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Original article

The anthropogenic impact on the western French coasts as revealed by foraminifera: A review

Mise en évidence par les foraminifères de l'impact anthropique sur les côtes ouest françaises : une synthèse

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Abstract

Coastal benthic foraminifera are widely studied as indicators of environmental disturbance. This paper presents a synthesis of the studies that showed correlations between foraminiferal assemblages and various environmental problems along the western French coasts. Pollution in coastal environments may be chronic, resulting from current activities, or may result from accidental events. All the studies show that foraminifera may be used as indicators of pollution after deconvoluting from natural impacts. The most sensitive foraminifera identified by these studies are *Haynesina germanica*, *Ammonia tepida*, *Cribroelphidium excavatum*, bolivinids and *Eggerelloides scabrus*.

Keywords: Foraminifera; Bio-indicators; Anthropogenic impact; Western French coasts

Résumé

Les foraminifères benthiques côtiers sont largement étudiés comme indicateurs des perturbations de l'environnement. Cet article présente une synthèse des études qui ont mis en évidence une corrélation entre des assemblages de foraminifères et des problèmes environnementaux, le long des côtes occidentales françaises. La pollution peut être chronique, due aux activités courantes, ou résulter d'un évènement accidentel. Toutes les études montrent que les foraminifères peuvent être utilisés comme indicateurs de pollution après avoir écarté les causes naturelles de stress environnemental. Les foraminifères identifiés par ces études comme les plus sensibles sont *Haynesina germanica*, *Ammonia tepida*, *Cribroelphidium excavatum*, les bolivinidés ainsi que *Eggerelloides scabrus*.

Mots clés : Foraminifères ; Bio-indicateurs ; Impact anthropique ; Côtes ouest françaises

1. Introduction

Benthic foraminifera are increasingly used as environmental bio-indicators, especially in polluted environments where their sensitivity to pollutants may be expressed by a modification of the assemblages. Compared to other organisms used for environmental survey, foraminifera have the advantage to possess mineralized tests that are preserved in the sediment. They provide a dataset that can be used to reconstruct environmental changes at different time scales, and allow to investigate the impact of past events such as the beginning of industrialization on estuarine environments (Cearreta et al., 2000, 2002; Ruiz et al., 2004).

The studies of pollution effects on benthic foraminifera and of the possible use of these organisms as proxies were initiated by Resig (1960) and Watkins (1961), although pollution effects on foraminifera were mentioned earlier (e.g., Zalesny, 1959). Many studies dealing with benthic foraminifera as bio-indicators of coastal pollution have recently been carried out (review in Boltovskoy et al., 1991; Alve, 1995b; Yanko et al., 1999; Scott et al., 2001). Most of these papers focused on the effects of chronic pollution upon foraminiferal distribution and morphology and dealt with domestic and agricultural wastes (e.g., Alve, 1991a;

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Yanko and Flexer, 1992; Yanko et al., 1994), paper mill effluents (Schafer, 1970, 1973; Buckley et al., 1974), or trace metals in sediments (Alve, 1991a; Sharifi et al., 1991; Alve and Olsgard, 1999; Debenay et al., 2001; Armynot du Châtelet et al., 2004). Other papers dealt with catastrophic temporary pollution such as oil spills (Seiglie, 1968; Armynot du Châtelet et al., 2004; Morvan et al., 2004). Various papers considered the impact of human activities that may change environmental characteristics, but do not necessary generate pollution, such as the closure of an estuary by the construction of a dam with lock (Rouvillois, 1967), or the modification of water circulation and energy by the installation of aquaculture sites (Bouchet et al., 2007b). All these studies demonstrated the high sensitivity of foraminifera to pollution, but also concluded to the difficulty in deconvoluting the impact of pollution from natural stress. Also none of them offers overview of the advantages and difficulties to use them as bio-indicators.

