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Benthic habitat condition of the continental shelf surrounding oil and gas platforms in the Santa Barbara Channel, Southern California

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ABSTRACT

The continental shelf of southern California is an important location for the extraction of petroleum and natural gas. Many platforms in the region have been operating for more than four decades and are being targeted for decommissioning. Information on the condition of surrounding habitats to the platforms will be important for regulators. The condition of sediments near (250 m–2 km) four active oil/gas platforms was evaluated with measures of macrobenthic infauna, toxicity, and chemical composition using standardized assessment indices and compared to that of equivalent locations across the region without platforms. Assessment scores indicated that the sediments surrounding the oil platforms were in a relatively good state, with reference-condition infauna, minimal levels of chemical exposure, and five instances (25% of samples) of low-level toxicity. Samples from around the oil platforms were in overall similar condition to the region, with slightly better condition infauna, nearly identical chemistry, and slightly worse toxicity.

1. Introduction

The continental shelf of southern California is an important location for the extraction of petroleum and natural gas within the coastal waters of the United States. There are 23 platforms of varying ages within Federal waters offshore of California (McCrary et al., 2003; BSEE, 2018), with the oldest installed in 1967 (Love et al., 2003; BSEE, 2018). Fifteen of these platforms are within the Santa Barbara Channel portion of the Southern California Bight. The Santa Barbara Channel is an ecologically unique and complex region of the US Pacific Coast, as it is a transition between biogeographic regions (Oregonian to the north and Californian to the south), contains a number of marine protected areas, and borders the second largest metroplex in the United States (Schiff et al., 2016).

A variety of operational platform-related activities (e.g., drilling, maintenance, waste water production), as well as the physical presence of the platform itself, have the potential to influence the condition of the seafloor habitat near the platform (Bishop et al., 2017; Heery et al., 2017; Henry et al., 2017). The cables, pipes, and support structures provide protection from predation and represent more hard substrate for epifauna to grow on than the low-profile soft sediments that comprise much of the continental margin seafloor. In many cases, demersal fishes and megainvertebrates may actually benefit from the structural complexity created by the platform (Love and York, 2005; Page et al., 2008; Claisse et al., 2014).

In contrast to demersal and pelagic fauna, sessile infauna abundance and species compositions are often negatively impacted by platform operations (Denoyelle et al., 2010; Manoukian et al., 2010; Ellis et al., 2012). When wells are drilled for oil and gas exploration or production, fluids and sediments from the drilling process can be released into the water and settle onto the sea floor. Deposits from drilling can bury organisms and increase sediment toxicity over time due to additives introduced to improve the performance of the drilling fluid (Neff, 1987). The amount of materials released from drilling can be substantial – nearly 2000 metric tons of material may be discharged during drilling of an exploration well (Neff, 1987). The size of the area affected from drilling deposits depends on the volume of released materials, the age of the platform, depth of water, sediment characteristics, and ocean conditions. As such, the area of deposition can range from distances of 10 to 20 m from the discharging platform (Neff, 2005) to over 2000 m (Davies et al., 1984).

The investigation of benthic impacts was an important area of study for Federal platforms in southern California early in their development and installation. A large survey in 1975–76 examined metals, chemicals, sediments, and infauna communities associated potential areas for development throughout the Southern California Bight (Callahan and Shokes, 1977). Later, the California Outer Continental Shelf Monitoring Program evaluated the effect of drilling 39 wells from three offshore

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platforms off Point Arguello, California from 1986 to 1995 (Hyland et al., 1991a; Lissner, 1993).

Most of the platforms in the Santa Barbara Channel ecosystem have been in operation for four to five decades and a number of them are approaching the end of their productive lifespans (Schroeder and Love, 2004; Henrion et al., 2014; Bull and Love, 2019). Many of these older platforms are being targeted for decommissioning, which in California currently means the complete removal of oil and gas facilities. Data on the present-day conditions of the benthic habitats around the platforms are important for managers and regulators seeking to predict potential disturbances stemming from changes in platform operation and activities. It would be best if that information would be observational in nature– as opposed to generalized conceptual models – and have as close spatial and temporal proximity to any planned activities as is possible.

Unfortunately, at the present moment nearly all the information available in the scientific literature detailing the relationships between sediment habitat condition and oil and gas platform operation are not from southern California (e.g., North Sea – Olsgard and Gray, 1995; Gulf of Mexico –Montagna and Harper Jr., 1996; Hernández Arana et al., 2005; Mediterranean Sea – Manoukian et al., 2010; Terlizzi et al., 2008). Hyland et al. (1990, 1991a, 1991b, 1994) represents that most recent analysis of sediment chemistry and infauna from soft-sediment habitats near southern California oil platforms, which were based upon sampling conducted more than 30 years ago. As such, there is a lack of current information on the condition of benthic habitat surrounding platforms from southern California, leaving local managers at a disadvantage as decommissioning assessments begin.

The goal of this study was to assess the benthic habitat condition of continental shelf sediments surrounding four active oil/gas platforms in the Santa Barbara Channel in southern California. Condition was evaluated with macrobenthic infaunal community composition, sediment toxicity, and sediment chemical composition. To provide a regional context for our observations of condition, results were compared to those from the most recently completed Southern California Bight Regional Monitoring Program Survey, conducted in 2013 (Schiff et al., 2016).

2. Methods

2.1. Study area and sampling design

Sampling was focused around four active offshore oil and gas producing platforms (A, B, C, and Hillhouse) in the eastern part of the Santa Barbara Channel (Fig. 1). This area of the Southern California Bight is on the continental shelf with water depths of ~60 m (i.e., mid-shelf depths). This is an area oceanographically influenced by the cold-water California Current flowing to the south mixing with the warm-water Davidson Countercurrent flowing to the north (Bray et al., 1999), as well as seasonal upwelling of nutrient-rich bottom waters (Chhak and Di Lorenzo, 2007). Additionally, these waters are adjacent to a densely populated United States metro-center (http://california.us.censusviewer.com/client) and receive point-source and non-point source discharges from more than 23 million people (County Sanitation Districts of Los Angeles County, 2016; Orange County Sanitation District, 2017).

Two sampling strata were created around the platforms, representing polygons with 0–1 km and 1–2 km distances from any of the platforms. Within these strata, 250 m exclusion buffers were created around the platform structures, underwater pipes and cables, as well the shell mounds associated with each platform. These buffers ensured sampling crew safety, prevented damage to the platform infrastructure, and maximized the likelihood of finding sediments suitable for sampling via a grab (i.e., not on shell debris or consolidated sediments). Ten sample sites were allocated within each stratum via a stratified, random tessellated design (Stevens and Olsen, 2003, 2004; Olsen and Peck, 2008). The random allocation process allows for an even distribution of sites among strata. An additional 20 overdraw sites were selected for each stratum in case samples could not be collected at any of the initially identified sampling sites.

