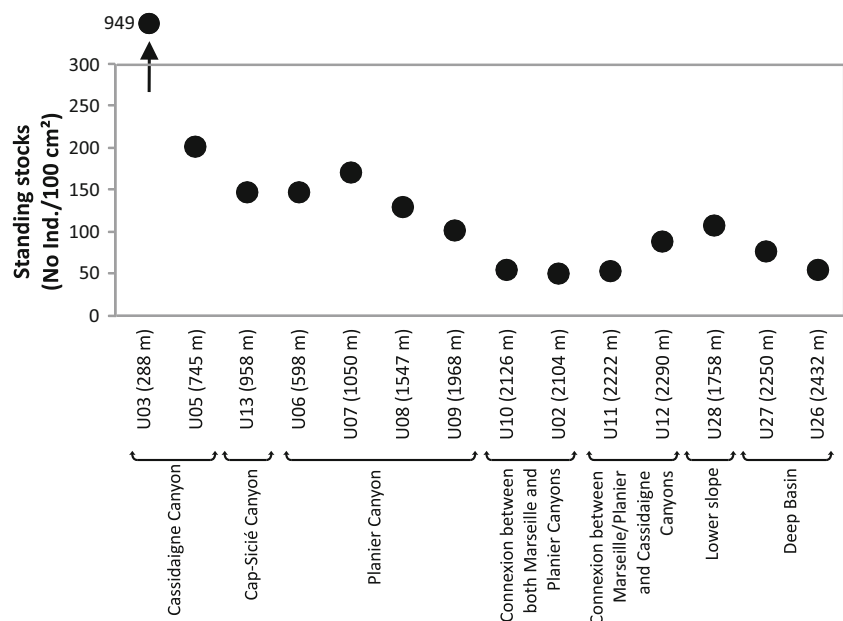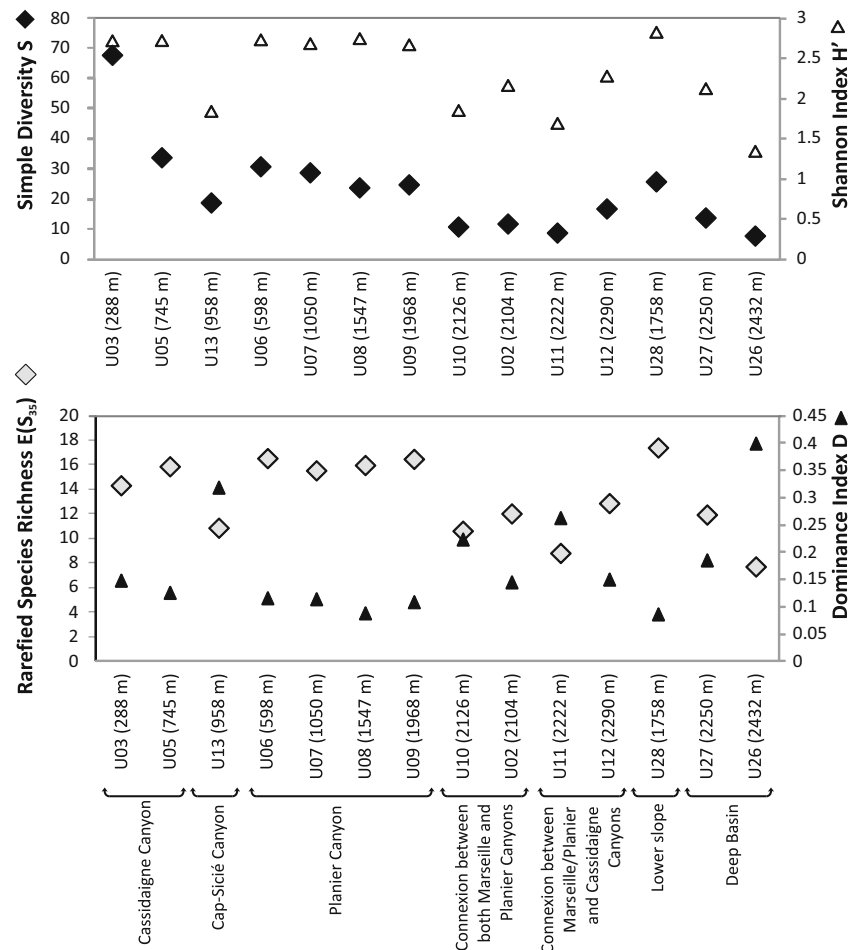
Fig. 4 Simple diversity S, Shannon diversity index H', Rarefied Species Richness $E(S_{35})$ and Dominance index D of living (stained) foraminiferal faunas at the 14 investigated stations. Stations are organized by both physiographic setting and increasing depth

