New Zealand Journal of Marine and Freshwater Research

ISSN: 0028-8330 (Print) 1175-8805 (Online) Journal homepage: http://www.tandfonline.com/loi/tnzm20

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To cite this article: G. A. Knox & Graham D. Fenwick (1981) Zonation of inshore benthos off a sewage outfall in Hawke Bay, New Zealand, New Zealand Journal of Marine and Freshwater Research, 15:4, 417-435, DOI: 10.1080/00288330.1981.9515934

To link to this article: http://dx.doi.org/10.1080/00288330.1981.9515934

New Zealand Journal of Marine and Freshwater Research, 1981, Vol. 15: 417–435

Zonation of inshore benthos off a sewage outfall in Hawke Bay, New Zealand

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Abstract Benthos was sampled quantitatively on a rectangular grid perpendicular to shore directly off a sewage outfall. Faunal samples were washed through a 0.5 mm sieve, and resulting species frequency data subjected to the 'flexible' classification. Crustacea and Polychaeta contributed most of the 100 species; most individuals were polychaetes. Five groups of species were found. Five faunal zones parallel to shore and progressively wider further offshore were distinguished. Community structure increased offshore, and faunal density decreased offshore from the second zone. Inshore zones were obviously polluted, with the capitellid *Heteromastus filiformis* occurring in densities up to 36 950 per square metre 500 m from shore. Furthest from shore, the fauna was more 'normal' with *Heteromastus* densities of 6000 per square metre. Unique to New Zealand shores is a dense (440 per square metre) zone of holothurians at 8–10 m depth. Deposit-feeders dominated all stations with mean sediment sizes finer than 1.0 ϕ, whereas suspension feeders dominated the benthos of coarser sediments.

Keywords Hawke Bay; benthos; sewage effluents; pollution effects; benthic environment; classification systems; community composition; aquatic communities.

INTRODUCTION

A recent review of marine benthic studies, principally in the northwest Atlantic Ocean, defined a general pattern of changes in the fauna resulting from organic enrichment (Pearson & Rosenberg 1978). Of the few such studies from the Southern Hemisphere, however, none is sufficiently detailed to confirm this pattern of changes as universal. Further, the response of New Zealand marine species to organic enrichment is unknown, and for monitoring purposes the identification of 'indicator' species is imperative.

Since 1938 the effluent from the city of Hastings, the town of Havelock North, and their associated industries has been discharged offshore from Clive in Southern Hawke's Bay. In 1973 an additional outfall to discharge further offshore was proposed, and the present study was undertaken to obtain a baseline for monitoring subsequent changes in the benthos.

STUDY AREA

Hawke Bay is a large shallow bay on the east coast of the North Island of New Zealand (Fig. 1). The study area lies on the southern side of the bay between the mouths of the Ngaruroro and Tukituki rivers. Here the bottom slopes steadily from about 4 m depth at the inshore station to 17 m at the outer stations. Depths were determined from echo-sounding traces and from soundings at each station, corrected to mean low water.

There is a strong inflow of water along the mid line of the bay which diverges to flow around the bay's margins (Ridgway 1960, Ridgway & Stanton 1969). Inshore the direction of wave approach results in a predominantly northward longshore drift (Ridgway 1962), but river outflow may greatly alter this pattern. Burgess (1972) reported surface currents travelling to all points of the compass at velocities ranging from 1.4 km/h to 2.2 km/h, with 50% of all currents at less than 0.92 km/h. Tidal currents were most important, but wind-generated drift currents superimposed on these were significant in the top metre of water (Burgess 1972).

The steep sand–shingle beach in this part of Hawke Bay reflects the importance of wave action in the nearshore environment. Wave periods tend to increase in winter months, probably as a result of more frequent southerly winds and swells (Smith 1968, Burgess 1972). No seasonality of wave heights was evident, although during April–May 1969 there was a 25% frequency of waves higher than 2.5 m (Burgess 1972).

Received 30 March 1981; revised 21 July 1981

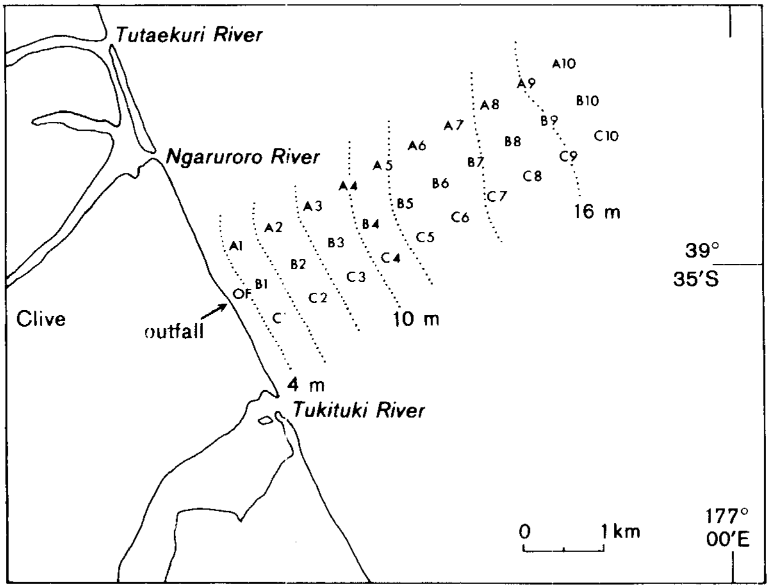

Fig. 1 Grid of stations and the sewage outfall station (OF) in southern Hawke Bay sampled for benthos and sediments, 30 Mar – 6 Apr 1976 (dotted lines are 2 m isobaths).

Ridgway & Stanton (1969) found extensive vertical mixing in the shallow waters of the bay, so the dilution effects of the rivers are usually slight. Our study area fell within their 34.0‰ surface and 34.3‰ bottom isohalines. Surface and bottom salinities measured during this study ranged between 28.99 and 34.52‰ and 34.29 and 34.89‰ respectively. There was no pattern to the salinities, except bottom waters were usually more saline than surface waters, suggesting poor mixing close inshore.

Little is known of the sea temperatures in Hawke Bay. In shallow waters off Hastings in November 1965, Ridgway & Stanton (1969) recorded sea temperatures ranging from 14.7 to 15.4°C. No water temperature patterns were detected while sampling for this study; both surface and bottom temperatures ranged between 17.5 and 19.3°C.

