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Benthic foraminifera from the deep-water Niger delta (Gulf of Guinea): Assessing present-day and past activity of hydrate pockmarks

C. Fontanier[a,b,*], K.A. Koho[c,d], M.S. Goñi-Urriza[e], B. Deflandre[f], S. Galaup[g], A. Ivanovsky[f], N. Gayet[h], B. Dennielou[a], A. Grémare[f], S. Bichon[f], C. Gassie[e], P. Anschutz[f], R. Duran[e], G.J. Reichart[d]

[a] IFREMER, Laboratoire Environnements sédimentaires, Centre de Brest, Technopôle de Brest-Iroise, BP 70, F-29280 Plouzané, France
[b] Université de Nantes/Angers/Le Mans, CNRS, LPG UMR 6112, BP 92208, F-44322 Nantes Cedex 3, France
[c] Department of Earth Sciences – Geochemistry, Faculty of Geosciences, Utrecht University P.O. Box 80.021, 3508 TA Utrecht, The Netherlands
[d] Royal Netherlands Institute for Sea Research, Landsdiep 4, 1797 SZ 't Horntje, The Netherlands
[e] Université de Pau et des Pays de l'Adour, CNRS, IPREM 5254 – Equipe Environnement et Microbiologie, BP 1155, F-64013 Pau Cedex, France
[f] Université de Bordeaux, CNRS, Environnements et Paléo-environnements Océaniques et Continentaux, UMR 5805, F-33400 Talence, France
[g] Ecole d'ingénieurs en Environnement, Géoressources et Ingénierie du Développement durable, IPB-ENSEGID, F-33607 Pessac Cedex, France
[h] IFREMER, Laboratoire Environnements Profonds, Centre de Brest, Technopôle de Brest-Iroise, BP 70, F-29280 Plouzané, France

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ABSTRACT

We present ecological and isotopic ($\delta^{18}O$ and $\delta^{13}C$) data on benthic foraminifera sampled from 4 deep-sea stations in a pockmark field from the deep-water Niger delta (Gulf of Guinea, Equatorial Atlantic Ocean). In addition, a series of sedimentological and (bio)geochemical data are shown to back up foraminiferal observations. All stations are located within 1.2 km of each other, so prevailing oceanographic conditions can be assumed to be similar at each site. Two of the sites (GMMC-01 and GMMC-02) are located in a pockmark (named "pockmark A") where current methane seepages were recorded by ROV observations. A third station (GMMC-03) is located in the topographic depression interpreted as a collapsed pockmark (named "pockmark B"). The fourth site (GMMC-04) is a reference station, without evidence of past or present seepages. Our observations show that degraded organic matter with low bioavailability is present at all stations with a preferential burial of organic compounds in topographic depressions (GMMC-03 station). Authigenic aragonite is abundant in surface sediments at stations GMMC-01 and -02. Its precipitation is likely related to high rates of methane oxidation during past seep events in episodically active pockmark A. In contrast, the absence of anaerobic methanotrophic Archaea (ANME) during the sampling period (November 2011) suggests that only moderate sulphide and methane oxidation take place close to the sediment–water interface. Compared to the reference site GMMC-04, living foraminifera at the collapsed and episodically active pockmarks show minor changes in terms of diversity, standing stocks and faunal composition. However, the $\delta^{13}C$ signal of living and dead (but well-preserved) foraminiferal species (*Ceratobulimina contraria*, *Melonis barleeanus*, *Uvigerina peregrina*) is depleted in the episodically active pockmark A compared to the other stations. Overgrowth of authigenic carbonate on altered foraminifera generates an important shift to lower $\delta^{13}C$ values. Dead faunas carry a complex time-averaged message, integrating taphonomic gains and losses related to the temporal variability of gas emission. They reveal major faunal differences that may be useful to detect gas hydrate seepages in different pockmark stages.

1. Introduction

Hydrocarbon seeps on continental margins provide interesting settings for investigating the biogeochemical functioning and biodiversity of extreme deep-sea benthic environments and also for industrial exploitation of hydrocarbon resources. In these areas, methane and hydrogen sulphide trickle out of sediments through the seabed into the overlaying water. In sediments below the seafloor, these fluid seepages sustain a succession of biogeochemical redox reactions (e.g., Campbell, 2006). At the sediment–water interface, hydrogen sulphide and methane that have escaped oxidation in deeper sediments can sustain chemosynthetic communities, including endemic benthic metazoans (e.g., vesicomyid

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[*] Corresponding author at: IFREMER, Laboratoire Environnements sédimentaires, Centre de Brest, Technopôle de Brest-Iroise, BP 70, F-29280 Plouzané, France. Tel.: +33 621919348.
E-mail address: Christophe.Fontanier@ifremer.fr (C. Fontanier).