2.2. Analytical approach

Habitat condition was assessed at each site with three types of measurements: benthic infaunal community composition, sediment chemistry, and sediment toxicity. Sediment for the three assessment components was collected from each of the 20 sampling sites using a double 0.1 m^2 Van Veen grab following the sampling protocols detailed in the Southern California Bight 2018 Regional Marine Monitoring Survey Sediment Quality Assessment Field Operations Manual (Bight "18 Field Sampling and Logistics Committee, 2018). All measurements from the platform strata were compared to measurements from across the region at the same mid-shelf depth range (30–93 m) that were collected as part of a prior regional survey (2013 Southern California Bight Regional Monitoring Program Survey [Bay et al., 2015; Dodder et al., 2016; Gillett et al., 2017]).

Macrobenthic communities were quantified and characterized using univariate and multivariate comparisons of taxonomic composition, while habitat condition was assessed from these data using the Southern California Benthic Response Index (BRI [Smith et al., 2001]). Sediment chemistry was quantified by measurements of individual compounds (metals, PCBs, PAHs, and pesticides) and habitat condition was assessed from the chemical concentrations via potential exposure scores using the California Chemical Score Index (CSI [Bay et al., 2014]). Sediment toxicity was evaluated using a 10-day amphipod survival test (US Environmental Protection Agency (USEPA), 1994; American Society for Testing and Materials (ASTM), 2010) and habitat condition was interpreted from these data with the California Sediment Quality Objectives (SQOs) framework (Bay et al., 2014). Individual condition assessment categories based upon macrobenthic community, sediment chemical content, and toxicity test results (see Table 1) are combined to give an overall condition assessment (e.g., minimal chemistry exposure + low disturbance macrobenthos + moderate toxicity = Likely Unimpacted) for each sample following Bay et al. (2014).

2.3. Benthic infauna

Methods for processing and identification of benthic infauna followed the guidelines of the Southern California Bight 2018 Macrobenthic Sample Analysis Laboratory Manual (Bight '18 Benthic Committee, 2018). In short, sediments were sieved on a 1-mm screen, the material retained on the screen was placed in a chemical relaxant solution, and then fixed with 10% buffered formalin. Samples were rinsed and transferred from formalin to 70% ethanol 2–5 days after collection. Organisms were sorted from the retained material, counted, and identified to the lowest possible taxonomic level following the Southern California Association of Marine Invertebrate Taxonomists (SCAMIT) Edition 12 species list (Southern California Association of Marine Invertebrate Taxonomists (SCAMIT), 2018). Quality assurance and control protocols and data quality objectives for sample sorting, identification, and enumeration are detailed in the Southern California Bight 2018 Benthic Committee Lab Manual (Bight '18 Benthic Committee, 2018).

Taxonomic composition among the platform samples was visually compared by ordination of untransformed abundance Bray-Curtis dissimilarity values in a 2-D non-Metric Multi-Dimensional Scaling (nMDS) plot. Similarly, the composition of the platform samples was compared to all mid-shelf depth samples from the 2013 regional survey (2018 data were not available at time of publication). Differences in taxonomic composition between the platform samples and the regional mid-shelf samples were quantified with a 1-way permANOVA ($\alpha = 0.1$,

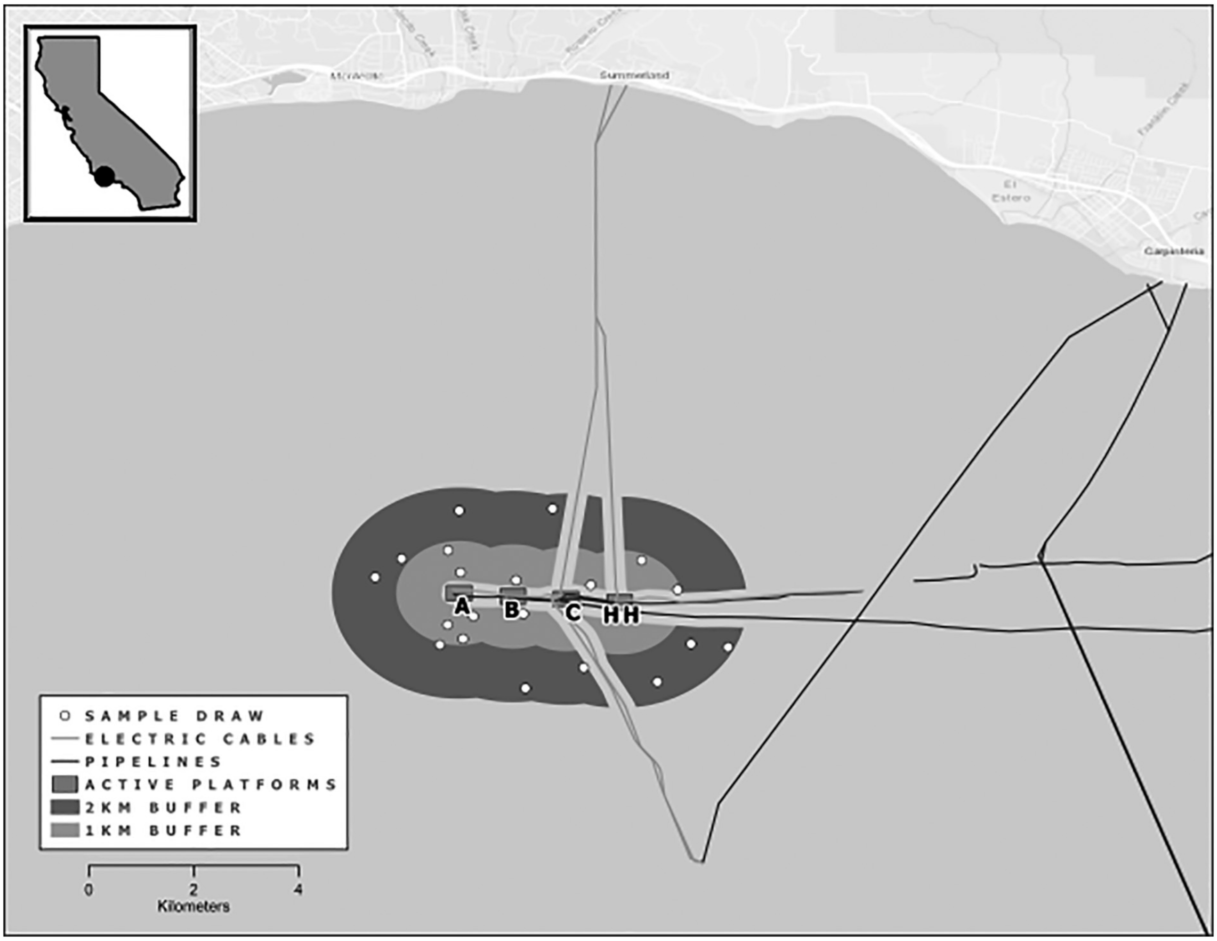

Fig. 1. A map depicting the approximate location of the twenty sampling sites within the1-km (medium grey) and 2-km (dark grey) strata around the A, B, C and Hillhouse (HH) oil platforms. The inset shows the location of the area with respect to the Pacific Coast of the US.