The Clive outfall consisted of a 175 cm diameter, open-ended pipe discharging (in 1973) 96 830 L/min of effluent 50 m offshore. Effluent from Hastings and Havelock North (total population 37 000) consisted of raw sewage and effluents from 2 large meat processing works, 3 wool scouring plants, 2 large fruit and vegetable processing factories, and a number of other industries. At times vegetables and fat globules were abundant on the gravel beaches and floating on the surface for some distance around the outfall. Large quantities of wool and fat were collected in a fish trawl towed parallel to and 500 m away from shore during part of this study.

METHODS

Field and laboratory

Thirty-one stations on a rectangular grid were sampled between 30 March and 6 April 1976. The grid consisted of 3 parallel rows of 10 stations with the middle row following the line of the proposed outfall (Fig. 1). Rows and stations on rows were 500 m apart and the first station on each row was 500 m from shore. On the middle line, however, one additional station (OF) was established 250 m from shore, very close to the existing outfall.

Positions were fixed by triangulation using a sextant and markers spaced along the beach. The accuracy of position-fixing was within 25 m at the outermost stations and better than this closer to shore. At each station the boat was anchored while 3 0.1 m^2 bottom samples were taken with a Smith-McIntyre grab. Close to shore, where the bottom consisted of firm sand, up to 80 kg of lead was attached to the grab so that it would bite deeper. This weight was reduced further offshore where the bottom was softer.

The grab samples were used for faunal analysis. Each sample was washed through a nest of 3 sieves with 2.0, 1.0, and 0.5 mm mesh. Animals and debris retained on each sieve were preserved separately in 10% neutralised formalin. All animals in each sample were sorted in the laboratory under stereomicroscopes, identified, and total numbers of individuals of each species were recorded.

Table 1 Median sediment type (Wentworth scale), graphic mean (M_z), inclusive graphic standard deviation (σ), inclusive graphic skewness (SK_1) and kurtosis (K_G) values for sediments at each station, Hawke Bay, 30 Mar – 6 Apr 1976 (OF, outfall station; all values positive unless shown otherwise).

Stn	Median sediment type	M_z	σ	SK_1	K_G
A1	Coarse sand	0.23	3.26	0.08	1.22
2	Medium sand	1.73	3.84	0.21	1.68
3	Coarse sand	1.13	5.51	0.15	0.66
4	Very fine silt	7.53	2.19	0.12	0.98
5	Fine silt	6.93	2.59	0.05	0.90
6	Medium silt	6.05	3.37	0.35	1.02
7	Fine silt	6.93	2.37	0.18	0.84
8	Fine silt	7.16	2.75	0.30	0.95
9	Fine silt	7.10	1.96	0.14	0.84
10	Fine silt	7.06	2.27	0.23	0.71
B1	Coarse sand	0.53	2.12	0.14	0.16
2	Fine sand	2.33	1.77	0.32	1.42
3	Fine sand	2.90	2.04	0.32	1.40
4	Clay	8.99	2.73	0.11	0.89
5	Medium silt	6.80	3.80	0.50	0.86
6	Fine silt	7.80	3.03	0.35	0.76
7	Very fine silt	7.86	2.95	0.39	0.74
8	Very fine silt	7.53	2.17	0.10	0.87
9	Very fine silt	7.30	2.33	0.22	0.85
10	Very fine silt	7.60	1.88	0.10	0.87
C1	Medium silt	3.90	5.75	−0.22	0.89
2	Medium sand	1.93	2.78	0.21	1.63
3	Very fine sand	3.20	2.17	0.35	2.25
4	Very fine sand	3.43	2.08	0.39	2.36
5	Coarse silt	4.06	1.92	0.35	2.86
6	Coarse silt	5.56	2.70	0.44	1.03
7	Very fine silt	7.73	2.15	0.19	0.96
8	Very fine silt	7.60	2.33	0.13	0.87
9	Very fine silt	7.40	2.41	0.26	0.92
10	Very fine silt	7.50	2.38	0.18	0.83
OF	Medium sand	1.73	2.44	0.05	1.07

From the third sample a subsample of the upper sediment (dry weight about 200 g) was removed for later sediment analysis. The particle-size composition of each sample was determined by hydrometer analysis (Thomas 1973) in the Sediment Laboratory, Department of Geography, University of Canterbury. Cumulative size-frequency distribution curves were plotted for each station from these data and the various descriptive statistics (Table 1) were calculated following Folk (1965). Additional subsamples for organic carbon analysis were subsequently lost.

Classification of benthos data

Species abundance data were subjected to the flexible sorting strategy developed by Lance & Williams (1967). This method, now commonly used in marine benthic studies, clusters similar samples into 'site groups' ('normal' classification) and determines 'species groups' ('inverse' classification) of species with similar distributions among the site groups. The Bray-Curtis dissimilarity coefficient was used because of differences in species numerical dominance and the presence of zero records (Stephenson & Williams 1971, Stephenson 1973). According to the Bray-Curtis coefficient (d), the dissimilarity of 2 individuals is

$$d_{1,2} = \frac{\Sigma_j |x_{1j} - x_{2j}|}{\Sigma_j (x_{1j} + x_{2j})}$$

where x_{1j} and x_{2j} are the numbers of the jth attribute of the 2 individuals (Stephenson & Williams 1971).

The classificatory analysis was performed on the replicates combined data to minimise redundancy in the pattern of species abundance data as defined in such analysis. This was reduced further by excluding the rarer species that contributed least to the final pattern (Day et al. 1971). Thus species present at 10% or fewer stations were excluded from the analysis. Dissimilarity coefficients for the 'normal' or sample groups classification were calculated using data transformed to cube roots. Dissimilarity coefficients for the 'inverse' or species groups classification were calculated from data transformed by expressing each sample record of a species as a percentage of the total number of that species from all samples. These transformations were necessary because the Bray-Curtis coefficient tends to be dominated by abundant species (Stephenson & Williams 1971, Stephenson 1973).

Stations and species were clustered separately into related groups by the 'flexible sorting' classification using these resulting matrices of dissimilarity coefficients. The 'cluster intensity coefficient' for the classifications was set at the conventional value, −0.25 (Stephenson 1973).

