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Benthos response following petroleum exploration in the southern Caspian Sea: Relating effects of nonaqueous drilling fluid, water depth, and dissolved oxygen

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ABSTRACT

The effects of linear alpha olefin (LAO) nonaqueous drilling fluid on benthic macrofauna were assessed over a six year period at a southern Caspian Sea petroleum exploration site. A wide-ranging, pre-drilling survey identified a relatively diverse shelf-depth macrofauna numerically dominated by amphipods, cumaceans, and gastropods that transitioned to a less diverse assemblage dominated by hypoxia-tolerant annelid worms and motile ostracods with increasing depth. After drilling, a similar transition in macrofauna assemblage was observed with increasing concentration of LAO proximate to the shelf-depth well site. Post-drilling results were consistent with a hypothesis of hypoxia from microbial degradation of LAO, supported by the presence of bacterial mats and lack of oxygen penetration in surface sediment. Chemical and biological recoveries at ≥200 m distance from the well site were evident 33 months after drilling ceased. Our findings show the importance of monitoring recovery over time and understanding macrofauna community structure prior to drilling.

1. Introduction

Studies on impacts to aquatic environments associated with oil and gas exploration and production have been conducted over the past few decades, with many focusing on benthic community effects from discharge and accumulation of drill cuttings and nonaqueous drilling fluid (NADF) on the seafloor (Kingston, 1992; Neff et al., 2000; Schaanning et al., 2008). Effects include physical smothering and acute toxicity, as well as habitat alteration, such as organic enrichment, changes to sediment particle size, and increased oxygen demand. The most widely used synthetic NADFs are esters, poly alpha olefins, and olefin isomers, including linear alpha olefin (LAO). These fluids tend to be less toxic and degrade faster in aquatic environments than their petroleum-based predecessors and hence, should present less risk to the receiving environment. The short-term toxicity of synthetic drilling fluids is well characterized in laboratory studies using standard test organisms (Still et al., 2000; Munro et al., 1998), as are in situ effects of ester-based drilling fluid discharged in offshore environments (Roberts and Nguyen, 2006). However, information is lacking on the effect mechanism and subsequent recovery over time of benthic macrofauna from LAO-based fluids and their associated drill cuttings.

This study assesses effects on macrofauna associated with discharged cuttings with adhered LAO at a single well site located at 145 m water depth, approximately 45 km off the Azerbaijan coastline in the southern Caspian Sea. Exploration drilling commenced in July 2001 and ended in January 2002. The well was drilled to a target sub-seafloor depth of approximately 6700 m using water-based drilling fluid in the top sections and LAO fluid for the deeper well sections. Barium, in the form of barite, was used in both sections as the weighting agent. Results are examined from an August 1998 regional pre-drilling survey and two focused post-drilling surveys conducted in September 2002 and November 2004 (Fig. 1).

The pre-drilling macrofauna community is described in Parr et al. (2007) as a relatively diverse macrofauna, numerically dominated by amphipods, cumaceans, annelid worms, and gastropods at shelf depths (<150 m), compared with increasingly hypoxic habitats dominated by a few species of annelid worms and crustaceans at deeper depths. Results for the 2002 post-drilling survey, conducted eight months after well completion, are reported in Tait et al. (2004). The present study expands on the 1998 regional pre-drilling and 2002 post-drilling studies by including 2004 results to examine LAO degradation and macrofauna recovery 33 months after drilling ceased, and to propose and evaluate the hypothesis that the primary effect mechanism on macrofauna at the well site was hypoxia from the microbial degradation of LAO.

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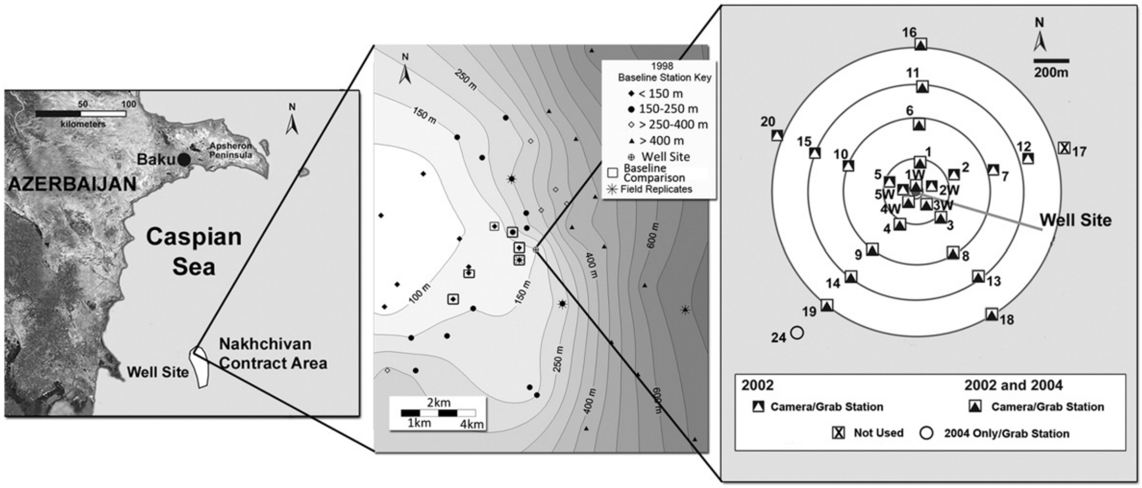

Fig. 1. Regional and survey area maps showing location of Nakhchivan contract area (left), 1998 pre-drilling stations (middle), and 2002 and 2004 post-drilling station locations (right). Shallow (120–170 m) pre-drilling stations used in post-drilling comparisons are identified (□, middle).