2,000 m water depth), *M. barleeanus* was still dominant. Its relative contribution is 10 % and 30 % at stations U13 (958 m) and U05 (745 m), respectively. *Globobulimina* spp. [mainly *Globobulimina affinis* (d'Orbigny, 1839)] were particularly dominant (~55 %) at station U13. *Uvigerina mediterranea* Hofker, 1932 and *Uvigerina peregrina* Cushman, 1923 were both important contributors (> 10 %) at stations U05, U13, U06, U07 and U08 (ranging between water depths of 745 and 1,547 m). Deeper than ~2,000 m, *Nodellum membranaceum* (Brady, 1879) was the dominant species, with percentages between 11 % (U02, 2,104 m) and 60 % (U26, 2,432 m) (Fig. 5). Porcellaneous taxa [*Pyrgo depressa* (d'Orbigny, 1826), *Pyrgo anomala* (Schlumberger, 1891), *Biloculinella labiata* (Schlumberger, 1891)], monothalamous agglutinated *Lagenammina* spp., and epilithic species attached on pteropod fragments (*Ammolagena tubulata* Rhumbler, 1931, *Crithionina mamilla* Goës, 1894, *Hemisphaerammina bradyi* Loeblich and Tappan, 1957) were secondary taxa (Appendix A). Cluster analysis (Ward's method) of the

foraminiferal faunas recorded at our 14 stations is illustrated by a cluster diagram (Fig. 6), which clearly shows that stations belonging to major bathymetric zones are grouped in rather well-constrained sub-clusters (see the sub-clusters 1, 2 and 3 in Fig. 6). The only outlier is station U13.

Discussion

Evidence of red mud dispersal

Reddish brown surface sediment observed at almost every station provides qualitative evidence regarding the geographical dispersal of bauxite residues (Table 1). Only stations U05 (725 m) and U13 (958 m) are not contaminated by red mud deposits. In fact, the titanium (Ti) content of surface sediments at these sites matches quite well with lithological observations (Table 1; Fig. 7). Titanium is considered a geochemical proxy of red mud dispersal (Dauvin 2010; Fontanier et al. 2012).

