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Opportunistic Sampling at a Deep-water Synthetic Drilling Fluid Discharge Site in the Gulf of Mexico

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Two opportunistic benthic surveys were conducted at an offshore semisubmersible oil drilling rig located in 565 m of water on the continental slope of the Gulf of Mexico to determine the extent of synthetic-based drilling fluid (Petrofree LE) concentrations in surrounding sediments and the composition of the associated macrofauna and megafauna communities. Sediment concentrations of Petrofree LE ranged from 89 to 198,320 μg/g in surficial sediments (0–2 cm) and from 4 to 85,821 mg/g in the 2–5 cm stratum. The highest Petrofree LE concentrations were located 50–75 m northeast of the discharge site, a phenomenon that may have been related to surface and midwater currents in the vicinity of the rig. Although no direct quantitative measures of in situ degradation are available, high concentrations of Petrofree LE relative to discharge periodicity suggest lower than anticipated rates at this deep-water site. Between July 1997 and March 1998, the densities of polychaetes and gastropods increased sharply in the study area. In March, polychaete (primarily dorvilleids) density, gastropod density, and Petrofree concentrations were all significantly higher northeast of the drill site compared with southwest. Polychaete and gastropod densities northeast of the drill site were roughly 3,600 and 3,000 times higher than those reported in eastern and western areas of the northern Gulf of Mexico at similar depths, respectively.

Prior to the 1990s, oil-based drilling fluids were used extensively in the North Sea and Gulf of Mexico (GOM) for a variety of specialty offshore drilling situations (Burke and Veil, 1995). Their toxic nature required costly land-based disposal of drill cuttings and muds and eventually led to the development of synthetic-based drilling fluids (SBFs) as a substitute. SBFs are free from detectable levels of priority pollutants (EPA, 1994; NOIA, 1995) and the on-site discharge of SBF-coated cuttings is allowed in some areas of the GOM under EPA General Permit GMG290000.

In August 1995, BP Exploration, Inc. (BP) installed a 43 × 24 m (140′ × 80′) subsea template on the continental slope of the GOM in Minerals Management Service's (MMS) Lease Block Mississippi Canyon 28 (Fig. 1). Designated as Pompano Phase II, the subsea template is an automated production and pumping relay station that rests on the sea floor in 565 m (1,860 ft) of water. Drilling at this site began in Oct. 1995 by use of a semisubmersible drill rig and continued through summer of 1997, when the rig was moved. The site was reoccupied from Jan. to April 1998 when an additional well was drilled.

Deep drilling at Pompano Phase II included the use of the SBF Petrofree LE, a blend of 90% linear-alpha olefins (LAO) and 10% ester. By virtue of their inherent chemical structure (linear aliphatic hydrocarbons), LAOs and ester-based SBFs are some of the more biodegradable deep-well drilling fluids presently available (Pitter and Chudoba, 1990; Battersby et al., 1992; Gough et al., 1992; Hanstveit, 1992; Wright et al., 1993; Burke and Veil, 1995; Chaineau et al., 1996; Vik et al., 1996; Munro et al., 1997). Between April 1996 and March 1998, a total of 7,657 bbls of Petrofree LE was discharged (adherent to cuttings) at discrete intervals during the drilling of seven wells.

During the latter phases of drilling, two opportunistic benthic surveys were conducted at the site to provide preliminary estimates of Petrofree LE concentrations in surrounding sediments and the composition of the associated macro-epifauna and -infauna communities. The first survey was conducted on July 10–11, 1997 and the second on March 13–14, 1998. Previous information concerning the fate of SBFs in the marine environment had been based on studies conducted in waters <200 m deep (Cranmer and Sande, 1991; Gjøs et al., 1991 [as cited in Burke and Viel, 1995]; Daan et al., 1995; ERT, 1995, 1997; Vik et al., 1996), and this represented the first opportunity to conduct benthic sampling at a deep-water site.