Community structure

The Shannon-Wiener diversity index (H') was used as it is the most consistently useful index of diversity which is relatively independent of sample size. It is defined as

$$H' = -\sum_{1}^{s} p_i \log_e p_i$$

where p_i is the proportion of individuals belonging to the ith species. Species richness (SR) was estimated using Margalef's (1958) measure of richness

$$SR = (s - 1)/\log_e N$$

where s is the number of species and N is the number of individuals. Evenness (J') was computed using Pielou's (1966) measure

$$J' = H'/H'_{\max}$$

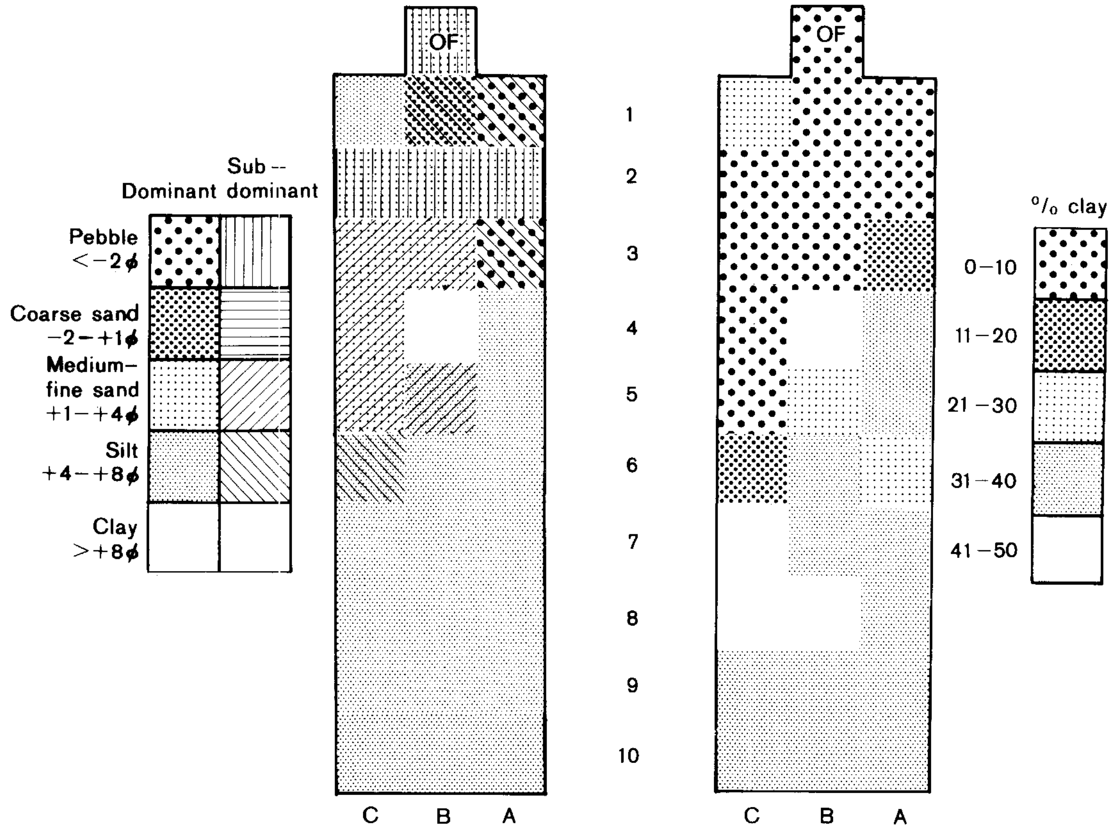

Fig. 2 Dominant and subdominant sediment types and percent clay at each station.

RESULTS

Sediment distribution

Percent composition by weight of the sediment from each station was determined; the dominant (modal) and subdominant sediment type (Wentworth scale) at the stations are shown in Fig. 2. Although a variety of sediments occurred among the inshore stations, there was a strong transition from predominantly sand inshore to silt and clay offshore. Sands were absent from the outer stations and the amounts of silts and clay at the inner stations were negligible (Fig. 2).

Table 1 shows the median sediment type (Wentworth scale), the graphic mean (M_z) particle size in phi units, the inclusive graphic standard deviation (σ) (a measure of sorting), inclusive graphic skewness (SK_I) (a measure of the equality of sorting of different particle sizes), and kurtosis (K_G) (a measure comparing the degree of sorting of the predominant size fraction with the sorting of less dominant size fractions). There was a decrease in particle size (increase in M_z) towards the offshore stations, but the transition from coarse particles inshore to fines offshore was irregular. Values for this statistic at each station (Table 1) further emphasise the patchiness of the sediments. Sediments at most stations were very poorly sorted (see Folk (1965) for verbal classification scale for σ), and extremely poorly sorted at Stns A3 and C1. Most sediments were fine skewed (+0.1 to +0.3) (Folk 1965) which means that finer fractions predominate.

In summary, the sediments of the study area were very patchy and poorly sorted; finer particles predominated and there was a marked change from sands inshore to fine silt and clay offshore.

Fauna

One hundred species were recognised from the samples (Table 2), although several could not be identified as known species. The Crustacea were represented by 47 species, the Polychaeta by 27, the

Table 2 Benthic invertebrates taken during the benthic survey, Hawke Bay, 30 Mar – 6 Apr 1976.