Fig. 5 Composition of the benthic live (stained) foraminiferal faunas at the 14 investigated stations. Only major species (at least > 5 % at one site) are illustrated. Stations are organized by both physiographic setting and increasing depth
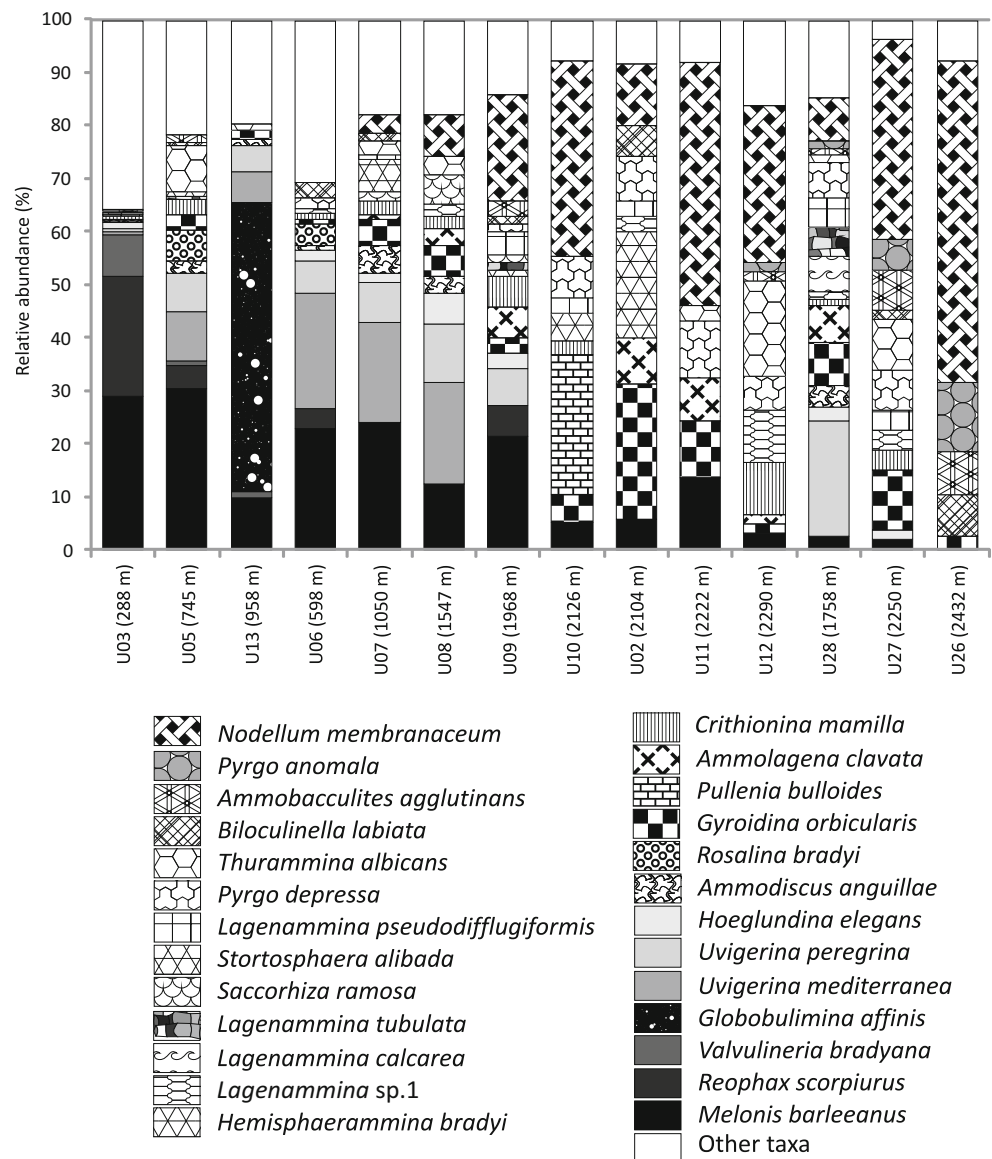
Fairly high Ti values were recorded at most stations in our study area (> 4.000 μg/g), even at great depths (10.500 μg/g at station U11, 2,222 m). In contrast, samples from station U05 and U13 yielded relatively low Ti content (< 2.000 μg/g) close to natural sedimentary signatures (Fig. 7) (Fontanier et al. 2012). It should be kept in mind that Ti content recorded at the 14 stations is much lower compared to those recorded by Fontanier et al. (2012) in the axis of the Cassidaigne Canyon (> 18.000 μg/g). Unsurprisingly, it seems that bauxite residues focus preferentially in the canyon axis, close to the pipe outlet.

Microscope observations of sieved sediment (> 125 μm) collected at all sites do not reveal any large-sized oxi-hydroxide minerals (boehmite, goethite) that characterize red mud layers sampled in the vicinity of the pipe (Fontanier et al. 2012). It is likely that only fine bauxite-derived particles rich in kaolinite compose the reddish brown layers and patches observed at our

sites. Nepheloid layers and sediment gravity flows are considered major hydro-sedimentary processes involved in the transfer of bauxite-derived material from the head of the Cassidaigne Canyon into adjacent canyons and deep basins (Dauvin 2010; Fabri et al. 2014; Fontanier et al. 2012). Furthermore, the episodically strong up-welling and down-welling currents coupled with efficient sediment transfer by both gravity and suspension flows could trigger the complete spatial coverage of the natural seafloor by anthropogenic discharges (Fabri et al. 2014). At a water depth of around 1,200 m, the narrowing of the canyon axis leads to the partitioning of the red mud flux, as a substantial amount of bauxite residue persists along the axis of the Cassidaigne Canyon while the remainder is diverted into the Planier Canyon (Ti frequently > 4.000 μg/g, Fig. 7). Finally, these two distinct pathways seem to converge at a water depth of around 2,000 m, where high Ti concentration is measured

Fig. 6 Cluster diagram using Ward's method based on the squared Euclidean distances between all cores. Clusters 1, 2 and 3 correspond to major bathymetric zones

