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Carbon processing at the deep-sea floor of the Arabian Sea oxygen minimum zone: A tracer approach

Lara Pozzato [a,*], Dick van Oevelen [a], Leon Moodley [a], Karline Soetaert [a], Jack J. Middelburg [b]

[a] Department of Ecosystem Studies, Royal Netherlands Institute for Sea Research NIOZ-Yerseke, Korringaweg 7, 4401CT Yerseke, The Netherlands
[b] Faculty of Geosciences, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, The Netherlands

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ABSTRACT

We have elucidated the trophic interactions in the foodweb of sediments from and close to the oxygen minimum zone (OMZ) of the Arabian Sea. Sediment cores from inside (885 m depth) and outside (1791 m depth) the OMZ were manipulated onboard by adding ^{13}C-enriched phytodetritus. The incorporation of phytodetritus by the benthic community was quantified after incubating for 7 days. To assess the effect of bottom-water oxygenation on the processing of organic matter, the oxygen concentration in the overlying water of the incubated cores was also manipulated. Biomass values inside and outside the OMZ were comparable for bacteria (1068 and 1276 mg C m^{-2}) and macrofauna (2528 and 3263 mg C m^{-2}), but not for meiofauna (63 and 1338 mg C m^{-2}). Uptake values in percentage of total added tracer were 0.8 and 0.5% for bacteria suboxic and oxic treatments inside the OMZ, and 0.5 and 1.2% for suboxic and oxic treatments outside the OMZ. Macrofauna uptake accounted for 17.4 and 4.4% in the suboxic and oxic treatments inside the OMZ, and only for 0.1% and 1.3% respectively outside the OMZ. Respiration accounted for 13% of total tracer added inside the OMZ for both treatments, 4.6 and 6.8% for oxic and suboxic treatments outside the OMZ, respectively. Our results show that phytodetritus is most efficiently processed at *in situ* oxygen conditions, that foraminifera and bacteria remain active both under elevated and lowered bottom-water oxygen levels and that macrofauna was present in high abundance and showed high tracer uptake.

1. Introduction

The balance of supply and consumption controls the oxygen concentration of water bodies. Below the photic zone, physical processes mainly control oxygen supply. Oxygen consumption in the water column relates primarily to the degradation of dissolved and particulate organic matter. Oxygen consumption may outbalance supply in water bodies that receive high loads of nutrients and organic matter through river run-off (e.g. the Po river outflow) or those underlying upwelling areas (e.g. Arabian Sea), especially when external factors such as high temperatures intensify the degradation of phytoplankton blooms, or when water-column stratification prevents oxygen replenishment. When these combined effects result in oxygen concentrations below 63 μM, aerobic degradation processes may become significantly impaired. Such water bodies are then described as "hypoxic" or "low-oxygen zones", or in case of open ocean settings "oxygen minimum zones" (OMZs) (Levin, 2003; Middelburg and Levin, 2009). Helly and Levin (2004) report that there is over 1 million km^2 of permanently hypoxic shelf and bathyal sea floor, distributed all around the globe. Some OMZ areas impinge on coastal areas (Stramma et al., 2008) and due to global change could become more pronounced, leading to permanent oxygen deficiency and ecosystem perturbation (Stramma et al., 2010).

Sediments underlying OMZs typically have a specialized protozoan and metazoan fauna that is dominated by few species. Macrofaunal biomass is higher in OMZ boundary sediments, which is thought to be an OMZ edge effect (Levin, 2003), and occurs because organic matter is abundant and oxygen concentrations are physiologically tolerable to metazoan macrofauna (Woulds et al., 2007). Fauna inhabiting these sediments has specialized adaptations, for example foraminifera can sustain low metabolic activity through denitrification (Piña-Ochoa et al., 2009; Risgaard-Petersen et al., 2006) and polychaetes have large external gills (Lamont and Gage, 2000; Levin et al., 2009) or high concentrations of oxygen-binding proteins and pyruvate (Gonzalez and Quinones, 2000; Pals and Pauptit, 1979; Ruby and Fox, 1976).