2. Study design and methods

2.1. Study design

The 1998 pre-drilling survey sampled sediments 30 months before the start of drilling in the northern half of the Nakhchivan contract area, which included the future well site location (Fig. 1). Fifty-six sediment samples were collected over a depth range of 67–692 m at 36 stations, including six stations with 3–5 field replicates to establish small-scale (within-station) estimates of variance to aid post-drilling sampling design. The well site location, which was designated later, was not sampled.

Post-drilling studies were designed to quantify spatial changes in macrofauna, sediment chemistry, and sediment particle size in relation to drilling operations and discharged cuttings. The post-drilling design was based on the spatial variability of macrofauna estimated from the 1998 regional dataset and hydrodynamic modeling (Nedwed et al., 2004), which predicted that LAO retained on drill cuttings would settle within 400–600 m of the well site, without strong directional bias due to persistently weak subsurface circulation. Comparison of pre-drilling mean results for nine key macrofauna variables showed no statistical differences (one-way ANOVA, $p > 0.05$) and homogeneity of variance (Levene, 1960) ($p > 0.05$) between tightly grouped station replicates and more distant non-replicated stations sampled within the same depth range as the well site (data not shown). Therefore, stations located at 800–1000 m from the well site at depths of 120–170 m could be used as a within-survey reference group to evaluate effects from the drilling-related discharge.

Twenty-five post-drilling sediment samples were collected in 2002, and 15 of those stations were re-sampled in 2004 (Fig. 1, right). In 2002, five stations each were located along five transects (N, NE, SE, SW and NW) at distances of 50 m (well site), 200 m, 400 m, 600 m, and 800 m (reference) from the well site. In 2004, only the N, SE, and SW transects were re-sampled, following 2002 results indicating near omnidirectional settling of discharged cuttings. The design was modified slightly in the 2004 post-drilling survey, resulting in the replacement of an 800-m station located at a depth of 192 m (station 17), with a 1000-m station located at a depth of 135 m (station 24), similar to the well site depth. Station 17 results were excluded from the 2002 dataset.

In 2000, 2002, and 2004 dissolved oxygen (DO) measurements from the water surface to within 5–10 m above the seafloor were profiled at 29 locations, ranging from 0 to 80 km of the well site. Near-bottom water DO at the 145-m deep well site was above the hypoxia upper limit of 2 ml l^{-1} (Diaz and Rosenberg, 1995), ranging from 4 to 6.5 ml l^{-1}. Concentrations at or below 1 ml l^{-1}, the lower limit of hypoxia (Levin, 2003), were measured in near-bottom waters >600 m. Combined results showed stable near-bottom concentrations ranging from >7 ml l^{-1} DO at shallow stations, grading into hypoxic conditions at stations deeper than 400 m (Fig. 2).

Regional pre-drilling and focused post-drilling sediments were analyzed for grain size, sediment organic carbon, macrofauna, 41 polycyclic aromatic hydrocarbons (PAH), nC$_9$–nC$_{44}$ saturated hydrocarbons (SHC), and 14 metals. Sediment profile imaging (SPI) photographs and analysis of LAO were conducted on post-drilling sediments only. SPI provided information on the horizontal and vertical extent of settled cuttings, evidence of bacterial mats, and estimates of reduction–oxidation potential discontinuity (RPD), a surrogate for the depth of oxygen penetration in surface sediment (Rosenberg et al., 2001). Except for total PAH, post-drilling chemical results, including sediment organic carbon,

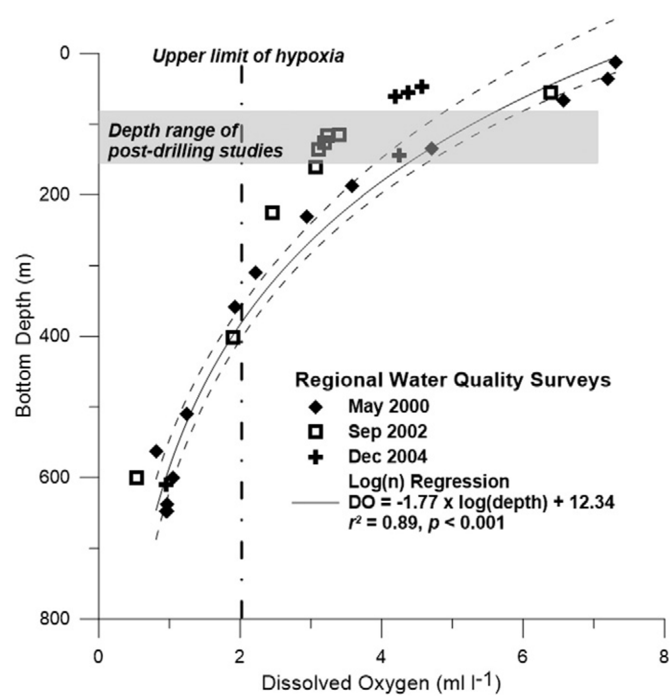

Fig. 2. Dissolved oxygen concentrations in near-bottom water measured in the southern Caspian Sea over a four year period. Hypoxia upper limit (2 ml l^{-1}) predicted at ~400 m bottom depth.