Tree Diagram for the 14 stations
Ward`s method
Squared Euclidean distances
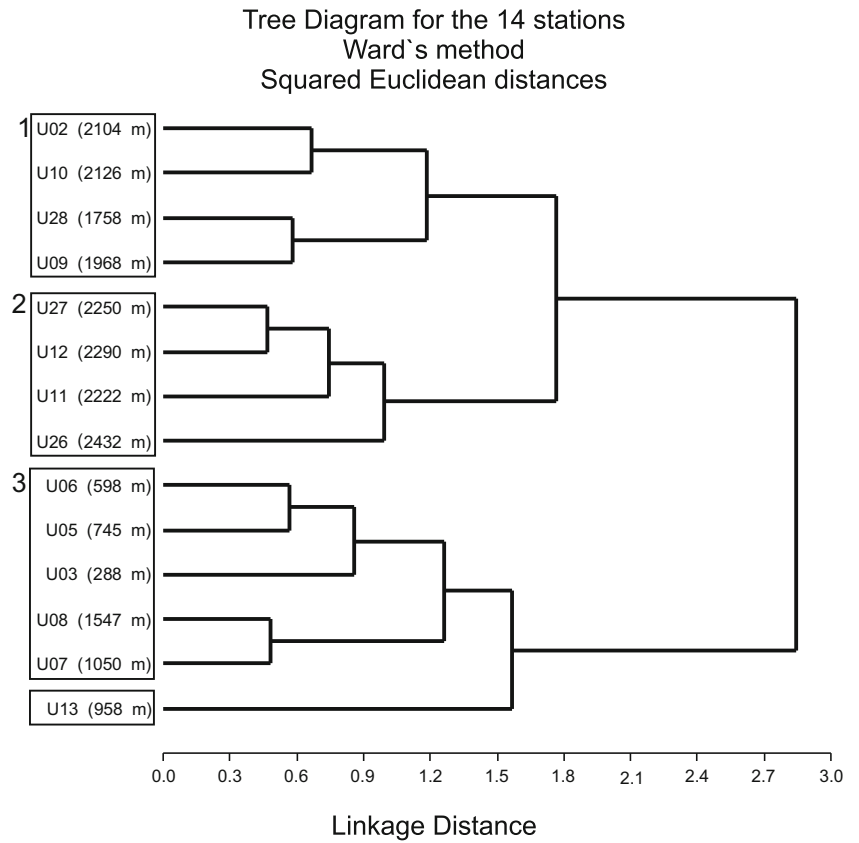
(10.500 μg/g at station U11, Fig. 7). From these observations, the total coverage of discharged red mud is estimated to be more than 900 km². In contrast, stations U05 (725 m) and U13

(958 m) are located in areas not accessible by the bauxite residue (Ti < 2.000 μg/g, Fig. 7). Station U13, located 25 km from the pipe outlet, is sheltered within the neighboring Cap-Sicié

Fig. 7 Titanium (Ti) and organic carbon (OC) content in surface sediments collected at 14 stations (ALPEJAN 01 cruise, September 2012). The Ti content is indicated using a three-class color code. Organic carbon is indicated by numerical values (in % dry weight). This data was taken from the survey report by CREOCEAN (unpublished data). A portion of this data is available on the ALTEO website (http://www. alteo-environnement-gardanne. fr/-Publications-du-Comite-). Titanium and OC values are also illustrated for both stations located in the axis of the Cassidaigne Canyon (Fontanier et al. 2012). Both stations are identified by *triangles*
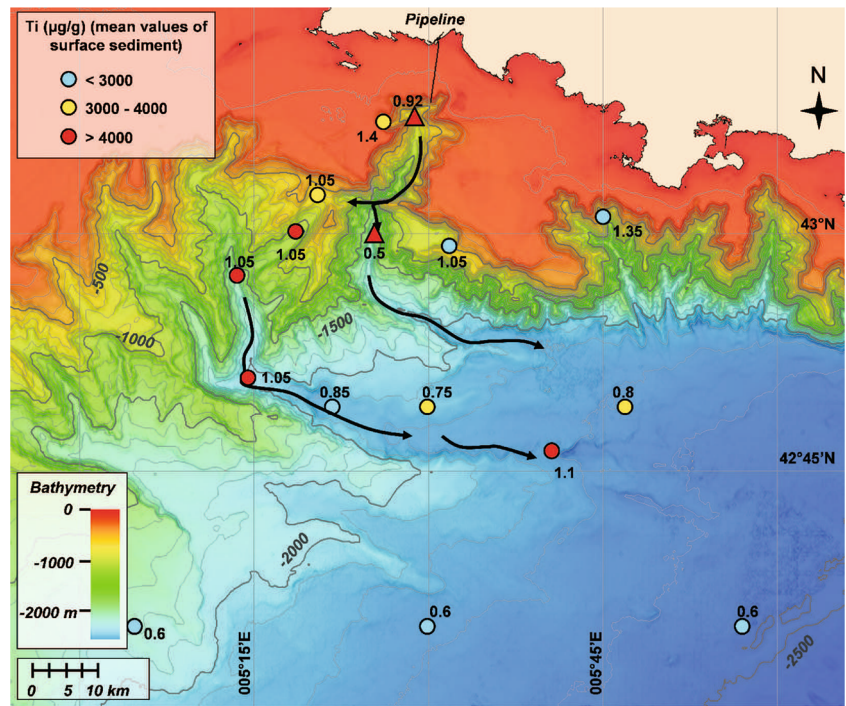
Canyon and sits beyond the natural dispersal range of the red mud. Even though station U05 is located proximal to the pipe outlet, its elevated position on a terrace 1,000 m above the canyon floor prevents deposition of bauxite material by sediment gravity flows.

