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Effects of an oil spill on the soft-bottom macrofauna of Arthur Harbour, Antarctica compared with long-term natural change

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Abstract: The macroinfauna at depths of 30–115 m was sampled in March–April 1989, *c.* two months after an oil spill that resulted from the grounding of the *Bahia Paraiso*. Stations consisted of the oil-spill site and a comparable control location, and two historical sites previously sampled in 1971. The historical sites were located at two distinct points along a known continuum of increasing physical stability with depth, attributed to disturbances from glacial calving. Macroinfaunal assemblages at most stations were characterized by very high densities and numbers of taxa. There were no significant differences ($P < 0.05$) between the oil-spill and control sites in numbers of individuals, species, or families; nor were there any major differences in dominant fauna or overall community composition. The absence of a detectable impact on the fauna is consistent with results of hydrocarbon analyses, which showed that subtidal sediments were nearly devoid of contamination emanating from the *Bahia Paraiso*. The assemblage at the shallower of the two historical sites, however, showed a substantial change over the 18-yr period between studies. This change consisted of a shift toward a more species-rich and abundant macroinfauna characteristic of the more physically stable parts of the harbour. This change may be related to the fact that the glacier face near this site has retreated *c.* 250 m over the last 20 yrs, resulting in less physical disturbance of the adjacent seafloor.

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Introduction

On 28 January 1989, the Argentine supply ship *Bahia Paraiso* grounded on shoals in Arthur Harbour off Anvers Island, about 2 km from the National Science Foundation's Palmer Station (Fig. 1). An estimated 6×10^5 l of oil, primarily diesel fuel arctic, spilled into the surrounding bays causing slicks within the first few days that covered 100 km^2 of sea surface (Kennicutt *et al.* 1990, 1991). The heaviest oiling occurred along rocky shores. Initial observations by scientists at Palmer Station provided evidence of lethal effects to biota including krill, intertidal invertebrates (mostly limpets) and shore birds, especially Adélie penguins and blue-eyed shags. Oil-coated macroalgae, seals, and additional species of birds (skuas, cormorants and giant petrels) were also noted.

The volume of oil spilled was relatively small compared to past major oil spills in other parts of the world. Within two months of the *Bahia Paraiso* accident, for example, *c.* 42×10^6 l of crude oil were spilled in Prince William Sound, Alaska as a result of the grounding of the *Exxon Valdez*. The spill in Arthur Harbour, however, was of significance for several reasons: 1) the distillate diesel oil, which also contained a JP-1 jet fuel component, was expected to have a relatively high toxicity compared, for example, to residual and crude oils which generally contain lower percentages of water-soluble compounds (National Research Council 1985); 2) because evaporation and bacterial decomposition of oil tend to slow down with decreasing temperature, there was a chance that the spilled oil would persist in the cold Antarctic waters; and 3) the spill occurred in a relatively pristine environment containing highly diverse and productive living resources, and representing sites used extensively in support of basic scientific research on the Antarctic ecosystem.

For these reasons, the National Science Foundation sponsored a rapid-response ecological survey of Arthur Harbour in March to April 1989 to examine potential effects of the oil spill. A preliminary overview of this programme is provided by Kennicutt *et al.* (1990). The present paper presents results of a component study of the potential effects of the spill on subtidal macroinfauna. This objective is addressed by comparison of replicate samples collected from the spill site and a comparable control location.

As part of the present study design, we also re-occupied two stations sampled in 1971 by Richardson & Hedgpeth (1977). These two sites represent disparate points along what has been described as a gradient of increasing physical stability and decreasing organic input (from macroalgae) with depth. One site, which is located in shallower water in an area physically disturbed by glacial calving and iceberg grounding, is characterized by lower species diversity; the second site, which

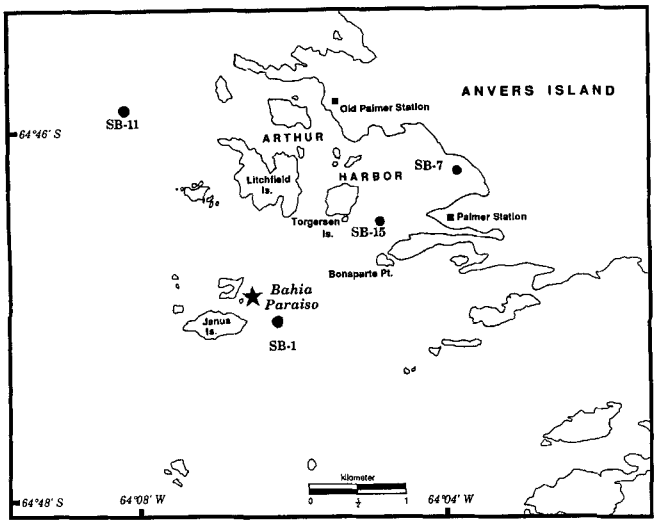

Fig. 1. Study area.

is located in deeper water in the middle of Arthur Harbour and more removed from such disturbances, is characterized by much higher species diversity. Neither site in the present study was contaminated by *Bahia Paraiso* oil. By re-occupying these historical sampling sites, we also were able to address a second more basic research objective of determining how stable (i.e., constant) the natural structure and spatial patterns of these assemblages are over long periods of time. The natural dynamics of this system are important to consider as a comparative base for evaluating the significance of future potential anthropogenic disturbances.