Table 1
Condition category thresholds for condition assessment tools used to interpret macrobenthic infauna (BRI [after Gillett et al., 2017]), sediment chemistry (CSI [after Bay et al., 2014]), and sediment toxicity (after Bay et al., 2014).

Assessment tool	Category	Response range
BRI score	Reference	0– < 34
	Low disturbance	34– < 44
	Moderate disturbance	44– < 72
	High disturbance	≥72
CSI score	Minimal exposure	< 1.69
	Low exposure	1.69–2.33
	Moderate exposure	> 2.33–2.99
	High exposure	> 2.99
Toxicity % survival (control adjusted)	Non-toxic	100–90
	Low toxicity	89 - 82[a]
	Moderate toxicity	59 - 81[b]
	High toxicity	< 59

[a] If the response is not significantly different than the negative control, then the category become Non-Toxic.
[b] If the response is not significantly different than the negative control, then the category becomes Low Toxicity.

1000 permutations, Bray-Curtis dissimilarities), with data source as the treatment variable. Differences in univariate measures of community composition (e.g., abundance, diversity, etc.) between oil platform samples and those from similar depths across the region were quantified using a 1-way ANOVA, with data source as the treatment variable ($\alpha = 0.1$). All nMDS ordinations and permANOVA analyses were conducted with the Vegan package (v 2.5–4) in R (v3.5.3). ANOVA analyses were conducted with the aov function in R (v3.5.3).

Habitat condition of the sediments at each site was assessed using the Benthic Response Index (BRI) (Smith et al., 2001). BRI scores and condition categories were calculated using the Southern California Coastal Water Research Project's online BRI calculator (http://data.sccwrp.org/upload/bri_map.v6.php). BRI scores were compared to those of other mid-shelf sites within the region using a 1-way ANOVA, with data source as the treatment variable ($\alpha = 0.1$).

2.4. Sediment chemistry

Methods for processing and measuring sediment contaminants, grainsize composition, and organic matter content followed Dodder et al. (2016). Individual target analytes included a suite of compounds typically measured in regional surveys: metals, polychlorinated biphenyls (PCBs), polynuclear aromatic hydrocarbons (PAHs), pesticides, measures of sediment grainsize, total organic carbon (TOC) and total nitrogen (TN) (Supplemental Material A). Briefly, grainsize samples were sieved on 2-mm and 1-mm screens to capture the gravel fraction and the remaining smaller particles were analyzed using a SM2560D laser refractometer. Sediments for TOC and TN analysis were acidified with hydrochloric acid vapors and combusted in a high temperature elemental analyzer with gas chromatography. Samples for all metals except for mercury were digested in a strong acid, with the digestate analyzed by inductively coupled plasma mass spectrometry. Mercury was analyzed using cold vapor atomic adsorption spectroscopy. The trace organics (PAHs, PCBs, and pesticides) were solvent extracted and analyzed with gas chromatography mass spectrometry. All analytes

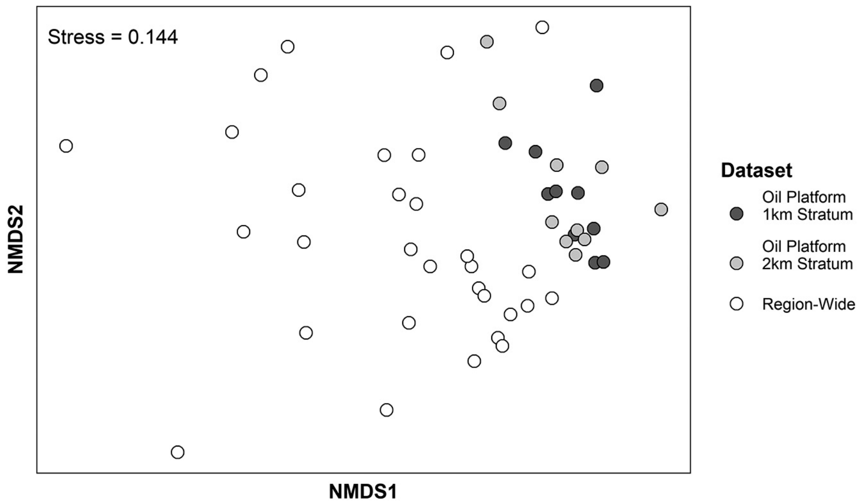

Fig. 2. A 2-D nMDS plot summarizing the similarity of benthic infauna in samples from the 1-km and 2-km strata of the oil platforms, as well as those from mid shelf depths across the Southern California Bight collected in 2013. The ordination was based upon Bray-Curtis dissimilarities calculated from untransformed species abundance.

were measured and summed with the same methods in both the present study and the regional survey.

Comparisons of key compounds of interest including Total PAHs, Low (< 4 aromatic rings) and High (> 3 aromatic rings) molecular weight PAHs, copper, barium, and total DDE, as well as TOC, TN, and grainsize were compared between the platform samples and those from mid-shelf depths across the region collected in 2013. Comparisons of individual compounds between oil platform and regional samples were quantified in a 1-way ANOVA, with the data source as the treatment variable ($\alpha = 0.1$). ANOVA calculations were conducted with the aov function in R (v3.5.3). Habitat condition based upon potential chemical exposure was assessed using the CSI framework (Bay et al., 2014). Comparisons of CSI scores and the distribution of habitat condition categories was made between the platform and regional samples.

2.5. Sediment toxicity

Laboratory methods, as well as quality assurance and control for whole sediment toxicity testing followed the guidelines of Bay et al. (2015). The toxicity of sediments collected from each of the platform stations was evaluated with a 10-day survival test using the amphipod *Eohaustorius estuarius* (US Environmental Protection Agency (USEPA), 1994; American Society for Testing and Materials (ASTM), 2010). Twenty amphipods were used in each replicate test at 15 ± 2 °C under constant illumination. Sediment toxicity was quantified as control adjusted survival after the 10-day exposure. Control adjusted survival rates for the platform samples was compared to that of similar mid-shelf depth samples from across the region collected in2013. Habitat condition based upon the toxicity of the sediment was evaluated using California's SQO assessment framework (Bay et al., 2014). The distribution of condition categories was compared that of similar mid-shelf depth samples from across the region.