This paper details the results of the two preliminary surveys at the Pompano Phase II facility. Biological data are compared to data collected at 18 MMS sampling locations at similar

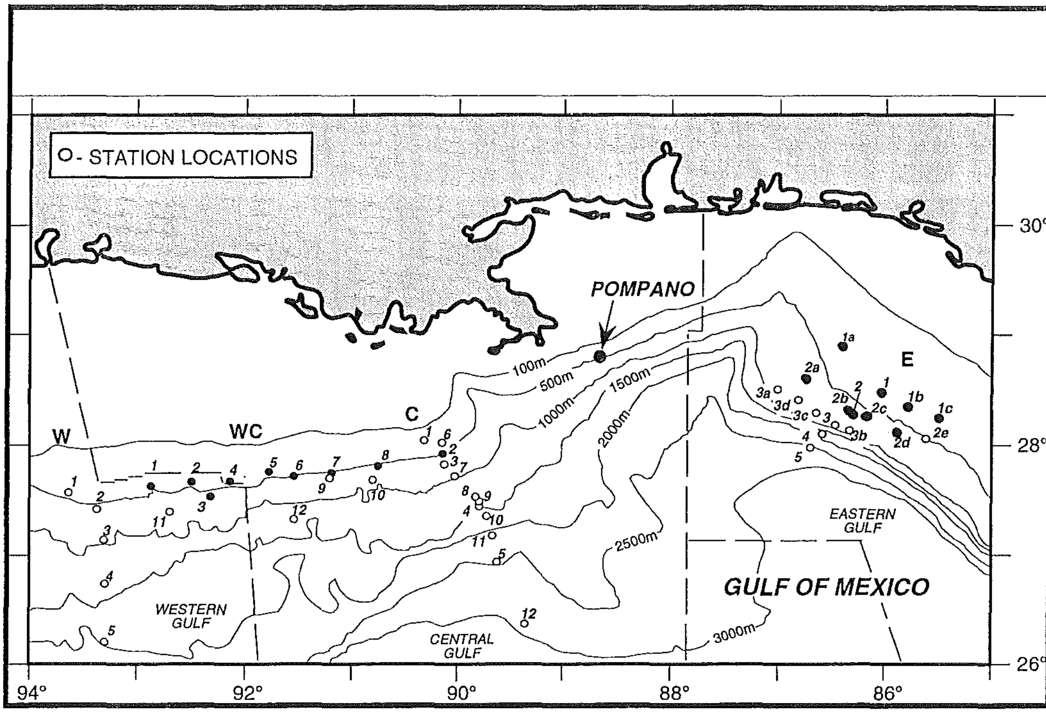

Fig. 1. The Pompano drill site relative to Minerals Management Service (MMS) benthic survey sites sampled during the mid 1980s. Only data from those MMS sites (solid symbols) located at the same approximate depth (~500 m) as the Pompano development were used for comparative analysis.

depths (~500 m) in the northern Gulf of Mexico (see Fig. 1).

Methods

Benthic samples.—Benthic chemical (C) and biological (B) core samples were taken by remotely operated vehicle (ROV) at 16 locations around the subsea template (Fig. 2). The long axis of the template coincided with the direction of prevailing currents, which were believed to have a dominant northeast-to-southwest flow. Cores B-6, B-7, B-8, and C-16 were added to the array following results of the first survey. Sites B-1 and C-7 were not sampled in 1998 because the ROV tether would not extend 90 m southwest of the template. The spatial scope of the sampling grid was limited by the tether length of the ROV.

Hydrocarbon and biological cores were taken in 2 $^{15}/_{16}$ inch OD byrate-plastic push-core sampling devices (designed by Texas A&M University). Prior to each use, corers were cleaned in a microcleaning solution, followed by three freshwater rinses. ROV manipulator arms inserted the corers at the designated sites, then sealed and stored them onboard. Samples were processed upon retrieval of the ROV. For the hydrocarbon samples, two separate aliquots (the top 2 cm and the following 3 cm) were sliced from each core, stored in precleaned jars, and frozen. Prior to processing each core, laboratory equipment was washed with water, rinsed three times with methanol, then rinsed three times with methylene chloride. Separate core samples were taken for biological analysis. Samples were treated similarly, except that only the upper 2-cm aliquot of sediment was taken and frozen. Logistics prevented sieving and preserving the samples in the field.