Materials and methods

Three replicate samples of the mud bottom were collected at 11 stations within or just outside of Arthur Harbour, between 31 March to 5 April 1989. Samples were collected from the RV *Polar Duke* with a 0.1 m^2 Smith-McIntyre grab sampler.

Table I. Macroinfaunal Stations

Station	Water depth (m)	Latitude, Longitude	Station attributes
SB1	98	64°47'3"S 64°6'6"W	0.5 km SE of *Bahia Paraiso* (spill site)
SB11	97–115	64°45'54"S 64° 8'6"W	2.25 km NW of *Bahia Paraiso* (control site of similar depth and sediment type as SBl)
SB7	30	(land bearings)	Coincides with RH Station 8 (high physical disturbance and low faunal diversity)
SB15	53–63	(land bearings)	Coincides with RH Station 2 (low physical disturbance and high faunal diversity)

Funding limitations restricted the analysis of samples to four of these stations (Fig. 1). Station descriptions and sampling rationale are summarized in Table I. Samples from Stations SB1 (spill site) and SB11 (control site of comparable depth and sediment type) were used to assess possible effects of the oil spill on the structure and composition of macroinfauna. The two remaining stations coincide with sites sampled in 1971 by Richardson & Hedgpeth (1977). Station SB7 (coinciding with RH Station 8) is located nearer the glacier face in an area physically disturbed by glacial calving and iceberg grounding; Station SB15 (RH Station 2) is in a deeper, less physically disturbed area in the middle of Arthur Harbour between Palmer Station and Torgersen Island. Data from these latter two stations were compared to the corresponding Richardson & Hedgpeth (1977) data as a basis for examining the natural temporal stability of these assemblages and their spatial patterns.

Each grab was subsampled for petroleum hydrocarbons, foraminifera and diatoms, sediment grain-size distributions, and organic content. Subsampling for these other variables was accomplished with small coring devices (diameters of 1.9–2.7 cm) which collectively removed only about 0.002 m^2 of sediment from each grab. In the present paper, only the hydrocarbon, grain-size, and organics data are considered in the interpretation of macroinfaunal distributions.

The content of each grab was sieved in the field on a 0.5 mm screen. Material retained on the screen was preserved in *c.* 10% buffered formalin and then shipped to the laboratory in Santa Barbara to be processed. There, samples were resieved on a nest of 0.5 mm and 1.0 mm screens and transferred to 70% ethanol. Samples were analysed with respect to both size fractions: 1 mm data were used to compare against the Richardson & Hedgpeth data (which were derived mostly from samples processed on a 1.0 mm screen); 1 + 0.5 mm data were used to support all other analyses made independently of the historical data.

Samples were sorted under dissecting microscopes. To facilitate the sorting process, samples were both elutriated, to separate fine and coarse fractions, and stained with a saturated solution of rose bengal for 4–24 h, to help distinguish organisms from the debris. All individuals were enumerated and identified to the species level wherever possible. Polychaetes were identified to the family level because of their enormous abundances in the samples and lack of funds to process them any further. Colonial forms and temporary members of the benthos were excluded from all data analyses. Specimens not recognizable as distinct taxa were excluded from most data analyses except estimates of density. A quantitative species list can be obtained from the senior author.

Statistical analysis of among-station and among-time differences in three response variables (numbers of individuals, species, and families) was performed using procedures available in SAS (SAS 1987). One-way analysis of variance (ANOVA) was used to test for differences in each of the three response variables among the four stations sampled in 1989. Each station level was represented by three replicate samples. Two-way ANOVA also was used to test for differences in each of these

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same response variables, due to the main effects of both station (SB7 = RH8 vs. SB15 = RH2) and time (1989 vs. 1971). The resulting 2 x 2 factorial consists of four replicates for each 1971 cell and three replicates for each 1989 cell. Because of the unequal number of replicates, the latter analysis was performed using General Linear Model procedures (GLM). Prior to running either ANOVA model, data were $\log_{10}(X + 1)$ transformed wherever necessary to establish conditions of normality and homogeneity of variances. The Einot-Gabriel-Welsch Multiple F (REGWF) test was performed following one-way ANOVA to test for the significance of all pairwise comparisons among stations. Day & Quinn (1989) have recommended using this multiple comparison procedure in the case of normally distributed data with equal variances. Because of the 2 x 2 factorial design for the two-way ANOVA, it was not necessary to run a multiple range test to identify significant year or station pairs.