Any platform samples that demonstrated toxicity were further investigated for potential causality by comparing the chemical concentrations and sediment conditions between non-toxic and toxic samples. Differences in the concentrations of major constituents (barium, copper, mercury, zinc, total high molecular weight PAHs, total low molecular weight PAHs, total PAHs, total DDEs, total nitrogen, total organic carbon, and clay composition) between samples were quantified with a one-way ANOVA, with toxicity test status as the treatment variable ($\alpha = 0.1$). ANOVA tests were conducted using the aov function in R (v 3.5.3).

The potential impacts of toxicity on benthic community were investigated by comparing differences in benthic community composition and condition between non-toxic and toxic samples. Differences in community composition were estimated visually with an nMDS ordination and quantified with one-way permANOVA between the groups of samples, with toxicity test status as the treatment variable ($\alpha = 0.1$) across 1000 permutations using untransformed abundance Bray-Curtis dissimilarities. Similarly, the difference in BRI score between the two groups of samples was quantified with a one-way ANOVA, with toxicity test status as the treatment variable ($\alpha = 0.1$). ANOVA tests were conducted using the aov function in R (v 3.5.3) and the permANOVA was conducted using the adonis2 function in the Vegan package (2.5–4) in R (v 3.5.3).

3. Results

3.1. Benthic infauna

Across the 20 samples, 338 different taxa were identified. A comparison of the benthic infauna collected from the 1-km and 2-km strata indicated that the strata were relatively similar to each other. Within both strata, the macrobenthic community was dominated by the ophiuroid *Amphiodia urtica*, and the polychaetes *Spiophanes duplex*, *Aglaophamus verrilli*, and *Mediomastus* sp., which were among the top ten most abundant taxa across all the samples. A permANOVA of Bray-Curtis dissimilarities (untransformed abundances) indicated that there were no differences between the infauna from the 1-km and 2-km strata ($p = 0.45$, df = 1,18). Multivariate comparisons between the platform samples and those from across the region suggest that there were differences in community composition and abundance between the two data sets (permANOVA $p = 0.001$, df = 1,48). A visual inspection of the ordination (Fig. 2) confirms the permANOVA results, in that platform samples clustered to themselves (i.e., more similar) than to the regional samples, albeit without complete separation from them.

From a univariate perspective, the samples from around the oil platforms were somewhat different than similar regional mid-shelf samples. The oil platform samples had significantly lower total abundance ($p = 0.012$, df = 1,48, f = 6.8), taxa richness ($p < 0.001$, df = 1,48, f = 24.4), and Shannon-Weiner taxa diversity ($p = 0.006$, df = 1,48, f = 8.2) than the regional samples based upon the results of the 1-way ANOVA tests (Fig. 3).

3.2. Sediment chemistry

Measurements were made for 87 different chemical contaminants, as well as measurements of sediment grainsize, TOC, and TN content, at each of the 20 sampling sites. Of the priority toxic compounds with published biological effects thresholds (Table 2), no compounds were observed at concentrations above their ERM or CSI High Impact values and most of the compounds were below any biologically meaningful

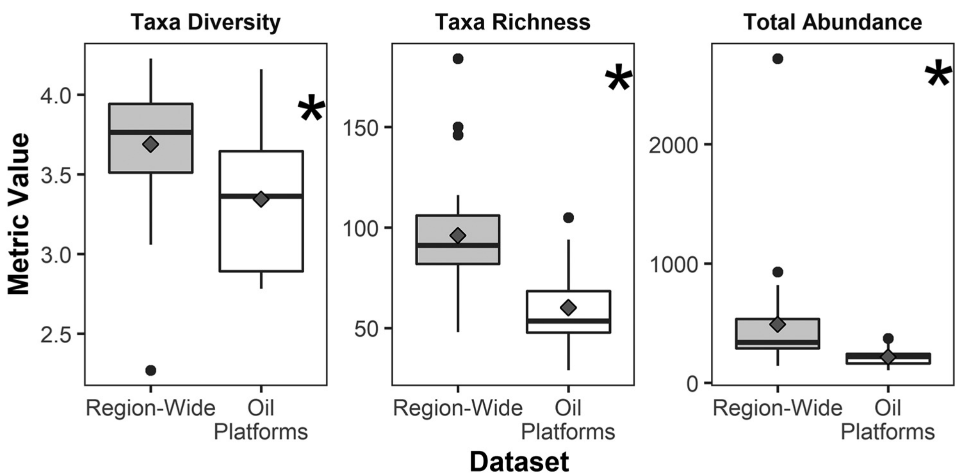

Fig. 3. Schematic box-plots comparing taxa richness (S), taxa diversity (H′), and total abundance (# $grab^{-1}$) between oil platform samples and those from mid shelf depths across the Southern California Bight collected in 2013. An asterisk indicates a significant difference (α = 0.1) in a 1-way ANOVA test between the Regional and Oil Platform datasets. The grey diamonds indicate the mean value for each metric.

Table 2
The counts of oil platform samples where concentrations of chemicals were measured in exceedance of their respective ERL/ERM (Long et al., 1995) or CSI Condition (Bay et al., 2014) thresholds. A blank cell indicates that the assessment framework did not have a threshold for that particular chemical compound.

Chemical	Greater than ERL	Greater than ERM	CSI condition thresholds		
			Low impact	Moderate impact	High impact
Arsenic	11	0			
Cadmium	0	0			
Chromium	0	0			
Copper	0	0	0	0	0
Lead	0	0	0	0	0
Mercury	0	0	0	0	0
Nickel	7	0			
Silver	0	0			
Zinc	0	0	0	0	0
2-methyl naphthalene	0	0			
Acenaphthene	0	0			
Acenaphthylene	0	0			
Anthracene	0	0			
Benzo(*a*)anthracene	0	0			
Benzo(*a*)pyrene	0	0			
Chrysene	0	0			
Fluoranthene	0	0			
Fluorene	0	0			
Naphthalene	0	0			
Phenanthrene	0	0			
Pyrene	0	0			
Summed high molecular weight PAHs			1	0	0
Summed low molecular weight PAHs			0	0	0
Sum of all PAHs	0	0			
Summed DDDs			2	0	0
Summed DDEs	16	0	19	2	0
Summed DDTs	0	0	5	0	0
Cis-chlordane			0	0	0
Trans-chlordane			0	0	0
Summed PCBs	0	0	0	0	0

concentration at all. Total DDEs (i.e., 2,4 DDE + 4,4 DDE) was the compound measured most frequently in exceedance of its thresholds: Nineteen samples had total DDEs above the CSI Low Impact threshold, with two of those samples above the Moderate Impact threshold; 16 samples had total DDEs above the ERL threshold. The contaminant with the second most exceedances was arsenic, with 11 samples above the ERL value.