The objective of this work is to summarize the studies carried out on the ecological impact of anthropogenic activities, as indicated by benthic foraminifera along the western French coasts. Anthropogenic activities, may result in chronic pollution, catastrophic pollution and impacts that are not directly related to pollution. Hence, it will be possible to answer two key questions: Can foraminifera be adequately used as bio-indicators? Which species are particularly sensitive to environmental changes?

2. The impact of chronic pollution

Chronic pollution originating from daily activities has a major impact on harbours and estuaries. As the freshwater input appears to be the main limiting parameter for foraminiferal distribution, chronic pollution in estuaries and zones without freshwater input should be separated. Several studies dealing with this pollution were carried out along the western French coasts, some of them already published, other ones only presented in scientific meetings. Pollutions are various and may give to each of the studied estuaries and harbours a true complex system with its own characteristic foraminiferal fauna impact.

2.1. Chronic pollution in estuaries dominated by freshwater input

2.1.1. Rance estuary

The first study on foraminiferal assemblages was carried out in Saint-Malo, (a French harbour on the British Channel coast) (Fig. 1) (Rouvillois, 1972). The assemblages reported from this harbour contained the same species generally found in subsequent studies of French harbours, but they were characterized by a higher proportion of *Eggerelloides scabrus*. This particularity may be due to specific conditions resulting from the position of the Saint-Malo harbour, near the mouth of the Rance river, since *E. scabrus* is abundant in estuaries, close to seagrass meadows (Debenay and Guillou, 2002).

2.1.2. The Adour estuary

The Adour estuary (Fig. 1) is affected by a strong freshwater discharge and is strongly impacted by human activities (De Casamajor and Debenay, 1995; Debenay et al., 2000a). The chronic pollution may originate from marina activity up to industrial potential output. The general distribution of foraminiferal assemblages is related to the salinity gradient, with *Miliammina fusca* at the upper stations with the lowest

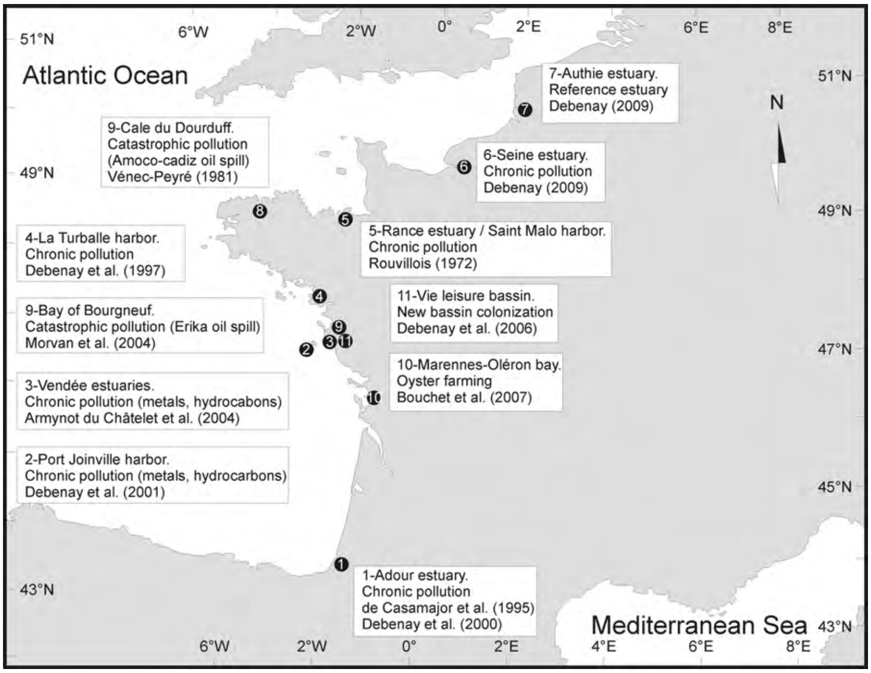

Fig. 1. Location of the studied areas that showed correlations between foraminiferal assemblages and environmental problems along the western French coast.
Localisation des zones d'études qui ont mis en évidence une corrélation entre des assemblages de foraminifères et des problèmes environnementaux, le long des côtes occidentales françaises.