Normal (Q-mode) numerical classification (Boesch 1977) was performed on untransformed data to identify patterns of faunal similarity among stations and sampling occasions. Group-average sorting (= unweighted pair-group method; Sneath & Sokal 1973) was used as the clustering method and Bray-Curtis similarity (Bray & Curtis 1957) was used as the resemblance measure. Results are expressed here in the form of dendrograms in which individual samples have been ordered into groups of increasingly greater similarity based on resemblances of component faunal abundances.

Differences among stations and sampling times were also examined by comparing lists of dominant fauna (ten most abundant taxa). Species (or higher-level taxa in some cases) were ranked from most to least abundant for each station/time entity as a basis for noting major shifts in dominance heirarchy.

Correlation analysis (Pearson's Product-Moment Correlation Coefficient) was used to test for the strength and direction of associations between macroinfaunal variables (numbers of individuals and species) and environmental variables measured in 1989. Environmental variables included in the analysis were sediment organic matter (total organic carbon, expressed as % dry wt), median particle size (in Φ units), sorting coefficient (quartile deviation, in Φ units), % gravel, % sand, % silt, % clay, sediment hydrocarbon concentrations (total hydrocarbon content, polynuclear aromatic hydrocarbons, and unresolved complex mixture), and water depth. Type I error probabilities for the two-tailed test of no correlation were also determined.

Results

Univariate statistical comparisons

There were no significant differences ($P < 0.05$) in mean numbers of individuals, species, or families of macroinfauna between Stations SB1 (spill site) and SB11 (control site), based on one-way ANOVA and the REGWF multiple comparison test performed on 1.0 + 0.5 mm data from stations sampled in 1989 (Table II). Although differences were not significant (at $P < 0.05$) the mean number of individuals was higher at the oil-spill than control site, while mean numbers of species and families were higher at the control than oil-spill site. There are no clear

Table II. Results of one-way ANOVA to test for differences in numbers of individuals (A), species (B), and familes (C) of macroinfauna among four stations sampled in 1989 (three 0.1 m^2 replicates per station; 1.0 + 0.5 mm data). Numbers of individuals and species were logtransformed ($\log_{10}$ X+l) prior to ANOVA. Stations connected by bars are not significantly different at $P<0.05$, based on results of Ryan-Einot-Gabriel-Welsch Multiple F (REGWF) test. Untransformed station means and standard errors (SE, n=3) are given for each response variable.

A. Number of individuals m^{-2}

	SB1	SB15	SB7	SB11
$\bar{x}$ ± SE:	32 207 ± 1574	26 827 ± 7207	26 640 ± 9409	21 570 ± 1442
P>F (3,8 d.f.) = 0.661				
REGWF Grouping:	SB1	SB15	SB7	SB11

B. Number of species $replicate^{-1}$

	SB11	SB1	SB15	SB7
$\bar{x}$ ± SE:	93 ± 17	79 ± 6	68 ± 10	45 ± 5
P>F (3,8 d.f.) = 0.040				
REGWF Grouping:	SB11	SB1	SB15	SB7

C. Number of families $replicate^{-1}$

	SB11	SB1	SB15	SB7
$\bar{x}$ ± SE:	67 ± 8	60 ± 5	49 ± 6	35 ± 3
P>F (3,8 d.f.) = 0.021				
REGWF Grouping:	SB11	SB1	SB15	SB7

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Table III. Results of two-way ANOVA. to test for differences in numbers of individuals (A), species (B), and familes (C) of macroinfauna due to main effects of station (SB7 vs. SB15) and time (1989 vs 1971). Results are based on three 0.1 m^2 replicates for each station in 1989 and four 0.07 m^2 replicates for each station in 1971; 1.0 mm data were used for all stations and years. Tests were run on untransformed data for all three response variables. Stations and years connected by bars are not significantly different at $P<0.05$. Untransformed means and standard errors (SE; $n=3$ for 1989, $n=4$ for 1971) are given by station and year for each response variable.

A. Number of individuals m^{-2}

		SB7	SB15
x ± SE:	1989	22 823 ± 7982	20 647 ± 4969
	1971	4132 ± 792	14 018 ± 1203

P>F: Year (1,10 d.f.) = 0.010;Station (1,10 d.f.) = 0.264; Year* Sta (1,10 d.f.) = 0.165

ANOVA Grouping: Year = 1989 1971; Station = SB15 SB7

B. Number of species replicate^{-1}

		SB7	SB15
x ± SE:	1989	40 ± 5	62 ± 11
	1971	19 ± 3	49 ± 5

P>F: Year (1,10 d.f.) = 0 .017; Station (1,10 d.f.) = 0 .001; Year*Sta (1, 10 d.f.) = 0. 546

ANOVA Grouping: Year = 1989 1971; Station = SB15 SB7

C. Number of familes replicate^{-1}

		SB7	SB15
x ± SE:	1989	32 ± 3	46 ± 7
	1971	17 ± 3	38 ± 4

P>F: Year (1,10 d.f.) = 0.027; Station (1, 10 d.f.) = 0 .082; Year* Sta (1,10 d.f.) = 0.477

ANOVA Grouping: Year = 1989 1971; Station = SB15 SB7

patterns in any of these three response variables that suggest an oil-spill impact.