Using caution with foraminifera in biomonitoring studies

This ecological study represents a snapshot of environmental conditions prevailing in September 2012 in the Cassidaigne Canyon and surrounding area. It does not follow a conventional ecological survey based on foraminiferal baselines. Fortunately, many works on living foraminiferal faunas 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, 2008b; Goineau et al. 2011, 2012; Schmiedl et al. 2000). They deal with various environmental settings (shelf, open-slope, active and passive canyons), and for this reason, provide useful information concerning what we might expect in terms of natural foraminiferal abundance and distribution in our study area. Furthermore, a foraminiferal response to red mud pollution has already been documented by Fontanier et al. (2012). This later work and other recent papers dealing with 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. To understand the overall variability of an ecosystem, it is recommended to study three replicates at each sampling site (Schönfeld et al. 2012). Therefore, the ecological interpretation of our foraminiferal data set may be problematic since only one core per station is described. However, in most ecological papers dedicated to living (stained) foraminiferal communities from deep-sea ecosystems, only one core per site is commonly investigated. Nevertheless, readers should consider our observations on living faunas with care and consider that our interpretations may be biased by potential spatial (decimetric to metric scale) variability that we unfortunately cannot appreciate with our data sets.

A concern with the use of coring devices for ecological research is the integrity of the retrieved sample. For this study, we used a box corer, which obtains representative samples without the loss of the surface veneer of sediment (Murray 2006). Weather and sea conditions were mild and favorable during the sampling period, which permitted optimal handling of the sampler and minimized sediment disturbance when the corer came back on deck. For instance, we observed well-preserved ripple marks on the sediment surface at the deeper stations (see photographs related to stations U27 and U26 in Fig. 2). For some shallower stations, the sediment surface was chaotic (see photographs related to stations U05, U13, U06, U07 and U10 in Fig. 2). This disturbance of surficial sediments may be related to bow-wave effects during corer penetration. In addition, some clear signs of disturbance of the surface sediments by contact with the box corer were evident at station U10 (Fig. 2). For all these reasons, we retrieved sediment subsamples in the least disturbed and the flattest areas of the box core.

The meso-oligotrophic setting of the Cassidaigne Canyon

Our foraminiferal data show a decrease of both standing stock and diversity (S) with water depth. Low-diversity foraminiferal faunas are recorded in the deeper basin, compared to more diverse communities from bathyal stations. Such an ecological trend was previously documented in slope and canyon environments from the Western Mediterranean Sea (Contreras-Rosales et al. 2012; Fontanier et al. 2008b). Along this margin, this trend is likely related to the scarcity of food at varying depths, which is fairly well illustrated by a decrease of organic carbon content in surface sediments (Fig. 6). This reduction of organic detritus with depth may be related to a diminishing of exported primary productivity. Alternatively, lateral input of altered organic compounds and inorganic particles by nepheloid layers and/or sediment gravity flows could dominate down-slope sedimentary fluxes. This may generate a complex interplay between the concentration and dilution of organic load within anthropogenic (red mud) and hemipelagic deposits. This scenario, based on a dominance of lateral sedimentary transport, can explain the high organic content (~1.10 % DW) recorded at the very deep station U11 (2,222 m), where both the Marseille/Planier and the Cassidaigne Canyons converge (Fig. 1).