salinities. Foraminiferal assemblages living around several sources of pollution were investigated. In the marina, the foraminiferal assemblage had a low density and was dominated by *M. fusca*, a species characteristic of low salinity environments (Debenay and Guillou, 2002; Murray, 2006), but that low density was also reported from polluted areas (Le Furgey and St Jean, 1976; Murray, 1991). The presence of abnormal tests in the assemblage could indicate the impact of pollution (e.g., Alve, 1995b; Yanko et al., 1998; Geslin et al., 2002; Elberling et al., 2003; Coccioni et al., 2005; Burone et al., 2006; Le Cadre and Debenay, 2006; Frontalini and Coccioni, 2008; Romano et al., 2008). Samples collected near outfalls from a fish farm and a slaughterhouse provided bigger foraminifera, which may be due to the higher availability of organic matter and/or to the proliferation of bacteria that had long been known to be part of the foraminiferal diet (Muller and Lee, 1969). The pollution by organic matter thus appears to favour microbenthos. This is in agreement with numerous studies that report favourable impacts of organic pollution on the diversity and density of foraminifera assemblages (Bandy et al., 1965; Nagy and Alve, 1987). However, if organic pollution might be favourable to some species, it can become toxic when concentration increases (Alve, 1991b; Schafer et al., 1995). In the Adour estuary, the strong tidal currents do not allow the accumulation of organic matter, and maintain the environment favourable to foraminifera.

2.1.3. The Seine and Authie estuaries

A multidisciplinary comparative study was carried out in two close estuarine systems along the French Channel Coast: the anthropogenically contaminated Seine estuary and the reference Authie estuary (Fig. 1) (Debenay, 2009). The main differences between the two estuaries were a higher percentage of *Ammonia tepida* in the Seine estuary while it was quite rare in the Authie estuary, and a lower density and species richness in the living and dead assemblages of the Seine estuary. These differences do not seem to be related to differences in elevation of the sampling stations or in sediment characteristics. Moreover, the relative distribution of *Haynesina germanica* and *A. tepida* (review in Debenay et al., 2000b) did not indicate a significant impact of the lower salinity recorded in the Seine estuary. Even if it was not possible to exclude an impact of the difference in sedimentation processes, with periods of erosion in the Seine estuary, both the lower density and higher proportion of *A. tepida* in this estuary are more than likely related to pollution. This is in agreement with the behaviour of *A. tepida* that often becomes dominant in highly impacted environments (Nagy and Alve, 1987; Alve, 1991a; Sharifi et al., 1991; Yanko et al., 1994; Samir and El-Din, 2001; Vilela et al., 2004).

Changes in foraminiferal assemblages, with a decrease in density and species richness, indicated variations in environmental conditions between 2003 and 2004. These changes should result from increasing toxic-element concentrations (e.g., Ferraro et al., 2006), but as the “non-polluted” Authie estuary was also affected, they might have been related to a more general phenomenon such as climate variations. The increase in the proportion of the tolerant species *H. germanica* in the Authie estuary is a supplementary indication of adverse conditions.

The increase in the proportion of *A. tepida*, associated with *H. germanica* in the sediment can be considered as an alarm signal, showing the negative impact of pollution on the benthos. These two species are particularly well-adapted to be used as environmental indicators in estuaries because they are euryhaline species strongly tolerant to natural restricted conditions.