Table III shows results of two-way ANOVA used to examine differences (based on 1.0 mm data) between Stations SB7 (glacial calving site) vs. SB15 (less physically disturbed site in middle of harbour), and the two sampling periods (1989 vs. 1971). Mean densities (averaged over stations) were significantly higher in 1989 than 1971 ($P>F = 0.010$) due primarily to a 5.5 fold increase at Station SB7, compared to a 1.5 fold increase at Station SB15. There was no significant difference ($P < 0.05$) in mean densities (averaged over years) between the two stations, largely because of the increase at SB7 from 1971–89. Both mean numbers of species and families were significantly higher at SB15 than at SB7, and both showed significant increases from 1971–89. Although station-time interactions were not significant (at $P < 0.05$), increases in all three response variables from 1971–89 were greater at SB7 than at SB15. These comparisons suggest that the macroinfauna in parts of Arthur Harbour has undergone substantial changes over the last few decades.

Numerical classification of macroinfaunal samples

Individual replicates from the four stations sampled in 1989 form three major cluster groups (Fig. 2). These groups separate largely by station. For example, Cluster Group 2 consists of all three replicates from Station SB15 (53–63 m) and Cluster Group 3 consists of all three replicates from Station SB7 (30 m). However, Cluster Group 1 contains a mix of samples from both Stations SB1 (spill site, 98 m) and SB11 (control site, 97–115 m). The relatively high similarity among samples from these latter two stations, compared to the lower similarity with the two shallower stations SB7 and SB15, suggests that the oil spill did not have a major effect on species composition of subtidal macroinfaunal assemblages in the immediate vicinity of the spill, or at least it did not cause a change in species composition that was larger than variations among stations that are due to depth or other natural factors.

Numerical classification of samples collected in 1989 and 1971 at each of Stations SB7 and SB15 produced four major cluster goups (Fig. 3). Cluster Group 1 consists of a mix of samples from both years at Station SB15, suggesting a relatively small change in faunal composition at this station over the 18-yr period, compared to the difference between years at Station SB7 or to differences between stations. Samples collected at SB7 in 1989 (Cluster Groups 2 and 3) have less of an affinity to samples collected at this same station in 1971 (Cluster Group 4) than to samples from SB15, reflecting a transition of the macroinfaunal assemblage at SB7 to one that is more characteristic of physically stable parts of the harbour.

Numerical classification of samples based on log-transformed species or family abundances (dendrograms not shown) produce similar faunal similarity patterns as described above, although sample pairs generally cluster at higher levels of similarity.

Dominant fauna

Dominant (ten most abundant) taxa and estimates of their abundances by station and sampling period are presented in Table IV. Taxa are ranked from most to least abundant. These taxa account for more than 75% of the cumulative percentage abundance of all taxa at a given station or sampling period. More than half of the cumulative percentage abundance of all taxa is usually represented by the top five dominants.

There was a clear shift in the dominant taxa between years at Station SB7. In 1971, for example, the most strongly ranked dominant was the polychaete family Cirratulidae, which was not among the ten most abundant taxa at this station in 1989. While cirratulids represented 73% of the total faunal abundance in 1971, an equivalent percentage was more evenly distributed among 5–6 taxa in 1989. In addition, only four taxa (Oligochaeta, Orbiniidae, Apistobranchidae, and *Heterphoxus videns*) appeared as dominants in both years at this station. Lastly, similar to the pattern for average numbers of species per sample, the total number of species (or higher taxa) identified from all three replicates nearly doubled from 1971–89, i.e. from 34 to 62.

There was less of a change in dominant fauna between years at Station SB15. For example, seven taxa appeared as dominants in both years at this station. Moreover, the distribution of

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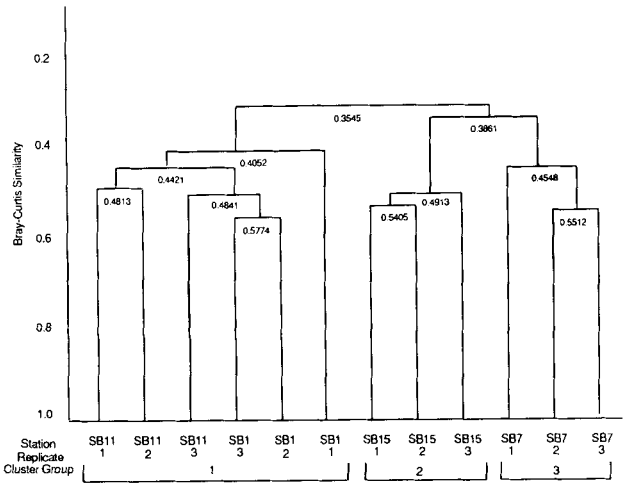

Fig. 2. Dendrogram resulting from clustering of replicate macroinfaunal samples from four stations sampled in 1989. Analysis based on 1.0 + 0.5-mm sieve size and untransformed species abundances (polychaetes lumped at family level).