	Code
Actinaria	
Edwardsia sp.	1
Actinarian sp. 2	90
Amphipoda	
Ischyrocerus longimanus (Haswell, 1880)	2
Lembos sp. 1	3
Lembos sp. 2	4
Liljeborgia barhami Hurley, 1954	5
Paradexamine sp.	6
Photis sp.	7
Podocerus manawatu Barnard, 1972	8
Proharpinia hurleyi Barnard, 1958	9
Oedicerotidae	10
Bivalvia	
Tellina spenceri Suter, 1907	11
Divaricella huttoniana (Vanatta, 1901)	12
Dosinia anus (Philippi, 1848)	13
Dosinia lambata (Gould, 1850)	14
Maorimactra ordinaria (Smith, 1898)	15
Nucula nitidula Adams, 1856	16
Spisula aequilateralis (Deshayes, 1854)	17
Theora (Endopleura) lubrica Gould, 1861	18
Arthritica bifurca (Webster, 1908)	19
Cephalocarida	
Chiltoniella elongata Knox & Fenwick, 1977	94
Cumacea	
Colurostylis pseudocuma Calman, 1911	20
Cyclaspis argus Zimmer, 1902	21
Diastylopsis crassior Calman, 1911	22
Eudorellopsis resima Calman, 1907	23
Eudorellopsis sp. 1	24
Eudorellopsis sp. 2	25
Leucon? *latispina* Jones, 1963	83
Leuconidae	84
Paraleucon suteri Calman, 1907	85
Cumacea sp. 1	93
Cumacea sp. 2	98
Decapoda	
Betaeopsis aequimanus (Dana, 1852)	26
Cyclohombronia depressa (Jacquinot, 1853)	27
Ogyrides delli Yaldwyn, 1971	28
Ovalipes catharus (White, 1843)	29
Pontophilus australis (Thomson, 1879)	30
Callianassa filholi Milne-Edwards, 1878	86
Pinnotheres novaezealandiae Filhol, 1886	92
Echinoidea	
Echinocardium cordatum (Pennant, 1777)	31
Juv. echinoid	32
Echiuroidea	
Urechis novaezealandiae (Dendy, 1897)	88
Gastropoda	
Odostomia sp.	33
Xymene plebejus (Hutton, 1873)	34
Holothuroidea	
Heterothyone ocnoides (Dendy, 1896)	35
Paracaudina chilensis (Muller, 1850)	36
Hydroida	
Tubularia sp.	37
Isopoda	
Cirolana sp.	38
Munna sp.	39
Mysidacea	
Mysid sp. 1	40
Mysid sp. 2	41
Mysid sp. 3	42
Nebaliacea	
Nebaliella sp.	43
Nematoda	87
Nemertina	
Nemertine sp.	44
Nudibranchiata	91
Ophiuroidea	
Amphiura aster Farquhar, 1901	45
Ostracoda	
Ostracod sp. 1	46
Ostracod sp. 2	47
Ostracod sp. 3	48
Ostracod sp. 4	49
Ostracod sp. 5	50
Ostracod sp. 6	51
Ostracod sp. 7	52
Ostracod sp. 8	53
Ostracod sp. 9	54
Ostracod sp. 10	55
Ostracod sp. 11	89
Ostracod sp. 12	98
Ostracod sp. 13	99
Phoronida	
Phoronis sp.	56
Polychaeta	
Aglaophamus verrilli (McIntosh, 1885)	57
Ampharete kerguelensis McIntosh, 1885	58
Amphinomidae	100
Aphroditidae (Siglioninae)	81
Chaetozone sp.	59
Cossura sp.	60
Eteone sp.	96
Glycera sp.	61
Glycinde trifida (McIntosh, 1885)	62
Goniada grahami Benham, 1932	63
Goniada sp.	64
Heteromastus filiformis (Claparède, 1864)	65
Heterospio sp.	66
Lumbrinereis magalhaensis Kinberg, 1865	67
Magelona sp.	68
Nerimyra sp.	95
Nephthys sp.	69
Onuphis aucklandensis Augener, 1924	70
Owenia fusiformis Delle Chiaje, 1844	71
Paraonis sp.	72
Pectinaria australis Ehlers, 1904	73
Piromis sp.	74
Polynoidae	80
Prionospio pinnata Ehlers, 1901	75
Prionospio sp.	76
Scoloplos sp.	77
Sthenelais sp.	78
Tharyx sp.	79
Pycnogonida	
Achelia dohrni (Thomson, 1884)	82

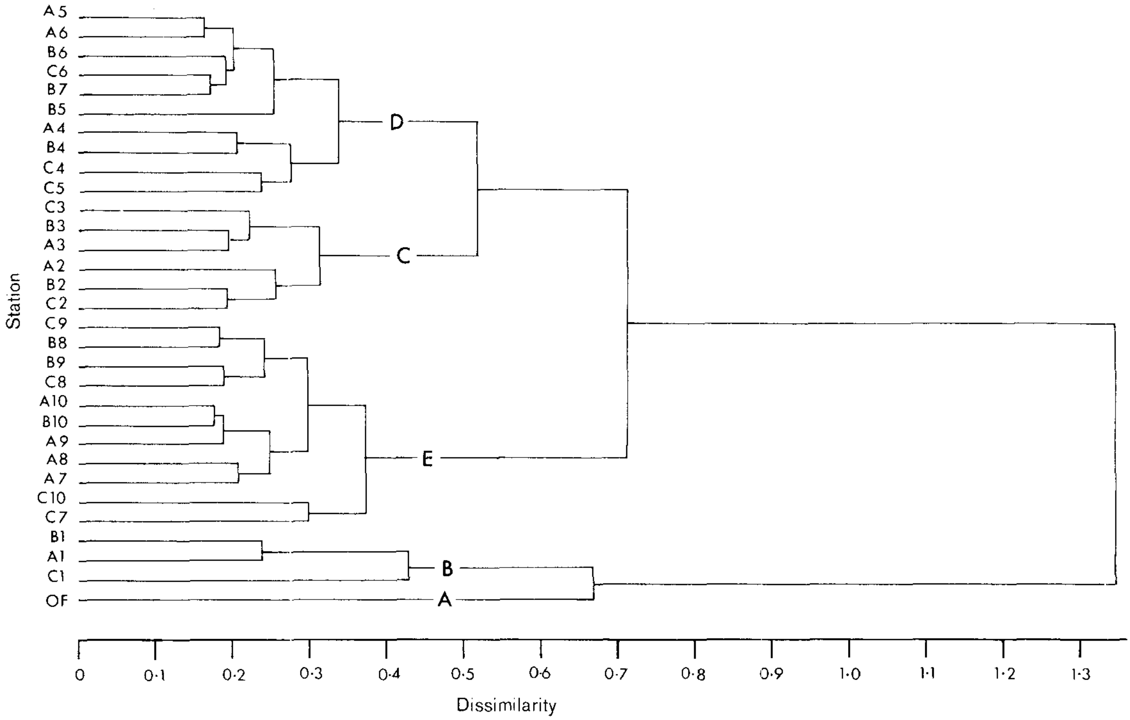

Fig. 3 Dendrogram of the flexible grouping of stations: site groups lettered (A–E) at right.

Mollusca by 11, and the Echinodermata by 5 species. Within the Crustacea there were 13 species of Ostracoda, 12 of Cumacea, 9 of Amphipoda, 7 of Decapoda, and a few representatives of the Isopoda, Mysidacea, Nebaliacea, and Cephalocarida.

By combining replicates, the classification of samples (hereafter called 'sites') was based on 65 species (35 species occurring in fewer than 10% of the samples were excluded) and the number of individuals per site was increased, thus providing a better basis for both normal and inverse classifications. A trial classification using replicates separate data resulted in very similar site and species groupings, but more species were excluded.