2.1.4. Vendée estuaries

Observations were made on foraminiferal assemblages collected in September 2000 in five harbours located in moderately polluted estuaries on the coast of Vendée (Fig. 1) (Armynot du Châtelet et al., 2004). Pollution in these five harbours mainly originated from fishing boat activities, painting and outfall of oil and motor-fuel. The Erika oil spill added some hydrocarbons to the area in December 1999. The concentration of ten heavy metals and hydrocarbons were measured. Zinc and copper were the most concentrated elements (up to respectively 210 mg/kg and 35 mg/kg). Despite the contamination of the studied area by the Erika oil spill, polycyclic aromatic hydrocarbon (PAH) contents were very low in almost all the samples (less than 1 mg/kg except for a few samples up to 6 mg/kg). The foraminifera species richness was higher within low-polluted areas, where the number of species could be more than threefold that of the more polluted areas. In the same way, the foraminiferal density was greater within low-polluted areas. In estuarine environments such as those studied in this work, it is always difficult to deconvolute the impact of anthropogenic stresses from the impact of natural stresses, mainly as a result of a change in salinity. For example, Vénec Peyré (1981) and Debenay et al. (2000b) pointed out it is more likely that a lowering of faunal diversity on a slipway was the consequence of low salinity than of pollution. The same observations were made in the studied area with a general decreasing trend of density and species richness upstream. On the other hand, Olsson and Rosenberg (1973) reported that meiofauna (mainly represented by foraminifera) was more clearly influenced by differences in pollution than differences in salinity. This trend could be observed with the highest density and some of the strongest species richness in the less polluted harbours.

The tolerance to pollution of *A. tepida* and *H. germanica* showed in this study is in agreement with the results of Coccioni (2000). These species could be used as pollution indicators in estuaries with the prerequisite they live in areas where natural conditions are favourable to their maintenance and reproduction (e.g., Boltovskoy and Lena, 1969; Schafer, 1973).

2.2. Marine harbours, without massive freshwater input

2.2.1. Port Joinville harbour – Yeu Island

Port Joinville harbour, located on Yeu Island (Fig. 1) receives only little freshwater input, contrary to most of the areas in this region where the influence of pollution on foraminiferal assemblages was studied. The pollution in the harbour mainly results from boats, including cleaning, painting and outfall of oil and motor-fuel. The study of Debenay et al. (2001) showed that the main factor that determined the distribution of foraminiferal assemblages was the geographical location within the harbour with on the one hand direct influence of ocean water and on the other hand more confined areas distributed in the various docks of the harbour. This geographical influence was underlined whatever the season. The more confined zones also correspond to the most noticeable polluted surroundings. As freshwater inputs are very limited, freshwater – normal marine salinity gradient could not be the major parameter, as already observed in the Adour estuary or in many other studies (Debenay and Guillou, 2002; Hayward et al., 2002; Murray, 2006).

Total heavy metals ranged from 130 to 1876 mg/kg (mostly copper and zinc, respectively from 9 to 1100 mg/kg and from 69 to 1000 mg/kg). The correlation that occurred between heavy metals and the silt and clay fraction made it difficult to determine whether sediment characteristics or pollution had the stronger influence on foraminiferal assemblages. Nevertheless, it was shown that the nature of the sediment had a great influence on bolivinids, while strong pollution near the careening areas was indicated by the tolerant pioneer species *Cribroelphidium excavatum* and *H. germanica*. Moreover, the density of foraminiferal assemblages was negatively correlated with all the analyzed contaminants.

These observations reinforce the results of many studies dealing with the relationships between foraminifera and pollution that considered heavy metals as important parameters acting on ecosystems and affecting foraminifera distribution (e.g., Alve, 1995b; Yanko et al., 1998; Coccioni, 2000; Frontalini and Coccioni, 2008). Heavy metals, even in moderate concentrations have a noticeable impact on foraminiferal density and to a lesser extent on species richness.

In Port Joinville, the highest hydrocarbon concentrations were correlated to the pioneer species *C. excavatum* and *H. germanica*. Nevertheless, it was difficult to deconvolute between heavy metals and hydrocarbons impact since both of them were found in the most polluted samples.