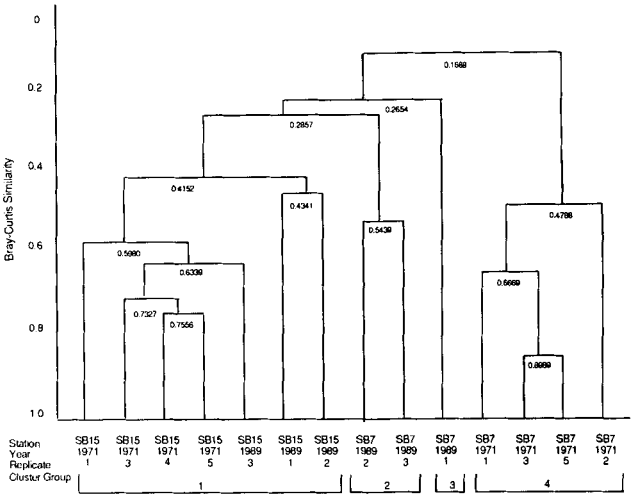

Fig. 3. Dendrogram resulting from clustering of replicate macroinfaunal samples collected in 1971 and 1989, each from Stations SB7 (= RH8) and SB15 (= RH2). Analysis based on 1.0 mm sieve size and untransformed family abundances.

abundance among dominants was very similar between years, with the four most strongly ranked dominants representing *c.* 50% of total faunal abundance in both years. Cirratulid polychaetes and oligochaetes were among the three most strongly ranked dominants in both years. Total numbers of taxa were also comparable between years, i.e. 85 in 1971 vs. 89 in 1989.

Stations SB1 (oil spill site) and SB11 (control site) had similar dominant fauna. Nine of the ten taxa that were dominant at SB1 were also dominant at SB11, although their relative ranks varied. There were a total of 107 taxa at SB1 and 118 taxa at SB11.

Relationship between biological and environmental variables

Pearson's correlation coefficients and Type I error probabilities between macroinfaunal and abiotic environmental variables, based on replicate samples collected from the four stations in 1989, are presented in Table V. The data used to derive the correlation matrix is presented in Table VI.

There were no significant correlations (at $P < 0.05$) between macroinfaunal densities and any of the 11 abiotic variables examined (Table V). Numbers of macroinfaunal species showed significant correlations with four environmental variables: % sand ($P = 0.002$), % silt ($P = 0.0027$), median particle size ($P = 0.0014$), and depth ($P = 0.0253$). Numbers of species were positively correlated with depth and % sand, and negatively correlated with % silt and particle size in Φ units (larger Φ values indicate finer sediments). Thus, there was a pattern of greater species numbers occurring in deeper coarser sediments. The strongest correlation was between species numbers and % sand (0.870).

Triaxial plots of particle size, % sand, and depth of each sample form three separate sample groups, which match the cluster groups derived by numerical classification of the macroinfaunal species data (Fig. 4). Cluster Group 1, consisting of samples from Stations SB1 and SB11, is characterized by depths of 97–115 m, sediment particle sizes of 3.8–4.8 Φ (very fine sand to coarse silt), and sand percentages of 26.0–48.6%. Cluster Group 2, consisting of samples from Station SB15, is characterized by depths of 53–63 m, sediment particle sizes of 4.5–5.1 (coarse to medium silt), and sand percentages of

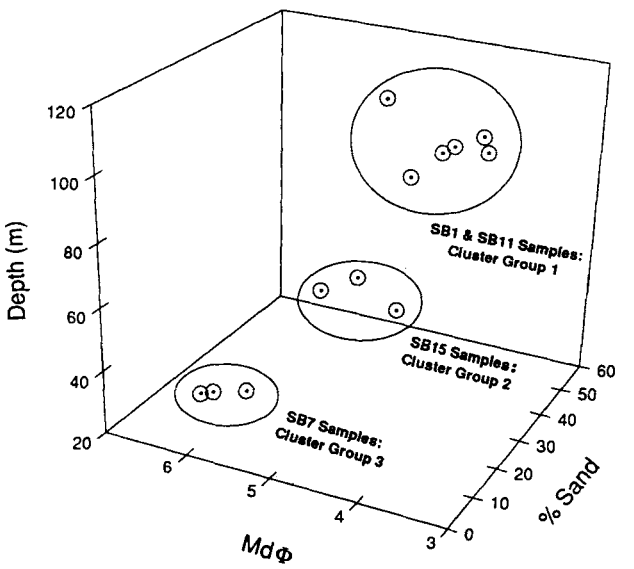

Fig. 4. Relationship of particle size (MdΦ), % sand, and depth (m) to the separation of station cluster groups derived from numerical classification of the macroinfaunal species data. Data derived from three replicate (0.1^2) samples collected from each of the four stations in 1989.

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Table IV. Dominant macroinfauna for each station and sampling time (1-mm sieve). A = Amphipoda, B = Bivalvia, C = Cumacea, O = Oligochaeta, P = Polychaeta, Si = Sipuncula, T = Tanaidacea.