Hydrocarbon laboratory analysis.—Laboratory analyses of sediment hydrocarbons were conducted by the Texas A&M University, Geochemical and Environmental Research Group, College of Geosciences and Maritime Studies, Dr. Guy Denoux, Project Manager. Sediment samples were thawed, homogenized and a 50% subsample dried in a 40 C convection oven. Dried samples were ground, weighed, and placed in an extraction thimble. A surrogate solution containing deuterated C^{12}, C^{20}, C^{24}, and C^{30} was added to the sample in the thimble and soxhlet extracted for 12 hr by use of dichloromethane. The samples were concen-

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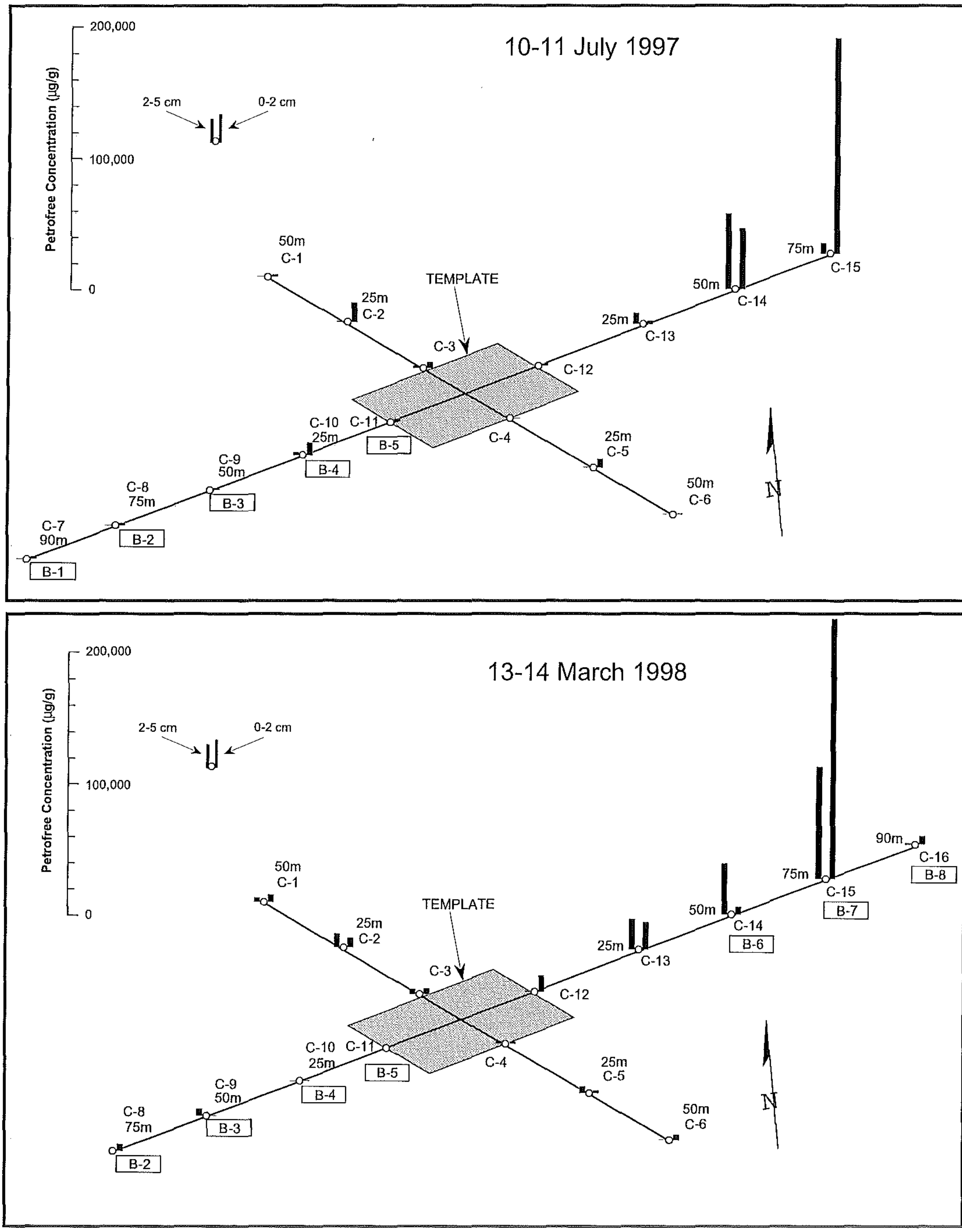