2.2.2. *La Turballe*

La Turballe is the biggest harbor in Loire Atlantique (Fig. 1). It harbours a marina and a fishing dock. Foraminiferal assemblages were characterized by a low species richness compared with neighbouring coastal areas (65 instead of more than 200) (Debenay et al., 1997). The density could also be very low, which indicates unfavourable conditions, despite the natural regular renewing of water resulting from mesotidal conditions. Living specimens were rare, belonging mainly to bolivinids, known to survive low oxygen conditions and to develop in nutrient rich areas (e.g., Murray, 1991; Gooday, 1994; Bernhard and Sen Gupta, 1999; Thomas et al., 2000). Their maximum abundance was found in the marina. *C. excavatum* was dominant near graving areas, near a rainwater outfall and in front of the auction hall, indicating the main sources of pollution.

3. The impact of catastrophic pollution (oil spill)

Three catastrophic oil spills seriously impacted the western coasts of France. They were caused by the wreck of the Amoco Cadiz in March 1978, the Erika in January 2000 and the Prestige in May 2003. Samples were collected to investigate the impact of the first two events on foraminifera.

A first study was carried out before and after the oil spill of the Amoco Cadiz supertanker along the Northern Brittany coast with samples collected in the tidal flat of Cale du Dourduff (Finistère, Fig. 1) (Vénec-Peyré, 1981). In this highly impacted environment, the dominant foraminifera species, *Protelphidium paralium* (= *H. germanica*), though resistant to both the pollution and freshwater influence of the river (see former results of chronic pollution), underwent a slowdown of the growth and high rates of morphological abnormalities in the tests that Vénec-Peyré (1981) put down to the toxicity of the product.

A second study was carried out on the impact of the Erika oil spill in December 1999 (Morvan et al., 2004). The Bay of Bourgneuf (Vendée, Fig. 1) was selected to study the impact of this oil spill on intertidal areas (mudflats and saltmarshes). Benthic foraminifera from these environments were monitored for 40 months, from January 2000 to April 2003, on a monthly/bimonthly basis. During the first 21 months, the density and the species richness of living assemblages remained very low (about 50 individuals in 50 cm^3 of sediment and 10 species). After a strong and temporary increase at the end of 2001 (density increased up to 1050 individuals per 50 cm^3), the density varied irregularly until the end of the study with a weak increasing trend, whilst the species richness remained higher (19 species).

Contrary to what was reported by Vénec-Peyré (1981), the rates of morphological abnormalities observed in the Bay of Bourgneuf never exceeded those recorded in unpolluted environments (Geslin et al., 2000) making it impossible to definitely identify a direct impact of the oil spill. Simultaneously with the field study, foraminiferal cultures with 0 to 72.0 mg per 100 ml of Erika oil were maintained in controlled conditions in the laboratory (Morvan et al., 2004). The growth, reproduction and cytological characteristics of *A. tepida* used for these cultures were observed. In the cultures with 0 and 1.5 mg of oil per 100 ml of seawater, normal reproduction and growth occurred. An amount of 5.5 mg of oil per 100 ml of seawater allowed reproduction, but generated up to 45% of morphological abnormalities, and reduced the number of juveniles emitted during reproduction. With 30.0 mg and 72 mg per 100 ml, no growth or reproduction occurred and foraminifera were dead after 2 months. These laboratory observations were considered by the authors as a possible explanation for the low densities often encountered in environments contaminated by hydrocarbons (Mayer, 1980 in Yanko and Flexer, 1992; Bonetti et al., 1999; Geslin, 1999). The cytological study of specimens presenting morphological abnormalities showed the same cellular modifications as the ones observed in individuals contaminated by heavy metals (Le Cadre, 2003).

The culture experiment clearly showed the potential toxicity of the Erika oil spill, but the field study indicated that this toxicity did not directly affect the foraminiferal assemblages, contrary to what had been observed during the Amoco Cadiz oil spill. The massive input of oil during the Amoco Cadiz oil spill had a toxic impact on environment, as this is attested by foraminiferal assemblages. On the contrary, foraminiferal assemblages did not show any noticeable toxic impact from the spreading oil input during the Erika spill suggesting a mechanical negative effect of the cleaning operations.