Demaison and Moore (1980) were among the first to suggest that oxygen depletion is responsible for organic matter (OM) accumulation in sediments, due to inefficient carbon processing and the lower oxidative power of anaerobic degradation pathways. This assumption has been debated: Calvert et al. (1995) and Pedersen and Calvert (1990) argue that high organic matter delivery (export production), sediment texture and dilution by other sedimentary components (such as relatively organic-poor terrestrial clays and the inorganic sediment matrix) rather than water-column anoxia control accumulation of organic matter in sediments. Other, non-oxygen related factors such as OM quality and sorption to the inorganic mineral matrix have also been suggested as primary causes for the OM enrichment in OMZ sediment (Hedges and Keil, 1995).

* Corresponding author. Tel.: +31 113577489; fax: +31 113573616.
E-mail address: lara.pozzato@nioz.nl (L. Pozzato).

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The mid-water OMZ in the Arabian Sea is permanent, well delineated and the largest on Earth (Helly and Levin, 2004). This oxygen depletion is due to respiration of high concentrations of OM produced during monsoon-driven upwelling of nutrient-rich waters, input of intermediate low-oxygen waters from the Southern Hemisphere and strong stratification (Cowie, 2005) and increased water residence times (Wyrtki, 1961). The Arabian Sea OMZ has persisted for many decades and has been reported for the first time in the early 20th century (Cowie, 2005). This makes it a natural field-laboratory to better comprehend the processes and the dynamics occurring in highly oxygen depleted areas. Studies have reported oxygen concentrations of <9 μM between 150 m and 1000 m water depths, which coincide with the maximal values for sediment OM quantity (Brand and Griffiths, 2009; Breuer et al., 2009; Cowie et al., 2009). The OMZ in the Arabian Sea persists roughly between ~100 and ~1000 m depths, although the boundaries fluctuate up to between 60 and 80 m and down to 1200 m depending on season and location (Brand and Griffiths, 2009).

Benthic organic matter cycling in Indian Ocean sediments has been studied for more than a decade because of high organic matter accumulation. Smallwood et al. (1999) and Jeffreys et al. (2009) reported that mega-, macro- and meiofaunas in the OMZ core affect OM quality, stripping away the more labile compounds and determining a change in OM quality. Wakeham et al. (2002) reported that mid-water column fluxes are not consistent with continual degradation of OM as it sinks in the Arabian Sea: in fact, despite temporal and spatial variability in amount and composition of OM reaching the sediment traps, fluxes towards the bottom were always higher, but accumulation rates and concentrations in surface sediments were substantially lower than the fluxes recorded in the traps, implying relative little remineralization occurring in the water column. This could then imply that the OM in the water column is already of poor quality as it sinks. All these processes going on both in the water column and in the sediment make it difficult to separate the single effects of oxygen concentration and OM quality on sedimentary biotic processing.

Studies based on ^{13}C and ^{15}N labeling of food sources can provide a quantitative indication of the OM remineralization and assimilation by biota and therefore can indicate their activity (Blair et al., 1996; Hunter et al., 2012a, 2012b; Middelburg et al., 2000). This methodology has also been applied to better understand the OM processing in the Arabian OMZ. Short-term incubations using lander chambers *in situ* or on-deck using controlled conditions carried out in the Pakistan Margin of the Arabian Sea (Andersson et al., 2008; Cowie and Levin, 2009; Woulds et al., 2007, 2009) have shown to be valuable in investigating the benthic response to a fresh OM deposition event and the fate of the OM added to the system. Already after a 2–5-day incubation period the authors found bacterial, foraminiferal and metazoan macrofaunal uptake to account for 2–32%, 1–17% and 0–46% of total OM processing, respectively. At some sites metazoan uptake was similar in magnitude to that of bacteria and/or total respiration, although in most instances bacteria processed most of the carbon. These studies also confirmed that the benthic community is active in low-oxygen conditions and that OM is utilized and processed both for respiration and biomass production.