	Fauna	Ind m^{-2}	Cum%		Fauna	Ind m^{-2}	Cum%
	SB7/1989				SB7/1971 (= RH8)		
1.	Oligochaeta (O)	7543	33.1	1.	Cirratulidae (P)	3000	72.6
2.	Orbiniidae (P)	2790	48.3	2.	*Eudorella gracilior* (c)	218	77.9
3.	Apistobranchidae (P)	2550	56.5	3.	*Hererophoxus videns* (A)	143	81.1
4.	*Hererophoxus videns*(A)	1S17	63.2	4.	*Nototanais anrarcticus* (T)	136	84.7
5.	Opheliidae (P)	1403	69.4	5.	*Ampelisca bouvieri* (A)	114	87.5
6.	*Tanaopaia antarcticus* (T)	1237	74.8	6.	Oligochaeta (O)	68	89.1
7.	Dorvilleidae (P) var. *charcoti* (P)	1120	79.7	7.	*Mysella minuscula*	68	90.7
8.	Maldanidae (P)	1087	84.3	8.	Orbiniidae (P)	54	92.0
9.	Paronidae (P)	943	88.4	9.	Apistobranchidae (P)	43	93.0
10.	*Isaeidae* sp. A(A)	187	90.4	10.	Flabellijeridae (P)	36	93.9
	All fauna (62 taxa)[a]	22 823	100.0		All fauna (34 taxa)[a]	4132	100.0
	SB15/1989				SB15/1971(= RH2)		
1.	Cirratulidae (P)	4983	24.1	1.	Oligochaeta (O)	2568	18.3
2.	Paraonidae (P)	2023	33.9	2.	Cirratulidae (P)	1847	31.5
3.	Oligochaeta(O)	1780	42.5	3.	*Eudorella gracilior* (C)	1861	42.6
4.	Terebellidae (P)	1630	50.4	4.	Maldanidae (P)	947	49.4
5.	*Cyamiocardium* cf. *denticulatum* (B)	1270	56.6	5.	Paraonidae (P)	918	56.0
6.	Orbiniidae (P)	1263	62.7	6.	*Vaunthompsonia meridionalis*(c)	672	60.8
7.	Maldanidae (P)	1040	67.7	7.	Orbiniidae (P)	657	65.6
8.	Leucon sagitta (C)	903	72.1	8.	Terebellidae (P)	639	70.1
9.	Syllidae (P)	827	76.1	9.	*Lepcognathia elongata* (T)	561	74.1
10.	*Eudorella gracilior* (c)	677	79.4	10.	Oweniidae (P)	554	78.1
	All fauna (89 taxa)[b]	20 647	100.0		All fauna (85 taxa)[b]	14 018	100.0
	SB1 (1989 Spill Site)				SB11 (1989 Control Site)		
1.	Cirratulidae (P)	4807	20.8	1.	Maldanidae(P)	2143	13.7
2.	Oligochaeta (O)	3817	37.3	2.	Syllidae (P)	1567	23.7
3.	Paraonidae (P)	3373	51.9	3.	Oweniidae (P)	1430	32.8
4.	Syllidae (P)	1347	57.7	4.	Paraonidae (P)	1367	41.5
5.	Maldanidae (P)	1270	63.2	5.	*Thyasira bongraini* (B)	1317	49.9
6.	Phyllodocidae (P)	1150	68.2	6.	Oligochaeta (O)	1240	67.8
7.	*Thyasira borgraini* (B)	1103	73.0	7.	Cirratulidae (P)	890	63.5
8.	Oweniidae (P)	1047	77.5	8.	*Goldfingiidae* spp.(Si)	797	68.6
9.	Terebellidae (P)	637	80.3	9.	Orbiniidae (P)	627	72.0
10.	Orbiniidae (P)	460	82.3	10.	Terebellidae(P)	527	75.4
	All fauna (107 taxa)[a]	23 110	100.0		All fauna (118 taxa)[a]	15 643	100.0

[a] From total of three replicate, 0.1 m^2 samples; [b] From total of four replicate, 0.07 m^2 samples

19.5–29.5%. Cluster Group 3, consisting of samples from Station SB7, is characterized by a depth of 30 m, sediment particle sizes of 5.8–6.2Φ (medium to fine silt), and sand percentages of 9.9–14.3%. These results suggest that grain size and depth (or depth-related variables) play important roles in structuring the macroinfaunal assemblages.

There were no significant correlations (at $P < 0.05$) between macroinfaunal variables and hydrocarbon variables (THC, PAH, UCM). Correlations between the three hydrocarbon variables and macroinfaunal densities were marginally significant ($P = 0.0667$–0.0768). However, given the direction of these correlations, there is no clear evidence of an oil-spill impact. Moreover, samples with the highest concentrations of hydrocarbons (e.g., SB7-2 and SB15-1) were from stations located the furthest from the *Bahia Paraiso* (Table VI). The high unresolved complex mixture (UCM) content of these samples also suggest the presence of degraded fuel residues from previous sources other than the oil spill.