4. Anthropogenic environmental perturbation unrelated to pollution

4.1. Oyster farming

The macrotidal Marennes-Oléron Bay (Fig. 1) is an area of intensive oyster farming where oysters are subject to summer mortality. Bouchet et al. (2007b) monitored the response of benthic foraminifera to short-term biogeochemical disturbances that may be involved in oyster summer mortality (hypoxia in early June in conjunction with a sudden rise in temperature, followed by an increase in the ammonia content of sediment porewater, leading to potentially maximal flux towards overlying waters). The foraminiferal assemblages of the topmost layer of the sediment were altered. *Ammonia tepida* was the most tolerant to temperature increase and hypoxic conditions whereas *Brizalina variabilis* and *Haynesina germanica* were sensitive to organic degradation and hypoxia. *Cribroelphidium gunteri* appeared as a pioneer species able to rapidly colonize the topmost sediment layers after the warm-season hypoxic event.

Temperature was noticed to have a paradoxical effect on living foraminifera. In this temperate environment, an increasing temperature enhances the reproduction until a critical value, as mentioned by Lee and Muller (1974). Above this critical value, temperature may become a limiting factor by acting on the metabolism of the species. In Marennes-Oléron Bay, however, temperature was shown to be an indirectly limiting factor through its influence on biogeochemical processes that led to unfavorable environmental conditions. According to the niche theory (Murray, 2001), the patterns of distribution of benthic foraminifera are controlled by those environmental factors that reached their critical thresholds. As it was shown for organic matter (Alve, 1991a), temperature seems to favour foraminifera development until it becomes damageable.

In the same area, large populations of living benthic foraminifera *Quinqueloculina poeyana carinata* were reported for the first time (Bouchet et al., 2007a). The species was previously described from the Adriatic and Tyrrhenian Seas and reported from the Eastern Mediterranean and Red Sea, as well as tropical and subtropical regions, but was unrecorded from the Western Mediterranean Sea and unknown in the eastern Atlantic. This supported the hypothesis that it had been accidentally introduced outside its natural range as a likely result of mariculture trade and/or shipping activities. This was the first report of a successful introduction of a non-indigenous benthic foraminifera to the Atlantic coast of Europe. The maximum abundance of living individuals in September suggests a massive reproduction during summer, when water is the warmest, in relation to the origin of the species.

4.2. Colonization of a recently dug leisure basin

Field experiments carried out by Buzas (1993) demonstrated that foraminifera colonize azoic sand within a few weeks, indicating rapid dispersal capabilities. Based on these conclusions, observations were carried out in a newly dug leisure basin, about 150 m outside the Vie estuary (Fig. 1), and 4 km inland from the mouth of the estuary (Debenay et al., 2006). The first observations were made in March 1996, a short time after the basin was filled with water pumped at high tide in the Vie estuary. Later, time series observations were made on a monthly basis, for one year, beginning when the basin was almost empty for maintenance works, during winter and spring 1999 to 2000, and ending in September 2000. *C. gunteri* had already colonized the area in March 1996. It must therefore be considered as a pioneer species that has a better colonization capacity and better dispersal ability compared to other species. At the beginning of the time series observations, when the basin was almost empty, porcelaneous tests were dominant and made up more than 80% of the assemblages with large occurrence of *Quinqueloculina seminula* var. *jugosa*. After the basin was filled, a sharp increase in the density of *A. tepida* occurred in July, followed by an increase in the density of *C. excavatum* and *H. germanica* in August. *C. gunteri* was rare, which suggests that competition with other species stopped its growth.

The growth of *C. gunteri* in the basin was surprising since it lives only at sparse stations in the estuary, which suggests that tidal currents are strong enough for the passive dispersal of “embryonic” juveniles throughout the whole estuary, up to the pumping station. Nevertheless, they can live and reproduce only in suitable habitats. This is consistent with Baas Becking’s laws (Baas Becking, 1934): “everything is everywhere” and “the environment selects”.