Normal classification

The dendrogram produced by the normal classification of sites is given in Fig. 3. Truncation of the dendrogram at the five-group level (0.45 dissimilarity) produced the most meaningful clustering of stations. The 5 site groups consist of A, Site OF; B, Sites A1, B1, C1; C, Sites A2–3, B2–3, C2–3; D, Sites A4–6, B4–7, C4–6; E, Sites A7–10, B8–10, C7–10. This grouping of sites shows a series of distinct zones parallel to shore (Fig. 4) and the zones are progressively wider further from shore.

Inverse classification

Because clustering strategies are 'group-size dependent' (Lance & Williams 1967), groups which differ greatly in size should not be selected by defining a fixed level of dissimilarity. Instead, groups are best selected by following down the dendrogram until the species remaining in a group subjectively have similar distributions among the site groups. Reference to the original data in the form of a site × species matrix greatly facilitates this process.

The species classification dendrogram, with the initial species groups numbered, is given in Fig. 5. Species groups III and VI were completely excluded because they consist of very infrequently occurring species only. Species of the remaining groups were carefully checked against the original data matrix for misclassifications, and another 6 infrequent species were excluded because they lacked any pattern of distribution among the site groups. They were: *Ogyrides delli* (28), ostracod 1 (46), *Echinocardium cordatum* (31), echinoid sp. (32), ostracod 5 (50), and *Spisula aequilateralis* (17).

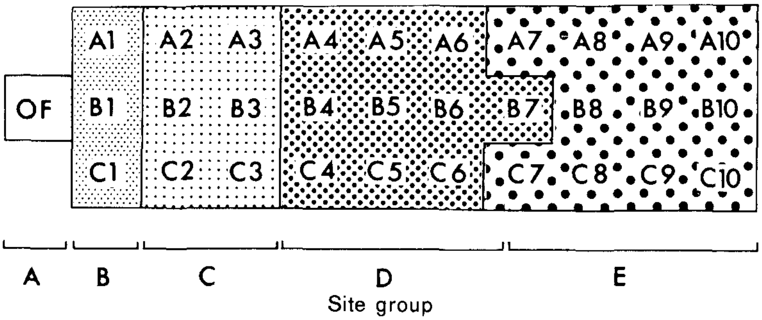

Fig. 4 Map of stations showing division into site groups.

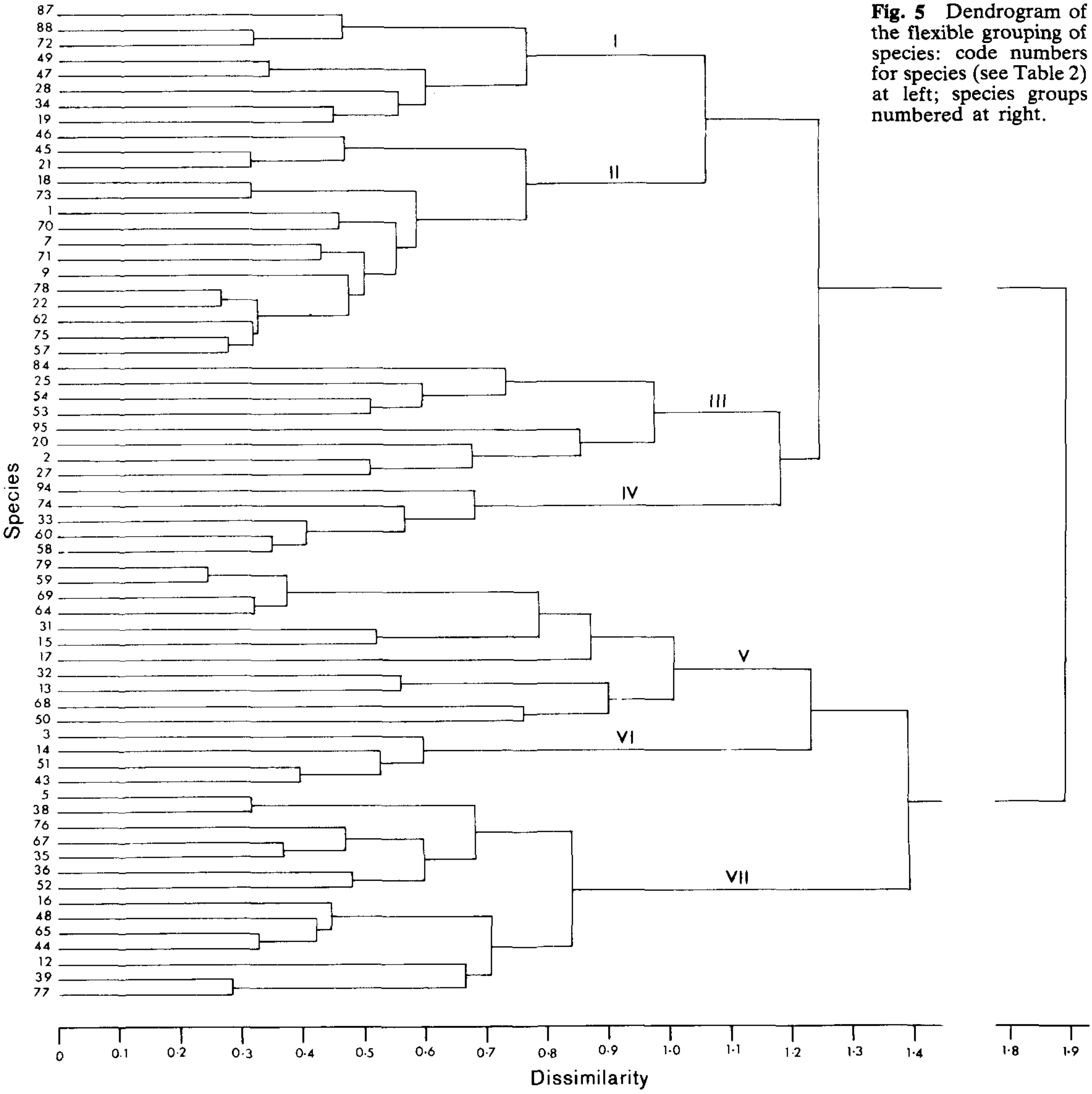

Fig. 5 Dendrogram of the flexible grouping of species: code numbers for species (see Table 2) at left; species groups numbered at right.