Compared to samples collected from mid-shelf depths across the region, samples from the oil platforms had significantly higher concentrations of barium ($p < 0.001$, df = 1,48, f = 14.5), high molecular weight PAHs ($p = 0.035$, df = 1,48, f = 4.7), and total PAHs ($p = 0.069$, df = 1,48, f = 3.5) (Fig. 4). In contrast, oil platform samples had similar amounts of copper ($p = 0.203$, df = 1,48, f = 1.7) and low molecular weight PAHs ($p = 0.474$, df = 1,49, f = 0.52) as the regional samples. The concentration of total DDE was higher in regional samples than those from the oil platforms ($p = 0.087$, df = 1,42, f = 3.1). Sediments from the oil platform samples were sandier ($p = 0.073$, df = 1,46, f = 3.4) than those from across the region. Sediment TOC content ($p = 0.252$, df = 1,46, f = 1.3), and TN content ($p = 0.987$, df = 1,39, f = 0.0003) were similar between the oil platform and regional samples (Fig. 5).

3.3. Sediment toxicity

Successful 10-day survival toxicity tests were conducted with sediments from each of the 20 oil platform sampling sites. Fifteen of the samples showed no toxicity. Five of the samples showed low toxicity, three of which were located in the 1-km stratum. Control adjusted survival was slightly lower among the oil platform samples compared to that of samples from mid-shelf depth sites from across the region (Fig. 6).

The low toxicity platform samples had significantly higher concentrations of copper ($p = 0.044$, df = 1,18, f = 4.7), mercury ($p = 0.007$, df = 1,18, f = 9.2), zinc ($p = 0.067$, df = 1,18, f = 3.8), and total DDEs ($p = 0.018$, df = 1,18, f = 6.8) (Fig. 7) than did the platform samples with non-toxic values. Additionally, sediments from the low toxicity samples contained significantly more clay ($p = 0.016$, df = 1,18, f = 7.0), nitrogen ($p = 0.015$, df = 1,18, f = 7.2), and organic carbon ($p = 0.022$, df = 1,18, f = 6.3) (Fig. 7). There were no differences in the amounts of barium or the different PAH mixes measured between the two types of samples. There were no differences in benthic community composition between the low toxicity and no toxicity platform samples (permANOVA $p = 0.405$, df = 1,18), which confirms the pattern apparent in the nMDS ordination of the data (Fig. 8).

3.4. Habitat condition

Based upon the BRI benthic infauna-based condition assessment tool, 100% of the sampling sites around the oil platforms were in reference condition. In comparison to the mid-shelf depth samples from across the region assessed during the Bight '13 survey, the oil platform samples had lower (i.e., healthier) BRI scores (Fig. 6) and a greater

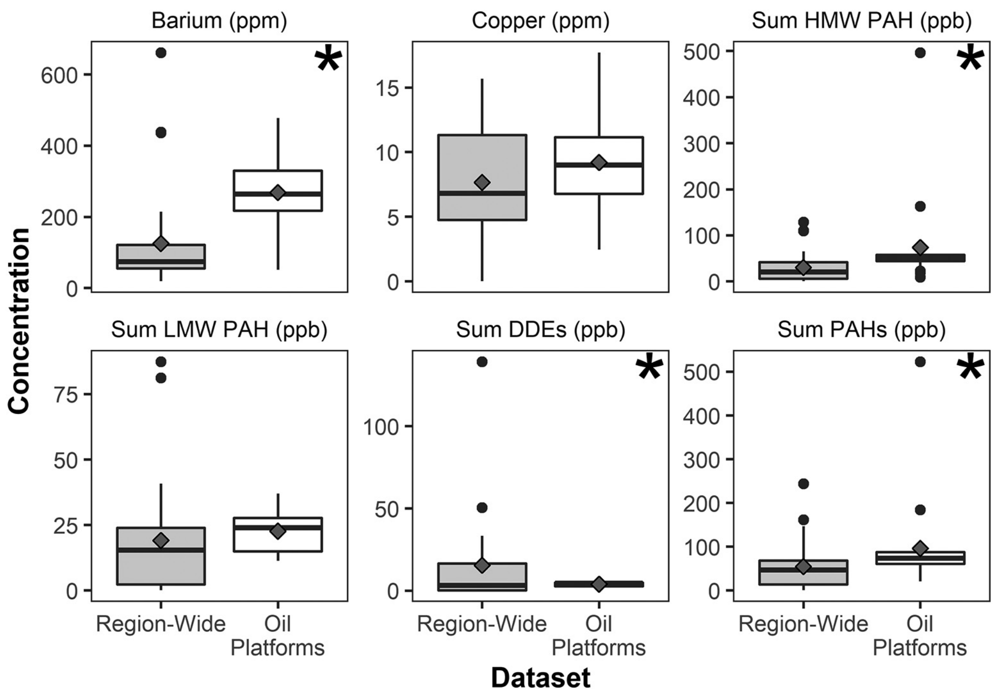

Fig. 4. Schematic box plots comparing select chemical compounds between oil platform samples and those from mid shelf depths across the Southern California Bight collected in 2013. An asterisk indicates a significant difference (α = 0.1) in a 1-way ANOVA test between the Regional and Oil Platform datasets. The grey diamonds indicate the mean value for each compound.

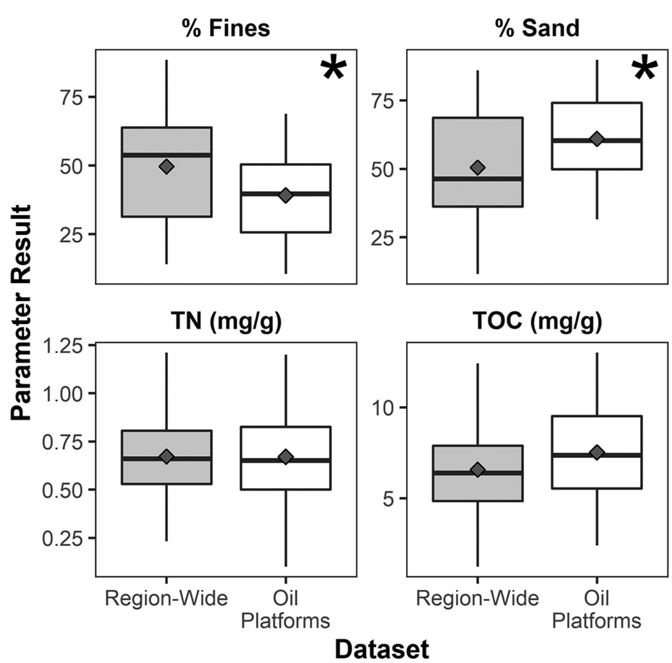

Fig. 5. Schematic box plots comparing measures of sediment grainsize composition (% Fines = %Mud + % Clay), total organic carbon (TOC), total nitrogen (TN) between oil platform samples and those from mid shelf depths across the Southern California Bight collected in 2013. An asterisk indicates a significant difference (α = 0.1) in a 1-way ANOVA test between the Regional and Oil Platform datasets. The grey diamonds indicate the mean value for each sediment parameter.

percent of the samples were categorized in reference condition than those from the regional dataset (90% reference, 6.7% low impact, 3.3% moderate impact). Based upon the CSI chemistry-based condition assessment tool, 100% of the sampling sites around the oil platforms had minimal potential chemical exposure. CSI scores of the oil platform samples were similar to that of the mid-shelf samples from across the region (Fig. 6). All of the oil platform samples were evaluated as having minimum chemical exposure to benthic infauna, as were 100% of regional mid-shelf samples. The toxicity -based condition tools indicated that of 75% of the oil platform samples were evaluated as non-toxic and 25% as low toxicity. Regional mid shelf samples were100% non-toxic. Overall, the oil platform samples had lower control adjusted survival than samples from mid-shelf depths across the region (Fig. 6).