5. Analyzing the impact of the different environmental disturbances

5.1. Stress caused by salinity variations

The studies reported in this synthesis show how difficult it is to deconvolute the impact of anthropogenic stresses from the impact of natural stresses. The parameters that act on foraminifera are numerous (review in Murray, 2006), nevertheless, in estuarine environments such as those of Vendée, the foraminifera distribution is mainly related to salinity. This parameter was mentioned as a major one in most of the studies reported in this synthesis. However, Olsson and Rosenberg (1973) concluded that meiofauna (mainly represented by foraminifera) was more clearly influenced by differences in pollution than differences in salinity: a low diversity was observed in a polluted coastal area while a higher diversity occurred in estuaries with comparatively lower salinity and less pollution.

Generally, abundant porcelaneous specimens are considered as characteristic of slightly hypersaline, restricted environment, relatively stable in time (Phleger, 1960; review in Murray, 1991), but in the leisure basin located near the Vie estuary, salinity was never higher than 31 and porcelaneous species could be temporary dominant. This shows that other parameters act on the distribution of these species (Murray, 2001).

5.2. Heavy metal pollution

The studies dealing with pollution that are summarized in this paper show that moderate concentrations of heavy metals may have a noticeable impact on foraminiferal density and, to a lesser extent, on species richness. When sediments are much more polluted, only a few opportunistic species are able to grow and to reproduce. These results are consistent with many studies dealing with the relationships between foraminifera and pollution, which considered heavy metals as important parameters acting on ecosystems and affecting the foraminifera distribution (e.g., Alve, 1995b; Yanko et al., 1998; Le Cadre and Debenay, 2006). In experiments on benthic foraminiferal colonization of Cu-contaminated sediments, Alve and Olsgard (1999) showed that, even if Cu had a minor negative effect, the lowest numbers of species were associated with the highest Cu-concentrations.

5.3. Hydrocarbon pollution

In some harbours of Vendée (Atlantic French coast), Armynot du Châtelet et al. (2004) observed a negative correlation of the PAHs with most of the species. Samples with the highest hydrocarbon pollution content exhibited the fewest number of species, which suggests the probable influence these contaminants have on foraminiferal assemblages. The massive input of oil resulting from the wreck of the Amoco Cadiz strongly impacted foraminiferal populations, leading to high deformation rates Vénec-Peyré (1981). This negative impact is consistent with the toxicity of petroleum shown by laboratory experiments (Le Cadre, 2003; Morvan et al., 2004), and with observations from Canso strait, Nova Scotia (Canada), where species richness was strongly reduced at the vicinity of an oil terminal (Buckley et al., 1974). However, the influence of hydrocarbons on foraminiferal assemblages is not always well-established. Locklin and Maddocks (1982) showed few negative effects of petroleum on the benthic foraminifera around a production platform, and one of the studies reported in the present work (Morvan et al., 2004) could not discriminate between the direct impact of oil spill and the indirect impact due to extreme perturbations generated by cleaning activities.

6. Foraminiferal species response

The studies summarized in this paper converge to the conclusion that three species, *H. germanica*, *C. excavatum* and *A. tepida* show particular tolerance to pollution. However, these studies also point out the difficulty in differentiating between the influence of salinity and the impact of pollution. This question is often debated in the literature, where the distribution of *Haynesina germanica* is often related to saline conditions (Cearreta, 1988; review in Murray, 1991; Debenay et al., 2000b), while other studies evidenced its relationship with pollution. Stubbles (1993) and Stubbles et al. (1996) considered that this species is tolerant to heavy metal pollution, which is consistent with the results of Armynot du Châtelet et al. (2004) and Debenay et al. (2001). *H. germanica* was also described as correlated to PAHs (Armynot du Châtelet et al., 2004). Thus, high proportions of *H. germanica* can be considered as an indication of environmental stress, supplementary observations being necessary to determine whether this stress is from natural or anthropogenic origin.