Table 3 Species groups, redefined after exclusions: D, deposit-feeding; P, predatory; S, suspension feeding; Sc, scavenging.

Group	Taxa
1	Echiuroidea (87) D, Nematoda (88) D, *Paraonis* sp. (72) D, ostracod 4 (49) D, ostracod 2 (47) D, *Xymene plebejus* (34) P, *Arthritica bifurca* (19) S
2	*Amphiura aster* (45) D, *Cyclaspis triplicata* (21) D, *Theora (Endopleura) lubrica* (18) D, *Pectinaria australis* (73) D, *Edwardsia* sp. (1) S, *Onuphis aucklandensis* (70) Sc, *Photis* sp. (7) S, *Owenia fusiformis* (71) S, *Proharpinia hurleyi* (9) P, *Sthenelais* sp. (78) P, *Diastylopsis crassior* (22) D, *Glycinde trifida* (62) P, *Prionospio pinnata* (75) D, *Aglaophamus verrilli* (57) P/Sc
3	Cumacean 11 (94) D, *Piromis* sp. (74) D, *Odostomia* sp. (33) P, *Cossura* sp. (60) D, *Ampharete kerguelensis* (58) D
4	*Tharyx* sp. (79) D, *Chaetozone* sp. (59) D, *Nephthys* sp. (69) P/Sc, *Goniada* sp. (64) P, *Maorimactra ordinaria* (15) S, *Dosinia anus* (13) S, *Magelona* sp. (68) D
5	*Liljeborgia barhami* (5) Sc, *Cirolana* sp. (38) Sc, *Prionospio* sp. (76) D, *Lumbrinereis magalhaensis* (67) P/Sc, *Heterothyone ocnoides* (35) D, *Paracaudina chilensis* (36) D, ostracod 7 (52) D, *Nucula nitidula* (16) D, ostracod 3 (48) D, *Heteromastus filiformis* (65) D, Nemertina (44) P, *Divaricella huttoniana* (12) S, *Munna schauinslandii* (39) Sc, *Scoloplos* sp. (77) D

Interpretation of species groups

Table 3 gives the redefined species groups after the above exclusions. Group 1 consists of 7 species, 4 of which are infaunal: Echiuroidea, Nematoda, the polychaete *Paraonis* sp., and a bivalve *Arthritica bifurca*. Both ostracods and the predatory gastropod *Xymene plebejus* live at the sediment surface. Five of these animals are deposit-feeders, one is a predator, and the bivalve is probably a suspension feeder. Of the 14 species in group 2, 6 are deposit-feeders, 3 are suspension feeders, 3 are predators, and 2 are scavengers. Twelve species are infaunal and the remaining 2, *Amphiura aster* and *Photis* sp., tend to dwell at the sediment surface. Species group 3 is composed of 4 deposit feeders, all burrowing forms, and a predatory gastropod, *Odostomia* sp. Group 4 species are all burrowers. Among these 7 species, 3 polychaetes are deposit-feeders and 2 are predatory, and 2 bivalves, *Maorimactra ordinaria* and *Dosinia anus*, are suspension feeders. Deposit-feeders (8 species) dominate species group 5. Three Crustacea, *Liljeborgia barhami*, *Cirolana* sp., and *Munna schauinslandii*, are scavengers, *Lumbrinereis magalhaensis* and Nemertina are predators, and *Divaricella huttoniana* is the only suspension feeder.

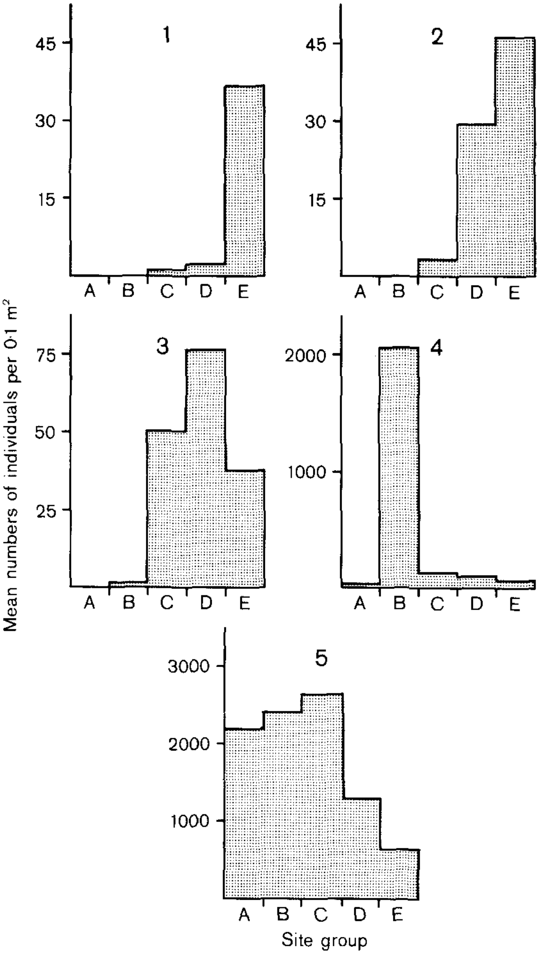

Fig. 6 Distribution of a representative of each species group among the site groups: 1, *Paraonis* sp.; 2, *Theora (Endopleura) lubrica*; 3, *Ampharete kerguelensis*; 4, *Maorimactra ordinaria*; 5, *Heteromastus filiformis*.

The distribution of each species group among the 5 site groups is given in Table 4. Here the mean frequency per 0.1 m^2 of the species group at a given site group is expressed as a percentage of the total frequency of that species group in all site groups. It is immediately apparent that each species group has a characteristic pattern of distribution among the site groups. This is further illustrated in Fig. 6, which shows the mean numerical frequency per 0.1 m^2 of an abundant species from each species group.