Fig. 2. Location where benthic chemical (C) and biological (B) core samples were obtained around the Pompano Phase II subsea template during the surveys of July 10–11, 1997 and March 13–14, 1998. Cores B-6, B-7, B-8, and C-16, located along the northeast transect, were not taken in July 1997. Cores B-1 and C-7, located along the southwest transect, were not taken in March 1998. Petrofree LE concentrations (µg/g) are depicted as histograms.

TABLE 1. Petrofree LE concentrations (μg/g) at the Pompano Phase II subsea template.

Transect and station	Distance (m) from template	July 11–12 1997 Depth (cm) 0–2	July 11–12 1997 Depth (cm) 2–5	March 13–14, 1998 Depth (cm) 0–2	March 13–14, 1998 Depth (cm) 2–5
1 NW (345°)					
C-3	0	4,976	2,146	4,693	4,158
C-2	25	14,921	1,025	7,523	10,575
C-1	50	180	38	5,884	3,417
Mean		6,692	1,070	6,033	6,050
2 SE (165°)					
C-4	0	312	4	1,697	2,017
C-5	25	6,861	68	2,301	5,416
C-6	50	986	33	4,268	524
Mean		2,720	35	2,755	2,652
3 NE (75°)					
C-12	0	1,973	15	12,451	1,045
C-13	25	2,746	8,501	20,997	23,396
C-14	50	46,561	57,790	5,739	39,170
C-15	75	—	8,322	—	85,821
C-16	90			6,321	1,510
Mean		54,083	18,657	48,766	30,188
4 SW (255°)					
C-11	0	2,986	59	89	103
C-10	25	10,134	2,566	691	77
C-9	50	1,626	309	603	5,490
C-8	75	2,066	13	5,535	209
C-7	90	2,046	528		
Mean		3,772	695	1,730	1,470

trated to ~7 ml using a rotary evaporator, then reduced to dryness by use of a gentle stream of purified nitrogen. The sample was transferred to an autosampler vial and internal standard added.

A Hewlett-Packard 5890 gas chromatograph with a splitless injection system capillary column (J&W Scientific DB-5 bonded phase) and a flame ionization detector were used to analyze the sediment extracts. Alkane calibration standards were prepared in five concentrations ranging from 1.25 to 50 μg/ml. The detector was linear within this range. One of the concentration levels is near, but above, the method detection limit. The initial calibration was verified by the measurement of calibration standards after every 8–10 samples. The average response factor of all n-alkanes was used for the concentration calculations. Internal standard and surrogate compounds were added at 4 μg/ml to all calibration standards. For sediments with higher concentrations of hydrocarbons, the surrogate concentration is appropriately increased. The internal standard and the surrogate compounds are deuterated alkanes (dC^{16}, dC^{12}, dC^{20}, dC^{24}, and dC^{30}). The first surrogate (dC^{12}) is frequently lost during rotary evaporation and was not used for quantification. Calculations are corrected for surrogate recovery normally based on dC^{20}.

The concentration of Petrofree LE present in the samples was quantified by use of a series of standard solutions containing internal standard (dC^{16}), surrogates (dC^{12}, dC^{20}, dC^{24}, and dC^{30}), and a neat solution of Petrofree LE provided by BP. Petrofree LE calibration standards were prepared in the concentration range from 10 to 100 μg/ml. Although samples were analyzed for total Petrofree and total petroleum hydrocarbons (TPH), TPH were only a minor component relative to Petrofree concentrations.