There was no clear expression of the patterns the sediment toxicity among the macrofauna observed at the 20 sites that were sampled around the platforms. The low toxicity result – within the interpretation framework we used – represents only a subtle potential impact to the environment (Bay and Weisberg, 2012). This is bore out in the profiles of taxa composition and abundance among all the samples, which – while not identical (Fig. 8) – did not follow a detectable pattern related to the toxicity status.

When the three measurements of habitat condition – macrobenthic community composition, sediment chemistry, and sediment toxicity – were combined together following the guidelines of the California SQO framework (Bay et al., 2014), all of the samples from around the oil platforms were evaluated to be in unimpacted condition.

4. Discussion

This work is the first comprehensive condition assessment of benthic habitats adjacent to oil and gas platforms in southern California in over 20 years. Using regionally calibrated assessment tools that measure habitat condition using benthic infauna, sediment chemistry and sediment toxicity, we demonstrated that the soft sediment seafloor surrounding the A, B, C, and Hillhouse oil platforms were in a relatively good state. Based upon this assessment framework, all of the sample area had reference-condition benthic infauna and sediments with minimal levels of potential chemical exposure, which was proportionally better than the region as a whole. When compared to regional data, however, statistical differences in benthic community composition and lower total infaunal abundances were observed in the sediments near the platforms. Similarly, sediments around the platforms had statistically higher concentrations of barium and total PAHs than the regional average. Taken together, these results would suggest that present day oil platform operations at these locations could be detected in the environment but were not substantially degrading the continental shelf habitat around them. This overall result illustrates the value of targeted

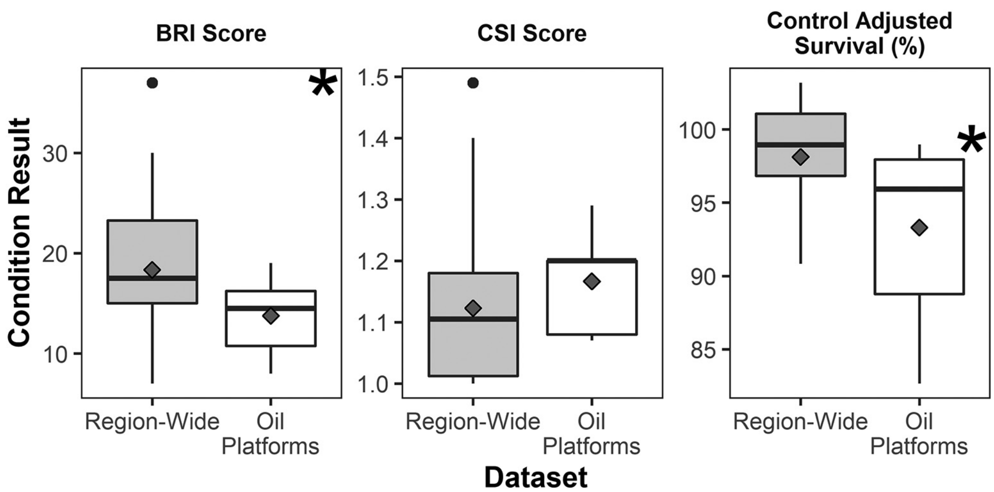

Fig. 6. Schematic box plots comparing benthic habitat condition scores between oil platform samples and those from mid shelf depths across the Southern California Bight collected in 2013 based upon benthic infauna (BRI Score), sediment chemical content (CSI Score), and sediment toxicity tests (Control Adjusted Survival. An asterisk indicates a significant difference ($\alpha = 0.1$) in a 1-way ANOVA test between the Regional and Oil Platform datasets. The grey diamonds indicate the mean value for each metric. Note that lower BRI scores indicate better condition infauna and lower CSI scores indicater less contaminated sediment.

assessment studies conducted within the larger framework of regional, probabilistic assessments. The combination of sampling schemes provides insight into the impacts of different human activities – oil and gas extraction in this case – on the coastal ocean. It allows for the answering of directed questions at spatial- or mechanistic-scales that would be more challenging to address with only regional monitoring program data, but it also produces results can still be placed within the milieu of the region as a whole.

The benthic infauna that were living around the oil platforms were typical of mid-shelf infauna found across the Southern California Bight (Ranasinghe et al., 2012; Gillett et al., 2017). The total abundance of organisms found in the oil platform samples was somewhat lower than what was typical for the region, but the samples were far from depauperate. Density of fauna in a location can be influenced by a mix of natural (e.g., predation or recruitment) (Wilson, 1990; Cowen and Sponaugle, 2009) or anthropogenic processes (Pearson and Rosenberg, 1978; Warwick, 1986). The habitat condition index we applied (Smith et al., 2001) indicated that all of the samples were in reference condition, which would suggest that the somewhat low abundance may have been biologically-based phenomena or related to oceanographic