That being said, the faunal composition of foraminiferal communities brings complementary and crucial information about the overall environmental conditions prevailing in the Cassidaigne Canyon and its surroundings. *Melonis barleeanus* is the major species at stations between ~290 and ~2,000 m where organic content is relatively high (> 1.0 % DW). Accordingly, this taxon is abundant in mesotrophic and well-oxygenated ecosystems (Caralp 1989a, 1989b; Duros et al. 2011, 2013; Fontanier et al. 2003, 2005, 2008a, 2008b; Koho et al. 2007; Kurbjeweit et al. 2000; Licari et al. 2003; Schmiedl et al. 2000). In both canyon and open slope settings, *M. barleeanus* thrives in deep microhabitats below the sediment–water interface where it feeds on degraded organic matter (Duros et al. 2011, 2013; Fontanier et al. 2003, 2005, 2008a, 2008b; Koho et al. 2007; Licari et al. 2003; Schmiedl et al. 2000). This supports the idea that most of the bathyal stations (except U13) are characterized by the input of low-quality organic compounds, likely transported 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 (Bizon and Bizon 1984; Contreras-Rosales et al. 2012; De Rijk et al.

2000; Fontanier et al. 2008a, 2008b; Schmiedl et al. 2000). These uvigerinids are generally described as shallow infaunal species able to feed on relatively fresh organic detritus in mesotrophic environments (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* can behave as an opportunistic taxon feeding on freshly exported phytodetritus in canyon and slope environments, whereas *U. mediterranea* is a reactive species able to grow and reproduce when food is available in the surface sediment (Duros et al. 2011, 2013; Fontanier et al. 2003). The faunal association between *M. barleeanus* and uvigerinids shows that mesotrophic conditions prevail naturally in canyon systems, independent of the presence of bauxite residues.

Valvulineria bradyana and *R. scorpiurus* are noticeably dominant (with *M. barleeanus*) at the shallowest station U03 (288 m). *Valvulineria bradyana* commonly thrives in outer-shelf and upper bathyal environments enriched in organic detritus (Fontanier et al. 2002; Goineau et al. 2011; Hess and Jorissen 2009; Langezaal et al. 2006). This species, which is potentially opportunistic, may rely on different types of marine phytodetritus produced throughout the year (Goineau et al. 2011; Langezaal et al. 2006). Moreover, *V. bradyana* is a major contributor in rich and diverse faunas encountered in canyon-head environments where no redepositional processes occur (Hess and Jorissen 2009). *Reophax scorpiurus* is well documented from upper to lower bathyal environments (Duros et al. 2011, 2013; Fontanier et al. 2002, 2005, 2013; Kurbjeweit et al. 2000). In some studies, it is reported to occupy a deep infaunal microhabitat, suggesting a preference for degraded organic detritus or bacterial biomass related to organic matter degradation (Gooday 1986). Alternatively, this taxon behaves like a recolonizer, flourishing in areas after physical disturbances such as enhanced bioturbation, turbidites, ash falls, nepheloid layers and deep-sea storms (Fontanier et al. 2013; Hess and Kuhnt 1996; Kaminski 1985). Although the co-occurrence of *V. bradyana* and *M. barleeanus* suggests that meso-eutrophic conditions prevail at the shallowest station, the strong contribution of *R. scorpiurus* (~23 %) may be related to an opportunistic response to physical disturbance driven by hydro-sedimentary instability at this site.

Below 2,000 m, living foraminifera are dominated by a faunal association including *N. membranaceum*, *P. depressa*, *Thurammina albicans* Brady, 1879, *Pullenia bulloides* (d'Orbigny, 1846) and *Gyroidina orbicularis* d'Orbigny, 1826. They are all typical of oligotrophic basins from the Western Mediterranean Sea (Bizon and Bizon 1984; De Rijk et al. 2000; Fontanier et al. 2008b, 2012). The presence of epilithic species and suspension feeders (e.g., *H. bradyi*, *C. mamilla*, *A. tubulata*, *Ammobaculites agglutinans* (d'Orbigny,

1846) and *Lagenammina* spp.) suggests that bottom currents sweep across canyon and deep basin floors (Contreras-Rosales et al. 2012; Fontanier et al. 2008b, 2013; Nigam et al. 2004; Schönfeld 2002). Such currents, when channeled by the local bathymetry, may contribute to the dispersal of bauxite residues from the upper canyons to the lower margin.