In those studies, the sediment-core incubations were however conducted at ambient oxygen concentrations. In an area that experiences temporary migrations of the OMZ zone, it makes sense to look at the response of the biota under short-term changes in oxygen concentration, in particular for the lower OMZ boundary exposed to such fluctuations. In our study on the Murray Ridge, we manipulated the oxygen concentration of sediments taken from inside and outside the OMZ so that the direct control of oxygen concentration on the short-term processing of phytodetritus can be identified. We hypothesized a higher response of the benthic community when exposed to higher oxygen levels. We also expected that when sediment underlying oxygenated waters, from the lower boundary of the OMZ, was exposed to oxygen concentrations as found inside the OMZ, the response in terms of uptake and respiration by benthic community would be impaired. Our focus was on the main benthic compartments based on traditional size-classes bacteria and meio- and macrofaunas. This study aims at (1) quantifying the effect of O_2 depletion on biotic processing of fresh particulate organic matter (POM) inside and outside the OMZ, and (2) quantifying benthic group-specific fresh carbon incorporation and total benthic respiration.

2. Material and methods

2.1. Study area

Sediment samples were taken from 2 stations on Murray Ridge, the offshore region of the Pakistan Margin (Fig. 1) during the PASOM cruise (64PE301) in January 2010. Station OMZ (22°32.9′N 64°02.4′E, 885 m) was located in the core of the OMZ, whereas the deeper station outOMZ (22°18.5′N 63°24.5′E, 1791 m) was below, outside the OMZ. Henceforth, these stations are referred to as STOMZ and SToutOMZ, respectively.

The Murray Ridge is located southwest of the Pakistan Margin. It starts about 100 km from the coast, and it is approximately 20 km

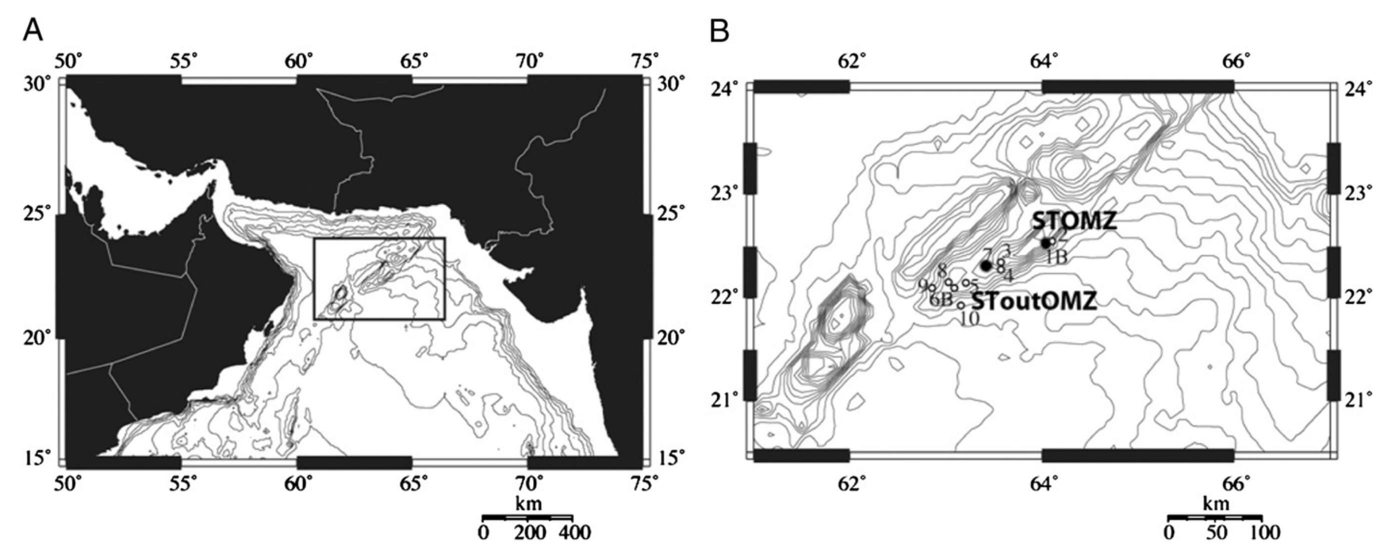

Fig. 1. Sampling area A: the Northern Arabian Sea and B: zoom-in of the sampling locations with the two stations investigated in this study. STOMZ is situated inside the OMZ, and SToutOMZ is situated outside the OMZ.