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Laboratory biological analyses.—A standard solution of 10% formalin and rose bengal was added to the frozen sediment/biological samples as they thawed. While they were thawing, the samples were frequently gently stirred to insure preservation and staining of biological organisms. Once thawed, the samples were sieved with tap water through a 300-μm mesh, to separate the macrofauna. The organisms from the samples were preserved in a solution of 70% ethyl alcohol. Organisms were examined under a dissecting microscope, sorted to major taxonomic group, and enumerated. Once sorted, the organisms were labeled and stored.

Results

Hydrocarbons.—Overall, Petrofree LE concentrations in the substrate around Pompano Phase II were highly variable, ranging from 180 to 165,051 μg/g in the 0–2 cm stratum and from 4 to 57,790 μg/g at 2–5 cm in July 1997 and from 89 to 198,320 μg/g (0–2 cm) and 77 to 85,821 μg/g (2–5 cm) in March 1998 (Table 1, Fig. 2). In both surveys, the highest concentrations occurred northeast of the drill site, with peak surficial concentrations (165,051 μg/g in 1997 and 198,320 μg/g in 1998) recorded at Station C-15, located 75 m northeast of the template.

During the July 1997 survey, surface sediment (0–2 cm) concentrations of Petrofree LE were significantly higher (P = 0.001, paired t test) than in corresponding 2–5 cm samples. In March 1998, there was no significant difference (P = 0.357, paired t test) between surface and corresponding subsurface Petrofree LE levels: concentrations were higher at 2–5 cm, relative to surface concentrations at 7 of 15 sites. Furthermore, between July 1997 and March 1998 there was no significant change (P = 0.940, paired t test) in surface Petrofree LE concentrations, but there was a significant increase (P = 0.005, paired t test) at 2–5 cm. In effect, from July 1997 to March 1998, the deep stratum concentrations of Petrofree LE appear to have increased to the point where, by March 1998, they were statistically indistinguishable from surficial concentrations.

The high Petrofree LE concentrations northeast of the template were unexpected because preliminary ROV information indicated that prevailing currents flowed from the northeast to southwest. Deposition was therefore expected to be southwest of the drill site and was the reason that the biological sampling stations were initially located along the southwest transect. (The July results prompted the addition of more sampling stations along the northeast transect for the March 1998 survey.) Although no detailed current data were available during the periods of Petrofree LE discharge, an Acoustic Doppler Current Profiler (ADCP) was in operation during July, August, Sep., and Dec. of 1996. The ADCP recorded current velocity and direction at depths of 33 m (near-surface), 281 m (midwater), and 529 m (near-bottom). Although the dominant direction for bottom currents was indeed to the southwest in every month sampled, the highest frequency of surface and midwater currents was actually to the northeast during July and Aug. Furthermore, surface current velocities during those months were 2–3 times greater than those recorded near the bottom. Data suggest that surface and midwater currents may have been responsible for the high Petrofree LE concentrations northeast of the drill site.

Macrofauna.—Invertebrates from six phyla were identified from the two benthic surveys: Mollusca (Bivalvia, Gastropoda, and Scaphopoda), Cnidaria, Nematoda, Nermertini, Annelida (Polychaeta), and Arthropoda (subphylum Crustacea [Copepoda: Cyclopoida and Harpacticoida]) (Table 2). Eleven families were identified within the class Polychaeta. Polychaetes, gastropods, cyclopoid copepods, and nematodes were the most numerically abundant taxa. The sampling protocol was too limited spatially to identify rare taxa.

Benthic macrofauna assemblages along the southwest transect differed markedly between the two surveys. Cyclopoid copepods were the dominant taxon in July 1997 at a mean density of 10,466 organisms/m^2. In March 1998, only a single cyclopoid copepod (67 organisms/m^2) was collected along the southwest transect, whereas northeast of the template, densities ranged from 1,068 to 3,738 organisms/m^2.

The mean density of polychaetes along the southwest transect increased significantly (P = 0.012; unpaired t test, $\log_e$-transformed data) from 1,815 organisms/m^2 in July 1997 to 18,623 organisms/m^2 in March 1998. Ninety-two percent of the polychaetes observed across all seven sample sites in March 1998 were of the family Dorvilleidae. Northeast of the template, dorvilleid density was 78,498 organisms/m^2, ranging from 34,443 organisms/m^2 at Station B-8 to 101,727 organisms/m^2 at Station B-6. Polychaete (Dorvilleidae) densities along the northeast transect were significantly (P = 0.049) higher than southwest of the drill site. This coincided with surface (P = 0.016; unpaired t test, $\log_e$-transformed data) and deep-

TABLE 2. Macrofauna counts and densities from benthic core samples taken at the Pompano Phase II subsea template during July 10–11 1997 and March 13–14 1998.