Station U13 (958 m) possesses a large proportion of *Globobulimina* spp. (54 %). This site is located in the western branch of Cap-Sicié Canyon, 25 km away from the pipe outlet and only 7 km from the coast. As explained above, this sample site is sheltered from the red mud dispersal area. There, sediment contains a high organic content (~1.4 % DW) thattriggers the dominance of *Globobulimina* spp.. These highly specialized taxa are able to rely on low-quality organic detritus that collects within canyon depressions (Fontanier et al. 2005, 2008a).

Assessing environmental stress in relation to red mud dispersal

In Fig. 8, we illustrate the proportion of opportunistic, stress-tolerant foraminiferal taxa that 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 et al. 2005; Hess and Kuhnt 1996; Kaminski 1985). At most stations, they account for less than 10 % of the living faunas. At station U03, where opportunistic species account for 30 %, *R. scorpiurus* may be a reliable proxy of sedimentary instability related to red mud deposition. Despite this, the dominance of *M. barleeanus* in the highly diverse faunas observed at this station supports the idea of a relatively stable environment. Our faunal observations differ strongly
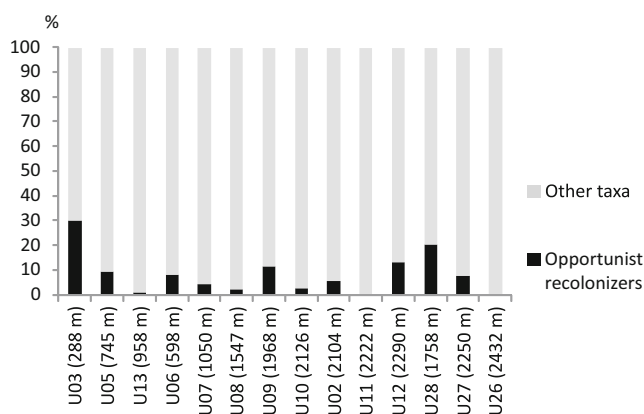

Fig. 8 Relative abundance (%) of opportunistic and stress-tolerant foraminiferal taxa that are considered to be potential recolonizers of freshly disturbed areas (*Psammosphaera* spp., *Saccammina* spp. *Technitella* spp., *Quinqueloculina seminula*; *Gyroidina umbonata*, *Bulimina marginata*)

from those found previously in the axis of Cassidaigne Canyon where opportunistic species (*G. umbonata* and *B. marginata*) constituted almost all living faunas (Fontanier et al. 2012). Therefore, in light of our foraminiferal data, it appears that the dispersal of bauxite residues in the surrounding Cassidaigne Canyon area has no major ecological impact on foraminiferal diversity.

Conclusions

A previous study performed at the head of the Cassidaigne Canyon (Western Mediterranean Sea) highlighted the impact of mechanical stress related to downslope transport of bauxite deposits on benthic biodiversity (Fontanier et al. 2012). Due to more extensive coring, we can evaluate the impact of red mud dispersal in the Cassidaigne Canyon and its surrounding area. Foraminiferal communities were sampled at 14 stations located between water depths of 288 m and 2,432 m at varying proximities to the pipe outlet (Fig. 1; Table 1). Most of these sites are located in a geographical zone where bauxite residues have been previously detected (Dauvin 2010). Deposits of red mud are observed in the Cassidaigne and Planier Canyons down to ~2,000 m (coverage area ~900 km^2). Our study shows that the diversity, composition and standing stock patterns for foraminiferal faunas in this area represent assemblages predominantly constrained by overall meso-oligotrophic conditions. The reduction of sedimentary organic detritus with varying water depths and the ecological constraint determined by bottom currents generate gradual changes in foraminiferal communities, regardless of red mud presence. Compared to the canyon axis, there was no obvious environmental impact of dispersed bauxite residues on benthic biodiversity during the sampling period (September 2012). Future foraminiferal studies focusing strictly on the Cassidaigne Canyon axis, close to the pipeline outlet, are required to fully appreciate the geographical extent of the aforementioned hydro-sedimentary pollution.

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