Discussion

Oil spill effects

There were no measurable effects of the *Bahia Paraiso* oil spill on subtidal macroinfaunal assemblages, based on the comparison of three replicate samples of the seafloor from the spill site and a comparable control site *c.* two months after the incident. There were no significant differences between sites in numbers of

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individuals, species, or families; nor were there any major differences in dominant fauna or overall community composition. While this conclusion is based on a limited data base, the results are consistent with the lack of evidence of major oil contamination of subtidal sediments, based on GC-MS analysis of hydrocarbons in sediments throughout the area (Kennicutt *et al.* 1991). Sediments below the intertidal zone were relatively uncontaminated by the spill, with the exception of sporadic indications of *Bahia Paraiso* oil in the center of Arthur Harbour and close to the wreck.

The most pronounced effects of the spill appeared to be on biota that had come into direct contact with the oil. Such effects included initial mortalities of intertidal invertebrates (mostly limpets), shore birds (especially Adélie penguins and blue-eyed shags), and nearshore pelagic biota (e.g. krill) exposed to surface slicks. Oiling of macroalgae, seals, and additional species of birds (skuas, cormorants, and giant petrels) was also noted. Intertidal limpet populations were reduced by 50% immediately after the spill and exhibited only partial recovery one year later (Kennicutt *et al.* 1991).

The apparent absence of a major oil-spill impact on subtidal macroinfauna suggests that oil never reached subtidal depths in significant quantities, a conclusion supported by hydrocarbon analyses, as mentioned above. Possible reasons for the minimal contamination include: the small size of the spill; dispersal of surface slicks due to rough seas immediately following the spill; the common occurrence of offshore winds and currents; removal of visible surface oil by clean-up operations; and evaporation of the highly volatile diesel fuel arctic. Moreover, the shoreline surrounding Arthur Harbour is predominantly rocky with minimal opportunities for oil to mix with fine-grained intertidal sediments and then redistribute to deeper offshore substrates as a result of waves and currents.

Kennicutt *et al.* (1991) provide evidence of the persistence of oil contamination at a number of locations one year after the spill and point out that continued chronic leakage from the ship was a possible source. While the present study did not reveal effects of the initial spill on subtidal macroinfauna, it is important to note the possibility that this chronic source of contamination may have caused longer-term impacts on these biota.

Table V. Pearson correlation coefficients (r) and Type I error probabilities ($P>\alpha$) between abiotic environmental variables and macroinfaunal variables (No. Ind. m^{-2} and No. species replicate^{-1}) from 12 samples collected in 1989 (three 0.1 m^2 replicates from each of four stations; 1.0 + 0.5 mm sieve size). Md Φ = median particle size in phi units, QD Φ = particle sorting coefficient (quartile deviation) in phi units, TOC = total organic carbon (%), THC = total hydrocarbons (μg/g), PAH = polynuclear aromatic hydrocarbons (μg/g), UCM = unresolved complex mixture (μg/g). Asterisks indicate significant correlations at $P = 0.05$.

Abiotic variable	Ind. m^{-2}		Species replicate^{-1}	
	r	p>α	r	p>α
% Sand	0.036	0.9127	0.870	0.0002*
% Silt	-0.216	0.5006	-0.782	0.0027*
% Clay	0.023	0.9432	-0.507	0.0925
% Gravel	0.290	0.3604	0.253	0.4275
Md Φ	-0.061	0.8500	-0.810	0.0014*
QD Φ	0.315	0.3192	0.146	0.6502
% TOC	0.393	0.2609	0.116	0.7507
THC	0.600	0.0667	-0.138	0.7031
PAH	0.597	0.0685	0.424	0.2224
UCM	0.583	0.0768	-0.157	0.6652
Depth (m)	-0.062	0.8481	0.639	0.0253*

Long-term natural variations

The soft-bottom macrobenthic community of Arthur Harbour has been recognized as one of high species diversity and abundances (Richardson & Hedgpeth 1977, Lowry 1975). Major components are deposit-feeding annelids, arthropods, and molluscs (Lowry 1975) in contrast to the suspension-feeding community of sponges, coelenterates, and ectoprocts typical of the Ross Sea (Dearborn 1968, Bullivant 1967) and East Antarctic (Uschakov 1963). Similar assemblages dominated by polychaetes, peracarid crustaceans, and molluscs, and characterized by high densities and numbers of taxa, were found in the present study.

Lowry (1975) also described this abundant and species-rich

Table VI. Untransformed values of macroinfaunal and abiotic environmental variables for replicate samples (0.1 m^2) collected in 1989. MdΦ = median particle size in phi units, QDΦ = particle sorting coefficient (quartile deviation) in phi units, TOC = total organic carbon (%), THC = total hydrocarbons (μg/g), UCM = unresolved complex mixture (μg/g), PAH = polynuclear aromatic hydrocarbons (μg/g). Biological variables based on 1.0 + 0.5 mm sieve sizes.