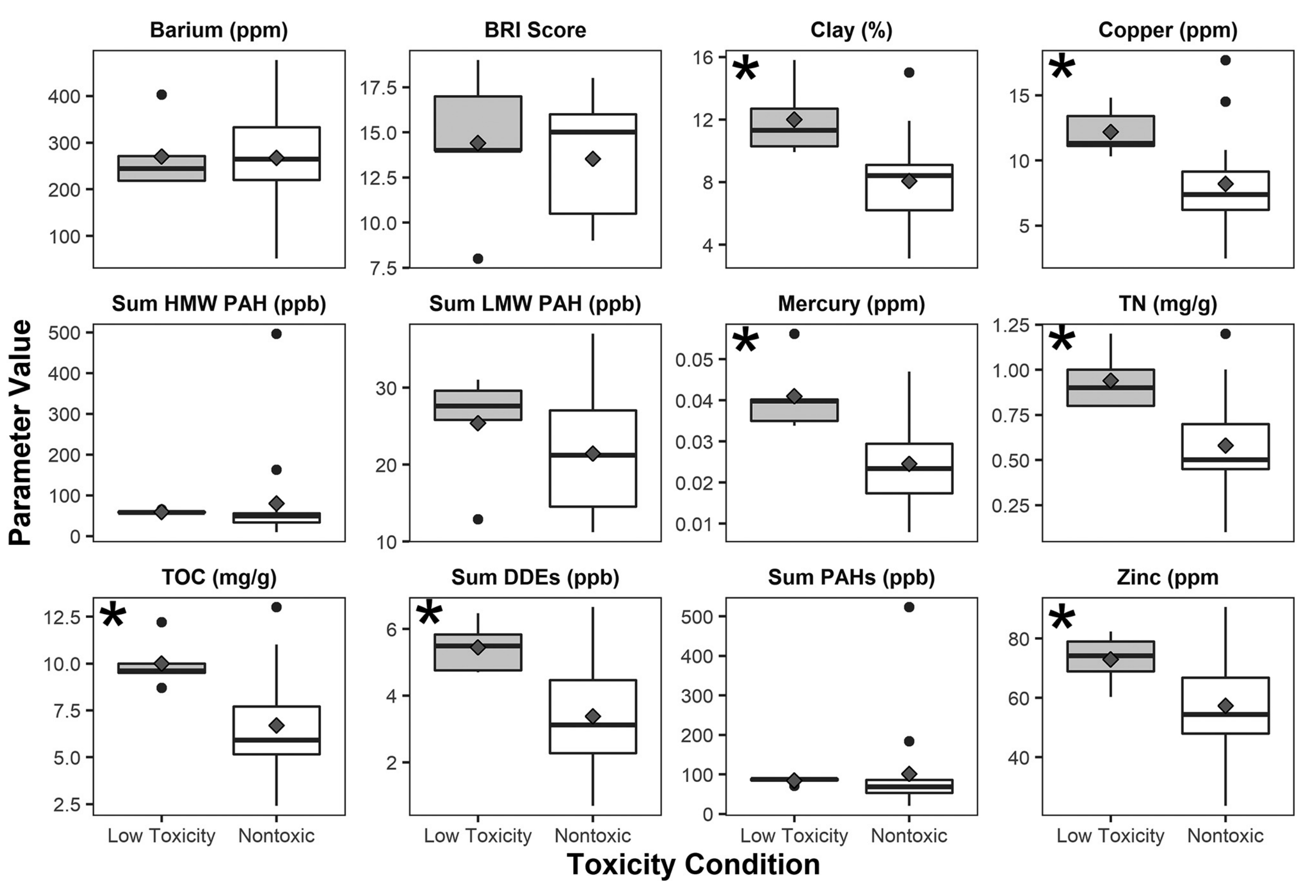

Fig. 7. Schematic box plots of important chemical compounds, sediment characteristics, and BRI scores between samples collected from around the four oil platforms that exhibited either low toxicity or no toxicity. An asterisk indicates compounds for which the low toxicity samples had significantly higher concentrations based upon the results of a one-way ANOVA ($\alpha = 0.1$). The grey diamonds indicate the mean value for each parameter. Note that lower BRI scores indicater better condition infuana.

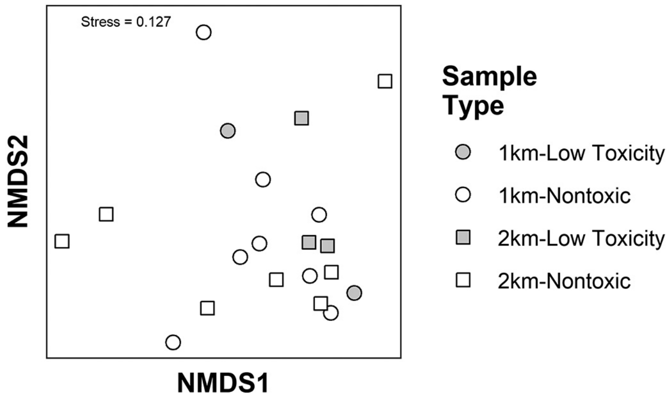

Fig. 8. A 2-D nMDS plot summarizing the similarity of low- and no-toxicity samples collected from the 1 km and 2 km zones around the four platforms. The ordination was based upon Bray-Curtis dissimilarities calculated from untransformed species abundance.

conditions in this northern portion of the region. Eventual comparison of the infauna from the oil platform samples to more recently collected benthic community information from the 2018 Southern California Bight Regional Monitoring Program, may provide further insight into the lower overall abundances and taxa richness observed in the samples.

Benthic infauna are one of the most important indicators of overall habitat condition in marine systems. Because of their relatively sessile lifestyle, intimate association with the sediment, and varied autecological traits, infauna accurately reflect potential impacts to the biological resources of a given location (e.g., McIntyre, 1984; Warwick, 1988; Gray and Elliott, 2009). Focusing on the health and condition of resident biota directly speaks to the motivations of nearly all regulatory monitoring programs (e.g., United States Clean Water Act [33 U.S.C. 1251], European Union Water Framework Directive [WFD 2000/60/EC]) and provides ecologically meaningful insight into any potential disturbances of an ecosystem. Specific to California, biologically-based assessment of habitat condition directly informs a number of the designated Beneficial Uses defined by the California State Water Resources Control Board (2012) and assigned to each water body within the state.

Sediment chemistry and toxicity measures of habitat condition provide contextual information that can help in interpreting the causality of any observed biotic degradation. While a variety of different chemical compounds were detected in the sediments surrounding these four platforms, very few of them were at concentrations likely to cause significant impacts the fauna of the system. This is good confirmatory evidence to support the results of the infauna-based assessment, which indicated the whole of the area sampled around the platforms was in reference condition. There were moderately high levels of the DDT breakdown product DDE, but that is a characteristic of much of the continental shelf sediments in the northern parts of the Southern California Bight (Niedoroda et al., 1996; Zeng and Venkatesan, 1999; Dodder et al., 2016) and most likely not related to the platforms. In contrast, barium and high molecular weight PAH concentrations were elevated in sediments from around the oil platforms compared to the regional average, which was not surprising given the association of both types of chemicals with drill cuttings (Olsen et al., 2007; Schaanning et al., 2008). Other chemicals one might associate with oil platform operation (e.g., low molecular weight PAHs from the petroleum or copper from anti-fouling paint) were not particularly elevated in the samples relative to regional background concentrations, nor were they at concentrations believed to impact the fauna living in the habitat.