	Station									
	Southwest									
	B-1 (90 m)		B-2 (75 m)		B-3 (50 m)		B-4 (25 m)		B-5 (0 m)	
Taxa	N	N/m^2	N	N/m^2	N	N/m^2	N	N/m^2	N	N/m^2
July 10–11, 1997										
Bivalvia	1	267								
Copepodia: Cyclopoida	14	3,738	98	26,165	16	4,272	60	16,020	8	2,136
Gastropoda			3	801			19	5,073		
Nematoda	1	267	3	801						
Polychaeta	2	534	3	801	9	2,403	19	5,339		
Scaphopoda							1	267		
Total	18	4,806	107	28,568	25	6,675	99	26,432	8	2,136
March 13–14, 1998										
Bivalvia			2	534	1	267				
Cnidaria							1	267		
Copepoda: Cyclopoida									1	267
Copepoda: Harpacticoida			1	267					1	267
Gastropoda					1	267	14	3,738		
Nematoda			23	6,141	2	534	12	3,204		
Nemertini			1	267						
Polychaeta			75	20,025	119	31,772	73	19,491	12	3,204
Totals	No sample		102	27,233	123	32,840	100	26,699	14	3,738

layer ($P = 0.033$) Petrofree concentrations that were likewise higher northeast of the drill site than southwest.

Gastropods were the second dominant faunal group observed in March 1998. Although there was no discernible difference in gastropod densities southwest of the drill site from July 1997 to March 1998, density along the northeast transect (68,707 organisms/m^2) in 1998 was nearly 70 times higher ($P = 0.004$) than southwest of the template (1,001 organisms/m^2).

Discussion

Results of the 1997 and 1998 surveys were based on limited sampling windows and must be considered preliminary and viewed in the broadest of terms. Surveys were opportunistic and centered around periods when the attendant ROV became available on short notice. Each survey was limited to <48 hr of support time. The scope of the study only allowed for faunal identification into major taxonomic designations and did not allow for rigorous replication. The study did, however, raise two interesting questions. The first involves degradation of the SBF and the second the observed macrofaunal abundance patterns.

Comparisons of 1997 and 1998 Petrofree concentrations proved no direct information regarding the in situ degradation or dissolution rates because the March 13–14, 1998 study was conducted as an additional 1,486 bbls of Petrofree LE was being discharged adherent to cuttings. However, the July 1997 survey was conducted a minimum of 4 mo after the last discharge of 1,081 bbls of Petrofree LE. Maximum Petrofree LE concentrations in July were 165,051 μg/g in the 0–2 cm stratum and 8,332 μg/g in the 2–5 cm stratum at Station C3-15. Field surveys involving Petrofree discharge in the North Sea reported a rapid decline in sediment concentrations within 12–18 mo after completion of drilling (ERT, 1995, 1997; Daan et al., 1995). However, the maximum initial concentrations in these studies were far lower than at Pompano Site C3-15: initial maxima ranged from 719 μg/g at BP Well 211/12a-18 (ERT, 1997) to 8,389 μg/g at BP 15/20b-12 (ERT, 1995). A study in the Norwegian North Sea did report higher initial concentrations of an ester SBF of 85,300 and 46,400 μg/g and a rapid decrease to <1 ppm 1 yr later (Gjøs et al., 1991 [as cited in Burke and Veil, 1995]; Veil et al., 1996), but the initial concentrations were still half those at C3-15. Simulated seabed studies indicated biodegradation half-lives of

TABLE 2. Extended.