Site groups may now be described in terms of species groups (Table 4). A very depauperate fauna was characteristic of site group A, species groups 1–4 were all rare, and group 5 species were uncommon. Group 4 species were very abundant in

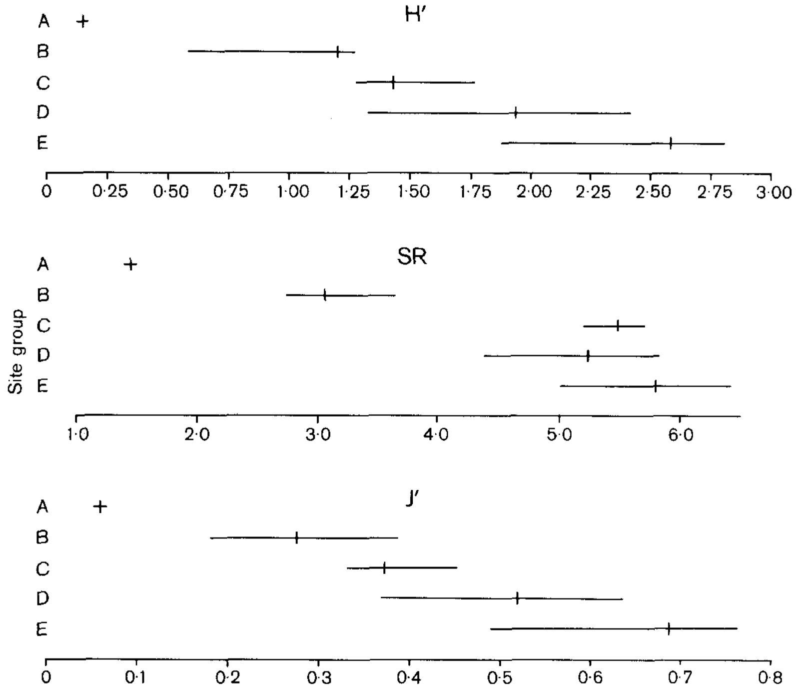

Fig. 7 Ranges and medians of species diversity (*H'*), species richness (*SR*), and equitability (*J'*) of samples in each site group.

Table 4 Species group occurrence at site groups (values greater than 20% in *italic* type).

Species groups	A	B	C	D	E
			Site groups		
1	0	5.8	2.4	9.5	*82.3*
2	1.7	2.8	18.0	*35.7*	*41.8*
3	2.4	0.6	*22.6*	*54.6*	19.8
4	0.3	*85.6*	8.9	3.7	1.5
5	*21.6*	*25.1*	*32.2*	14.9	7.2

Table 5 Percent dominance in each site group by the 5 most abundant species.

Species (and code)	A	B	C	D	E
			Site group		
Heteromastus filiformis (65)	97.86	48.98	71.83	53.96	35.74
Maorimactra ordinaria (15)	0.32	42.37	2.63	3.95	1.50
Prionospio pinnata (75)	0	0.10	2.25	9.07	6.63
Nucula nitidula (16)	0	0.10	3.59	5.49	2.47
Pectinaria australis (73)	0.05	0.04	1.78	1.94	6.25
All other species	1.77	8.33	17.92	25.59	47.41

site group B, group 5 species were uncommon, and the remainder were rare. At site group C, species group 5 was common, 2 and 3 were uncommon, and species groups 1 and 4 were rare. Species groups 1 and 4 were rare in site group D, 5 were uncommon, 2 was common, and 3 was abundant. Site group E was characterised by very abundant group 1 species, group 2 was common, and groups 5 and 6 were rare.

Community structure

Species diversity, species richness, and equitability all increased steadily from site group A to site group E (Fig. 7), although species richness was slightly higher at site group C than at D. This overall increase in diversity was a consequence of increases in the 2 components of diversity. Table 5 shows this in more detail by listing the percentage of the fauna at each site group contributed by the 5 most abundant species and by the remaining species. At site group A the capitellid polychaete *Heteromastus filiformis* (65) contributed almost 98% of the individuals, the remaining 2% being distributed among the other 11 species. This overwhelming dominance by *H. filiformis*, shared with *Maorimactra ordinaria* (15) in site group B, decreased from site group A to E and a parallel increase in the percent contribution by the other species occurred. Thus the equitability component of species diversity increased through site groups A to E.

The density of the fauna also differed between sites. Mean numbers of individuals per 0.1 m^2 at each site group are shown in Fig. 8. Highest densities occurred in site group B with a mean of 24 165 individuals per square metre. Faunal density at site group C was intermediate between the densities at B and at A and D. The density at site group E was slightly lower than at either A or D. However, when the contributions of *H. filiformis* and *M. ordinaria* are disregarded, there was a progressive increase in density from inshore to offshore.

Changes in density of different taxa which occurred with distance from shore, a complex of environmental factors, are examined in more detail in Fig. 9 and 10. Fig. 9 shows density changes in the 3 dominant taxonomic groups, the Polychaeta, Crustacea, and Mollusca. At site group B, 0.5 km from shore, nearly half of the total individuals were molluscs, whereas in the other site groups molluscs were relatively inconspicuous. In all other site groups the Polychaeta contributed the bulk of the individuals.

Mean densities of the 5 most abundant species at each station are shown in Fig. 10. One polychaete, *Heteromastus filiformis*, contributed most of the individuals of the Polychaeta as seen by the close approximation of their frequency distributions in Fig. 10 and 9 respectively. Similarly, the bivalve *Maorimactra ordinaria* contributed most of the individuals of the Mollusca.

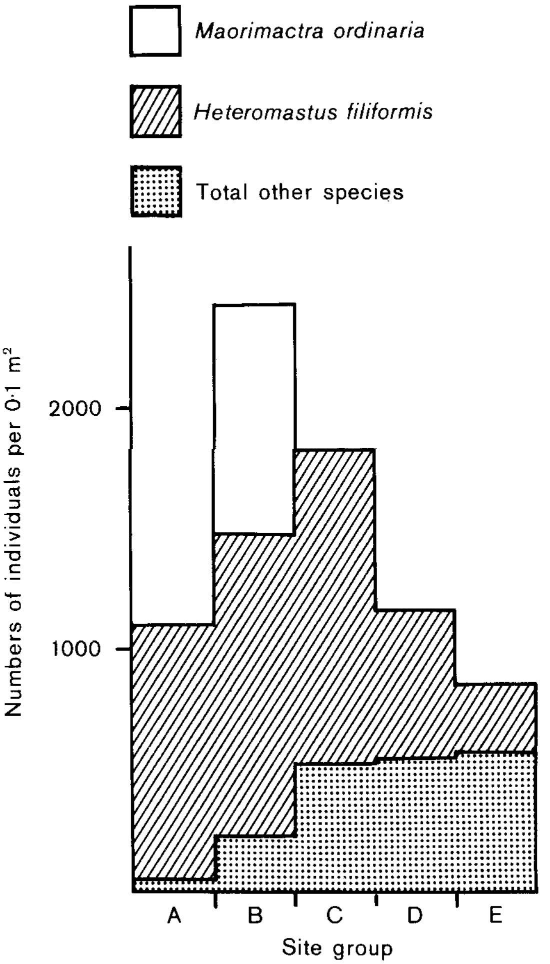

Fig. 8 Density of the total fauna and of the 2 most abundant species at each site group.