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and mytilid bivalves or siboglinid tubeworms) that thrive with mutual endosymbiotic prokaryotes (mainly sulphur-oxidizing bacteria) (e.g., Sibuet and Olu, 1998; Sahling et al., 2002; Levin and Mendoza, 2007). Differences in sulphide and methane fluxes in the uppermost sediment lead to the development of a specialized biozonation of chemoautotrophic prokaryotes and a patchy distribution of benthic eukaryotes (e.g., Sibuet and Olu, 1998; Sahling et al., 2002; Foucher et al., 2009).

Living benthic foraminifera (Eukaryota, Rhizaria) from modern cold seeps have been investigated in number of studies (e.g. Akimoto et al., 1994; Sen Gupta and Aharon, 1994; Kitazato, 1996; Sen Gupta et al., 1997, 2007; Rathburn et al., 2000, 2003; Bernhard et al., 2001; Torres et al., 2003; Martin et al., 2004, 2010; Heinz et al., 2005; Panieri, 2006; Mackensen et al., 2006; Lobegeier and Sen Gupta, 2008; Bernhard et al., 2010). The previous work suggests that foraminiferal species observed in cold seep areas are not endemic/exotic and may be recruited from adjacent non-seep zones (e.g., Sen Gupta and Aharon, 1994; Kitazato, 1996; Sen Gupta et al., 1997; Rathburn et al., 2000, 2003; Lobegeier and Sen Gupta, 2008; Martin et al., 2010). Metabolic adaptations (facultative anaerobic metabolism, mutualism with prokaryotes), habitat and food preference (elevated epibiotic habitat, bacteriovore) might explain foraminiferal occurrence in methane- and sulphide-enriched sediments (e.g., Bernhard et al., 2001; Panieri, 2006; Mackensen et al., 2006; Sen Gupta et al., 2007; Lobegeier and Sen Gupta, 2008; Bernhard et al., 2010). Additionally, stable isotopes ($\delta^{13}C$, $\delta^{18}O$) in foraminiferal tests have been studied in present and past cold seep environments (e.g., Sen Gupta and Aharon, 1994; Rathburn et al., 2000, 2003; Torres et al., 2003, 2010; Martin et al., 2004, 2010; Hill et al., 2004; Mackensen et al., 2006; Wiedicke and Weiss, 2006; Bernhard et al., 2010; Hayward et al., 2011; Panieri et al., 2012). The geochemistry of pore water may be strongly influenced by methane-rich fluid seepage (e.g., Teichert et al., 2005; Rongemaille et al., 2011). The $\delta^{13}C$ signatures of thermogenic and biogenic methane are generally lower than $-35‰$ and isotopically-light methane oxidation in the Sulphate–Methane Transition Zone (SMTZ) results in pore water that is enriched in light dissolved inorganic carbon (e.g., Rathburn et al., 2003; Martin et al., 2007). Therefore, the $\delta^{13}C_{DIC}$ (δ^{13} of dissolved inorganic carbon) of pore water may shift relatively rapidly from very depleted $\delta^{13}C$ to heavier bottom-water signatures according to (1) either diffusive or advective flows of methane-rich fluid toward the sediment–water interface, (2) efficiency of methane oxidation in a potential SMTZ, and (3) all biogeochemical processes influencing the budget of stable carbon isotopes in upper sediments (e.g., organic matter mineralisation) (e.g., Rathburn et al., 2003; Martin et al., 2010). The $\delta^{13}C$ values in (living) foraminiferal tests show the influence of methane-enriched fluid, with a clear shift to lower values compared to adjacent non-seep areas (Sen Gupta and Aharon, 1994; Rathburn et al., 2000, 2003; Torres et al., 2003; Mackensen et al., 2006, Martin et al., 2010). However, in some studies strong disequilibrium has not been noted between the $\delta^{13}C$ of living foraminiferal tests from cold seep zones and the expected very low $\delta^{13}C_{DIC}$ of hydrate-gas fluid (e.g., Sen Gupta and Aharon, 1994; Torres et al., 2003; Bernhard et al., 2010). Therefore, it has been suggested that foraminifera may calcify during periods low methane discharge or during intermittent episodes of seawater flow into sediments (Torres et al., 2003). In addition, foraminiferal $\delta^{13}C$ signatures may also reflect the ^{13}C-depleted food source (e.g. methanotroph bacterial biomass) and/or prokaryotic symbionts (Sen Gupta and Aharon, 1994; Rathburn et al., 2003; Panieri, 2006; Mackensen et al., 2006; Bernhard et al., 2010). Accordingly, Panieri (2006) documented lighter protoplasmic $\delta^{13}C$ for foraminifera living in hydrocarbon seeps compared to an adjacent non-seep area, suggesting that *Beggiatoa* (prokaryotes) may be a food source for the foraminifera. In contrast to living data, strong $\delta^{13}C$ depletion is recorded in fossil foraminifera. This may be related to diagenetic effects including post-mortem authigenic carbonate overgrowth and/or recrystallisation in high-alkalinity pore water around the SMTZ (e.g., Torres et al., 2003; 2010; Barbieri and Panieri, 2004; Wiedicke and Weiss, 2006, Panieri et al., 2009). Thus, previous work implies that the $\delta^{13}C$ of dead foraminifera might be unreliable for building an accurate chronology of seep activity throughout centuries and millennia.