	Station									
	Northeast						Southwest		Northeast	
	B-6 (50 m)		B-7 (75 m)		B-8 (90 m)		Total		Total	
Taxa	*N*	*N*/m²	*N*	*N*/m²	*N*	*N*/m²	*N*	*N*/m²	*N*	*N*/m²
July 10–11, 1997										
Bivalvia							1	53		
Copepoda: Cyclopoida							196	10,466		
Gastropoda							22	1,175		
Nematoda							4	214		
Polychaeta							33	1,815		
Scaphopoda							1	53		
Total	No sample		No sample		No sample		240	13,724	No sample	
March 13–14, 1998										
Bivalvia	1	267	1	267			3	200	2	178
Cnidaria	1	267					1	67	1	89
Copepoda: Cyclopoida	4	1,068	4	1,068	14	3,738	1	67	22	1,958
Copepoda: Harpacticoida	1	267					2	133	1	89
Gastropoda	484	—	220	58,739	68	18,156	15	1,001	772	68,707
Nematoda	1	267					37	2,470	1	89
Nemertini							1	67		
Polychaeta	427	—	393	—	142	37,913	279	18,623	962	85,616
Totals	919	—	618	—	224	59,807	339	22,628	1,761	—

31 d for Petrofree (ester only) and 43 d for an LAO (Ultidril), which further suggests rapid rates of biodegradation for both SBF components (Vik et al., 1996). Given the 165,051 μg/g Petrofree LE concentration reported 4 mo after completion of drilling at Pompano Phase II, either the degradation rate of Petrofree LE at Pompano is not as high as might be expected or rapid biodegradation and dissolution of the SBF did occur, but initial concentrations must have been substantially higher than 165,051 μg/g. Leaching from areas of higher deposition is possible but also suggests slow degradation.

Reduced rates of biodegradation for synthetic-based drilling fluids have been demonstrated in the laboratory. In solid-phase tests of six SBFs conducted in simulated marine sedimentary environments, the biodegradation of the ester and LAO were greater than that of a poly-alpha olfin, an internal olfin, an *n*-paraffin, and an acetal at test concentrations of 100, 500, and 5,000 ppm (Munro et al., 1997). However, the rates of biodegradation for the ester and LAO decreased 89% and 85%, respectively, when concentrations were increased from 100 to 5,000 ppm, which indicates a toxic or nutrient-limiting effect at high concentrations. On the basis of these results, Munro et al. (1997) cautioned that the biodegradation rate of SBFs in the field may be lower than anticipated when initial concentrations are extremely high. This phenomenon could account for the high concentrations at Station C3-15 4 mo after completion of drilling.

The second observation of the study was the order of magnitude increase in polychaetes (largely Dorvilleidae) at the drill site from July 1997 to March 1998 and the high densities of dorvilleid polychaetes and gastropods observed northeast of the drill coincident with the highest Petrofree concentrations in March 1998. An increase in dorvilleids and gastropods could reflect recolonization by opportunistic taxa into an area of local disturbance. However, the high relative densities of the two dominant taxa northeast of the drill site may also suggest that some component of the SBF is providing energy in support of a communal assemblages.

We compared the densities of the two dominant macrofauna (i.e., polychaetes and gastropods) with data collected at similar depths in the eastern and western GOM by MMS in the mid-1980s (Gallaway, 1988; Gallaway et al., 1988; Pequegnat et al., 1990). From July 1997 to March 1998, polychaetes (primarily Dorvilleidae) increased in the Pompano Phase II