	Ind m^{-2}	Species rep^{-1}	% Sand	% Silt	% Clay	% Gravel	Md Φ	QD Φ	TOC	THC	PAH	UCM	Depth (m)
SB15-1	37 810	84	29.5	52.0	6.7	11.8	4.5	3.2	1.20	5.50	0.276	5.0	53
SB15-2	29 420	71	26.9	67.7	5.1	0.3	4.9	1.6	0.43	3.33	0.253	3.0	63
SB15-3	13 250	49	19.5	75.2	5.3	0.0	5.1	1.4	0.44	3.05	0.026	3.0	63
SB7-1	15 540	36	11.3	64.7	24.0	0.0	6.1	2.4	0.35	2.06	0.049	2.0	30
SB7-2	45 350	51	9.9	68.1	22.0	0.0	6.2	2.3	0.53	9.79	0.238	9.0	30
SB7-3	19 030	48	14.3	67.5	18.0	0.2	5.8	2.1	0.37	2.06	0.038	2.0	30
SB1-1	35 350	69	26.0	42.9	11.3	19.8	4.3	4.6	0.43	2.09	0.087	2.0	98
SB1-2	30 790	77	38.3	55.7	5.7	0.3	4.3	1.3	0.24	1.04	0.031	1.0	98
SB1-3	30 480	91	48.6	43.1	8.2	0.1	4.1	1.8	0.27	1.07	0.067	1.0	98
SB11-1	24 340	121	43.5	44.2	11.6	0.7	4.3	2.3	0.41[a]	3.24[a]	0.228[a]	3.0[a]	97
SB11-2	20 880	95	39.2	39.0	8.1	13.7	3.8	3.2	NS[b]	NS	NS	NS	100
SB11-3	19 490	62	32.7	58.0	9.4	0.0	4.8	2.0	NS	NS	NS	NS	115

[a]Values are from nearby Station SB6 (depth = 95 m); [b] NS = Not sampled.

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community as being stable (i.e., constant *sensu* Orians 1975), with diversity maintained near its theoretical maximum, and identified mechanisms, such as brooding of young, that contribute to this stability. The underlying cause of faunal stability was attributed to a constancy of environmental factors such as temperature and salinity, which show little annual variation (bottom temperature, -0.1 to -1.9°C; bottom salinity, 33.68 to 34.62°/$_{oo}$) (Lowry 1975).

Richardson & Hedgpeth (1977) introduced the additional point that parts of Arthur Harbour are physically disturbed by glacial calving and iceberg grounding, and that this source of natural disturbance appears to play an important role in structuring macroinfaunal assemblages. A gradient of increasing environmental stability with increasing depth and distance from the glacier front was proposed. Stations SB7 and SB15 (Richardson & Hedgpeth Stations 8 and 2, respectively) represent distinct points along this gradient, with SB7 being shallower and closer to the glacier front. In both studies, there were fewer species found at the shallower nearshore station than at the deeper station in the middle of the harbour, where there is less physical disturbance of the seafloor from glacier calving and iceberg groundings.

The present study suggests that the macroinfauna in parts of Arthur Harbour has changed substantially over the 18 yr period since the earlier sampling. While densities and numbers of taxa increased at both stations from 1971–1989, the overall change in these assemblages is more pronounced at the shallower glacier-calving Station SB7. Average numbers of individuals, species, and families per sample at SB7 showed increases from 1971–89 by factors of 5.5, 2.1, and 1.9, respectively. The total number of taxa from all three replicates at SB7 nearly doubled from 1971–89, i.e. from 34 to 62. There also was a clear shift in the dominant taxa between years at SB7, with only four of ten taxa appearing as dominants in both years at this station. In contrast, seven of ten taxa appeared as dominants in both years at SB15. Cluster analysis indicated a relatively small change in overall community composition at Station SB15 over the 18 yr period, compared to a distinct difference between years at SB7. Cluster analysis further demonstrated that samples collected at SB7 in 1989 had less of an affinity to samples collected at this same station in 1971 than to samples from SB15, reflecting a transition of the macroinfaunal assemblage at SB7 to one that is characteristic of the more physically stable parts of the harbour.

The observed shift toward a more species-rich and abundant macroinfauna at SB7 suggests a possible reduction in the influence of natural physical disturbances on the fauna. In fact, this shift is consistent with the observation that the glacier front near SB7 has retreated *c.* 250 m over the last 20 yrs (L. Quetin, personal communication 1992) indicating that the shift in fauna may be due to a local change in the relative influence of glacial disturbances of the seafloor. Thus, the conventional view of the Antarctic seas harbouring a stable fauna, attributed to a constancy of environmental factors such as temperature and salinity, may need to be reconsidered to take into account the influence of such local sources of environmental change. Moreover, the natural temporal dynamics of these abundant and diverse faunal assemblages are important to consider as a comparative base for evaluating the significance of future potential anthropogenic disturbances, which become increasingly more probable as human activities in the southern oceans continue to grow.

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