All of the samples were evaluated as being in reference/minimal chemical exposure condition (i.e., non-disturbed) from the biology/chemistry- perspective, but 25% of those samples exhibited low levels of toxicity. This level of disagreement among multiple measures of habitat condition are not uncommon and illustrates the benefits of looking at multiple facets of benthic habitat condition (Chapman et al., 1997; Bay and Weisberg, 2012; Schiff et al., 2016). Conducting toxicity tests with ambient material provides a biological relevant test of any potentially harmful compound that is in the sediment – not just the ones that were measured in chemical analyses. As such, in its most direct interpretation, low toxicity results would suggest that some unmeasured compounds were present in the environment that may have had potentially negative consequences for some of the resident fauna, but these impacts not reflected in the measurement of the entire community. However, these types of toxicity tests typically use only a single species that is selected for consistency of results and sensitivity to toxic chemicals, not whether it was a component of the local faunal assemblages (Chapman et al., 2002). While this approach provides a reliable assessment of toxicity, the link between single-species toxicity tests and observable impacts in the community composition of resident biota is not always tightly coupled (Buchwalter et al., 2007; Poteat and Buchwalter, 2014).

The disconnect between toxicity tests and in situ benthic infauna was born out in our results, where there were no observable differences in community composition or benthic index score between the samples with low toxicity and nontoxic results. In contrast, there were interesting patterns between the sediment chemistry measures and the toxicity test results. The five samples that showed low-levels of toxicity had greater concentrations of copper, mercury, zinc, total DDEs, total nitrogen, and total organic carbon. However, those concentrations were below the most commonly used thresholds that imply potential toxicity or problems to resident infauna. The exception would be DDE, which was observed at concentrations above ERL (2.2 ppb) and CSI low impact (1.19 ppb) thresholds, though below the corresponding higher thresholds that have more likely biological effects. The amount of DDE may partially explain the observed toxicity, but it should be noted that nearly all of the no-toxicity samples also had DDE concentrations in excess of the ERL/CSI low impact thresholds.

Overall, we cannot rule out that the combination of multiple low-levels of these compounds or the presence of some unmeasured toxic chemicals in the sediments from around the platforms could have caused the observed toxicity. However, in addition to the elevated chemicals, the sediments of five samples also had elevated clay content compared to the 15 non-toxic samples. Sediments with a high clay content have been observed to cause mortality to the *E. estuarius* test organisms; especially if they are large specimens (Anderson et al., 2017). It is therefore possible that the low toxicity evaluation may not have been related to any toxic chemicals in the sediments, but instead to the granulometric composition of the sediments themselves. Given the lack of any clear response in the benthic community and the magnitude of the chemical concentration that were measured, it seems reasonable that the elevated clay content of the sediments was the most parsimonious factor behind the observed toxicity.

An important caveat with the patterns we observed, is that we actively chose to not sample within the shell debris/muds and cutting deposit fields of the platforms due the incompatibility of the sampling gear with consolidated, shell hash sediments. These sediments have been shown to be toxic to resident fauna and a potential source of chemicals to the surrounding environment (Neff, 1987; Schaanning et al., 2008; Ellis et al., 2012). These drill cuttings may have also been a source for the elevated amounts of clay observed in the low toxicity samples and possibly contributing to the observed toxicity. A targeted study of sediments and chemicals in the debris fields immediately surrounding the platforms, in conjunction with a soft sediment study would provide a more complete evaluation of the potential impacts of platforms on their adjacent sediment.

In situations where sediments could be sampled directly underneath or immediately adjacent to oil platform structures, other studies have observed habitat degradation in the form of altered benthic communities, elevated sediment contaminants (typically hydrocarbons, copper, and barium), and toxic responses to sediment (Chapman et al., 1991; Hernández Arana et al., 2005; Terlizzi et al., 2008; Spagnolo et al., 2014). A study of platform discharges near Point Arguello, California (~100 km WNW of the present study), detected minor biological changes in hard bottom assemblages approximately 1000 m from the discharge source, as well as elevated barium and a peak in sedimentation from drilling solids out to 1500 m from the platform (Hyland et al., 1994). The degree of habitat degradation observed in most studies from the Gulf of Mexico and the Mediterranean Sea declined when moving away from the platform and few effects could be detected beyond 1500 to 2000 m. Similar studies from the North Sea also report the effects of sediment contamination declining with distance from platforms, but with impacts persisting out to 6 km from the platform (Olsgard and Gray, 1995; Schaanning et al., 2008; Bakke et al., 2013). The differences in the spatial-scale of oil platform influence on the adjacent habitat is thought to be a function of the size of platforms and the nature of their operations (Spagnolo et al., 2014). The patterns in our study more closely resembled those of the Gulf of Mexico and Mediterranean platforms. Even then, the degree of impact we observed was much more constrained, with no meaningful departures from unimpacted conditions at distances from as little as 250 m up to 2 km from a platform.

In addition to their comparatively small size of operation, the muted impact of the four oil platforms in the present study to their surroundings could also be due to their use of water- and synthetic-based drilling fluids instead of oil-based ones. Much of the toxicity observed in platform adjacent sediment in other location has been associated with the discharge of oil-based drilling fluids, which contain toxic aromatic and poly cyclic aromatic hydrocarbons (Boehm et al., 2001). Discharge of these fluids to the adjacent ocean is no longer allowed within the waters of United States. In contrast, synthetic-based fluids contain manufactured hydrocarbons that are not petroleum based and therefore do not contain the aromatic hydrocarbons that contribute to the toxicity of sediments (Bernier et al., 2003). Water-based drilling fluids have mineral oil as the principal additive and are permitted for discharge to surrounding waters in most parts of the United States (MMS, 2007). Strong currents in the Santa Barbara Channel may also dampen the signal of the platforms in the surrounding seafloor by dispersing and thereby diluting the drill cuttings from the platforms (e.g., Coats, 1994) compared to platforms in in other regions.

Much of the oil and gas extraction infrastructure offshore of southern California is nearing the end of the practical lifespan and will most likely be decommissioned in the foreseeable future (McCrary et al., 2003; Schroeder and Love, 2004; Henrion et al., 2014). Any type of removal activity will invariably have the potential to disturb the surrounding sea floor habitat, the impacts of which will most likely need to be quantified. These results from our study could be used to represent the baseline environmental conditions of the sediment habitat surrounding the A, B, C, and Hillhouse oil platforms prior to any decommissioning activities that were to take place. Our characterization of the benthic infauna, the chemical content, and toxicity of the sediments around the platforms should be used as a point of reference for any future changes in operations and evaluating their potential impacts on the local environment. Furthermore, given the similarity of the benthic infauna observed in the present study to those of other parts of the Santa Barbara Channel and the region as a whole, infaunal data collected from the northern portions of the Southern California Bight during routine monitoring should also be used as a benchmark to interpret temporal patterns in benthic community change at the four platforms in our study, as well as other platforms in the region.

CRediT authorship contribution statement

David Gillett: Conceptualization, methodology, formal analysis, writing, editing, and visualization. Lisa Gilbane: Conceptualization, facilitation of sample collection, writing, review, editing, and funding acquisition. Ken Schiff: Conceptualization, methodology, review, editing, supervision, project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2020.111662.

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