Along the prominent deep-water Niger delta (Gulf of Guinea, Equatorial Atlantic Ocean), various studies have documented different sea-floor sedimentary features such as pockmarks, mud volcanoes, gas hydrates and carbonate build-ups associated with cold seeps (e.g., Damuth, 1994; Brooks et al., 2000; Sultan et al., 2007, 2010, 2014; Bayon et al., 2007, 2011; Ruffine et al., 2013). Despite those numerous geochemical and sedimentological observations, fossilising benthic foraminifera have never been studied in this area. In this paper, an ecological and isotopic dataset of benthic foraminifera (living and dead) is presented and their potential proxy value of cold seep activity is assessed. In more detail, the aims of the study are (1) to examine and compare living foraminiferal communities at stations experiencing current methane seepage and no seepage, (2) to compare dead benthic foraminiferal assemblages to the living ones and (3) to define whether seepage activity is recorded in the foraminiferal tests by an analysis of stable isotopes ($\delta^{13}C$, $\delta^{18}O$) in living and dead foraminifera.

2. Study area

The Gulf of Guinea (Equatorial Atlantic Ocean) is characterised by spatial gradients of surface productivity due to coastal and offshore seasonal upwelling, and river plumes (Soltwedel, 1997). In front of the Niger River mouth, nutrient concentrations in the river plume are high due to direct fluvial influence, especially silicate, and due to river-induced upwelling, mainly nitrate and phosphate (Van Bennekom et al., 1978). Nevertheless, primary production is reduced because of the high input of suspended matter clouding the waters (Eisma et al., 1978). Conversely, along adjacent coasts, seasonal upwelling results in very high primary production and enhanced exported productivity to the seafloor (Soltwedel, 1997). Terrestrial organic matter supplied by the Niger River focuses at depths between 400 and 1500 m depth along the so-called deep-water Niger delta (Altenbach et al., 2003). This deep-water delta constitutes a major physiographic unit of the Gulf of Guinea margin (Corredor et al., 2005) where high deltaic sedimentation rates and deformation by gravity driven tectonics result in a flattening of the continental slope down to water depths of more than 3000 m (e.g., Damuth, 1994; Riboulot et al., 2012). Sedimentary environments have been intensively studied along the slope because of abundant hydrocarbon resources (e.g., gas hydrate) (Bayon et al., 2007, 2011; Sultan et al., 2007, 2010, 2011, 2014; Rongemaille et al., 2011; Riboulot et al., 2012; Ruffine et al., 2013).

Four stations investigated in this paper are located at a depth of ~1200 m along the deep-water Niger delta (Fig. 1, Table 1). These stations are bathed by oxygenated waters related to the mixing boundary between Antarctic Intermediate Water (AAIW) and North Atlantic Deep Water (NADW) (Bayon et al., 2011). All stations are close to each other (less than 1.2 km distance) (Fig. 1). Sites GMMC-01 and GMMC-02 are located within pockmark A at a distance of about 100 m from each other (Sultan et al., 2010). This 500-m-diameter pockmark consists in a circular ring-shape feature (Sultan et al., 2007, 2010, 2011, 2014), where ROV dives have revealed gas hydrate seepage from the sea-floor and patches of *Bathymodiolus* spp. attached to prominent carbonate