H. germanica should, however, be used carefully when considering organic pollution, since it appears as tolerant to organic enrichment (Armynot du Châtelet et al., 2004; Debenay et al., 2005). But it is negatively influenced by the hypoxia resulting from this enrichment (Bouchet et al., 2007b), oxygen being a prime factor for the control and structuration of benthic foraminiferal assemblages (Alve, 1995a; Alve and Bernhard, 1995; Den Dulk et al., 2000).

C. excavatum is a motile species, highly adaptable to changes in environmental conditions (Linke and Lutze, 1993). It is able to successfully colonize polluted, near-shore environments (Schafer, 1973; Buckley et al., 1974; Bates and Spencer, 1979; Alve, 1991a). Sharifi et al. (1991) established that it is the most tolerant species to heavy metal pollution, followed by *H. germanica* and *A. beccari* in this order. In one of the studies summarized in this paper, Debenay et al. (2001) considered this species as a pollution bio-indicator, especially in open ocean harbours. Indeed, this species does not penetrate far in the estuaries (Debenay and Guillou, 2002), showing its sensitivity to low salinity. Consequently, it can hardly be used as a pollution indicator in upper estuaries, where it is near the limits of its environmental requirements because good indicators of pollution must live in conditions favourable to their maintenance and reproduction (e.g., Boltovskoy and Lena, 1969; Schafer, 1973).

A. tepida is resistant to the salinity gradient prevailing in estuaries (Debenay, 2000). In the study of estuarine harbours reported in this paper, *A. tepida* was demonstrated as tolerant to pollutants, mainly heavy metals and hydrocarbons (Armynot du Châtelet et al., 2004). In previous literature, it was reported as a tolerant species to chemical pollution, including fertilizers, heavy metals and hydrocarbons (Seiglie, 1975; Setty, 1976; Setty and Nigam, 1984; Yanko and Flexer, 1991; Yanko et al., 1994). The studies carried out along the western French coast confirm that, as suggested by Yanko (1997), *A. tepida* may be considered as a heavy metal pollution indicator.

Other foraminifera could be used as environment indicators, even if their status is not clearly determined. For example, the distribution of bolivinids (Debenay et al., 2001; Debenay and Guillou, 2002; Bouchet et al., 2007b) depends on the nature and quality of the sediment. The distribution of *E. scabrus* depends on particular geographical conditions (Rouvillois, 1972), but it was also reported as dominant in assemblages from an extremely polluted environment in Sorfjord, western Norway (Alve, 1991a).

As for the colonization of new environments, natural transport of adult foraminiferal tests is often very limited (Closs, 1964; Ellison and Nichols, 1970; Debenay et al., 2003). In the Vilaine estuary, Goubert (1997) observed that tidal currents were able to transport only juveniles of *C. excavatum* (size $< 80\ \mu m$). Thus, the release and transport of embryonic juveniles are likely to be the main mechanism responsible for passive dispersal and colonization. Zygotes or embryonic juveniles have a density comparable to seawater and therefore are easily transportable

(Alve, 1999; Alve and Goldstein, 2002). Indeed, juveniles are often thin and capable of extending numerous pseudopodia, which may increase their flotation and facilitate their passive transport in suspension. The dispersal of adult foraminifera may result from accidental transport by animals, including birds (Hayward and Hollis, 1994) and/or human activities (review in Sen Gupta, 1999).

7. Conclusion

The studies carried out along the western French coasts participate in the enhancement of the knowledge on foraminifera. They bring new arguments to demonstrate that foraminifera are sensitive to pollution, whatever its source, chronic or accidental. They show that foraminifera react to increasing concentrations in metals and/or hydrocarbons, often considered as very harmful for the environment. *A. tepida*, bolivinids, *C. excavatum*, *E. scabrous*, and *H. germanica*, show tolerance to environmental disturbance and pollution hence they are particularly suitable as bio-indicators in coastal areas. Finally, they contribute to claim that benthic coastal foraminifera should be applied as part of integrated programmes for pollution monitoring.

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