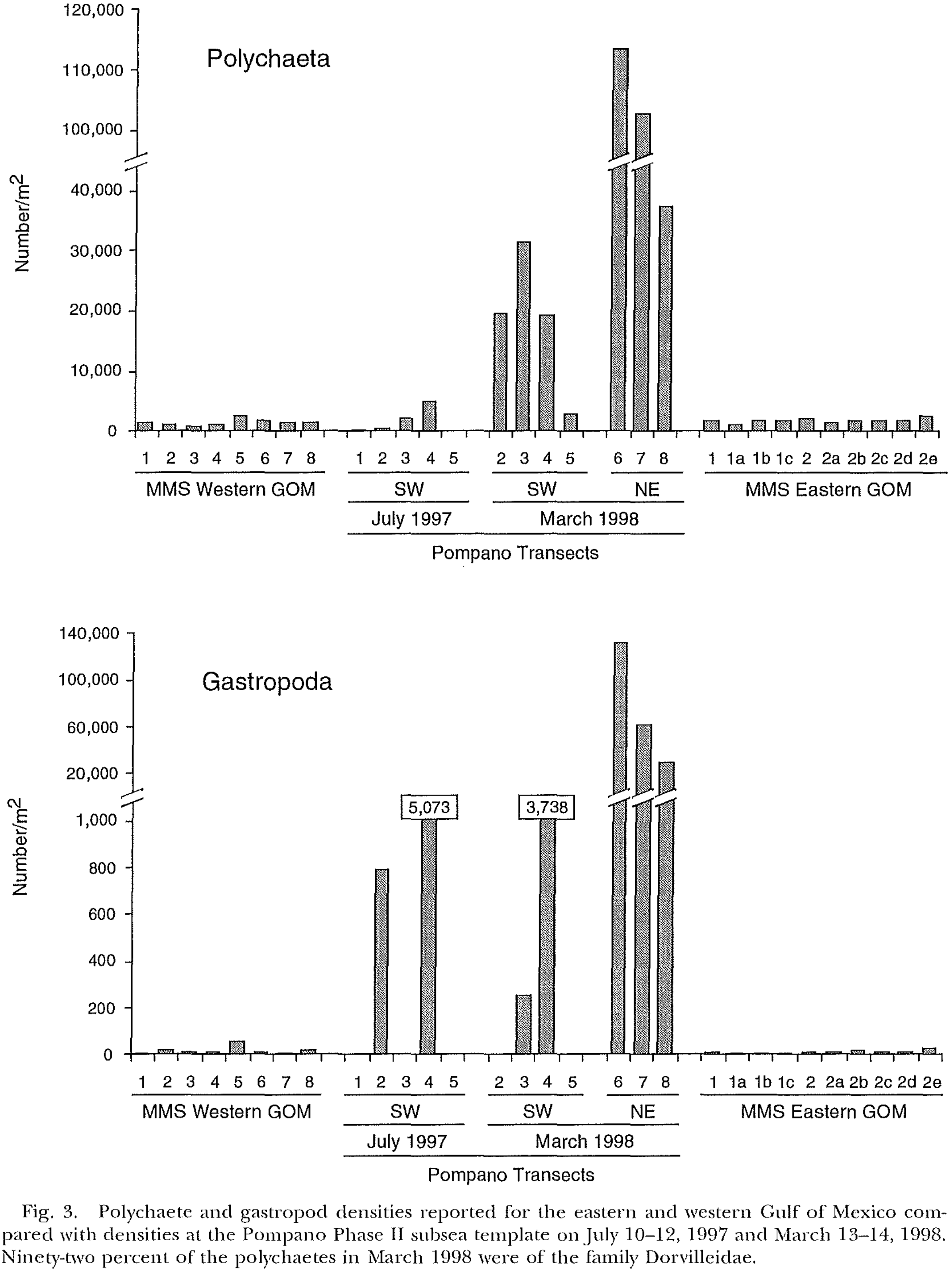

Fig. 3. Polychaete and gastropod densities reported for the eastern and western Gulf of Mexico compared with densities at the Pompano Phase II subsea template on July 10–12, 1997 and March 13–14, 1998. Ninety-two percent of the polychaetes in March 1998 were of the family Dorvilleidae.

area to such an extent that their mean density around the template was >2,100 times higher than MMS baseline estimates and nearly 3,600 times higher along the northeast transect (Fig. 3). Gastropod density along the northeast transect in March was 68,707 organisms/m^2, compared with MMS estimates of 19 organisms/m^2 in the western Gulf and 23 organisms/m^2 in the eastern Gulf.

Although comparisons with MMS data re-

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flect broad taxonomic designations and provide no information on species composition within taxa, they do raise two interesting possibilities. Either composite polychaete and gastropod densities on the continental slope in the area of Pompano are dramatically higher that those found at depth in the GOM east and west of the drill site or some feature unique to Pompano is supporting the higher number of organisms.

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