DISCUSSION

Species distribution

Pearson & Rosenberg (1978) reviewed the effects of organic enrichment on marine benthos and concluded that a certain level of enrichment superimposes its own gradient on the marine environment. In response there is a steady faunal transition along this gradient from abiotic at the enrichment source to 'normal' some distance away. Depending on the level of input the abiotic zone may be absent or several kilometres in radius (Poore & Kudenov 1978). Although the organic content of the sediments was not determined in the present study, a gradient of decreasing organic input with increasing distance from shore is almost certain.

Very obvious gradients of faunal composition and structure are characteristic of organically polluted waters and have been considered in detail by Pearson & Rosenberg (1978). Within the extremes of the transition from abiotic to normal, 3 zones are recognised: (1) an opportunistic zone with high numbers of few species; (2) an ecotone point of overlap between opportunists and 'normal' faunal species, characterised by low abundance of a few equally dense species; and (3) a transition zone of 'normal' faunal species at 'non-normal' densities. The opportunist zone is most characteristically associated with organically enriched environments.

No abiotic zone was detected in Hawke Bay, but, if present, it must be less than 200 m in radius. An opportunist zone is evident in site groups A and B and perhaps C, those closest to the outfall (Fig. 11). In site group A, the total faunal density is moderate, but species diversity is very low since almost the entire benthos consisted of the small opportunistic capitellid worm *Heteromastus filiformis*. This site

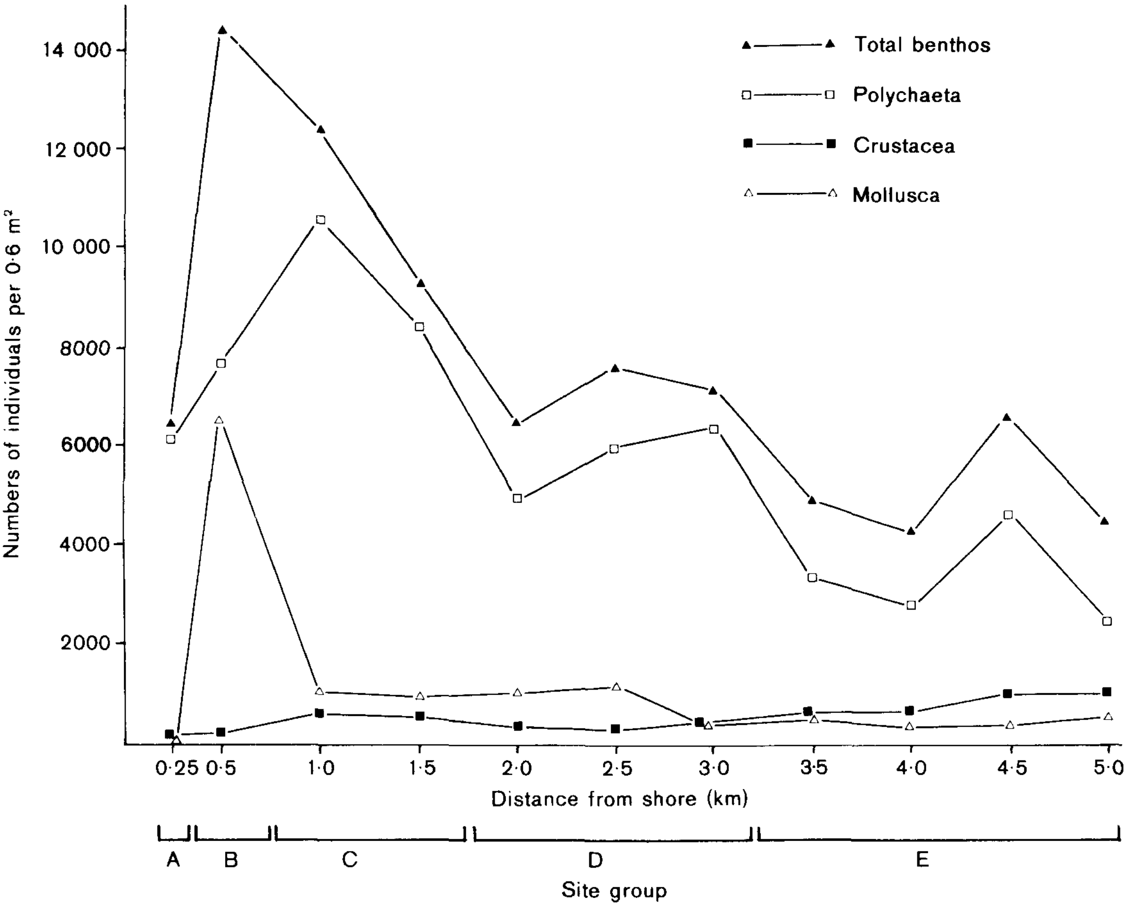

Fig. 9 Distribution of total fauna and major taxa among the stations and site groups.

group is probably close to an abiotic zone. In site group B, *H. filiformis* is co-dominant with the bivalve *Maorimactra ordinaria* and, although the total faunal density is higher, the relative numerical contribution by other species is similar. Thus, the peak of opportunists (PO), the highest abundance of opportunistic species, falls within site group B. Although the peak in *H. filiformis* density is in site group C (Fig. 10), the density of other species has also increased markedly (Fig. 8). Seaward of this site group the total benthos density, excluding *H. filiformis*, increased only slightly in site groups D and E, while the *H. filiformis* density declined steadily. Further, species richness increased markedly from site groups A and B to reach a distinct point of inflexion in site group C and remained at similar levels in groups D and E, while equitability, the evenness of distribution among species, continued to increase. Thus, site group C must contain the ecotone point as defined by Pearson & Rosenberg (1978) and marks the beginning of a transition zone (Fig. 11). The transition zone in Hawke Bay extends for at least 3.5 km from site group C to beyond site group E where *H. filiformis* still contributes about 26% of the total individuals. In Hawke Bay, therefore, the faunal transition resulting from sewage enrichment extends for more than 5 km from the sewage source. Although no abiotic zone was detected, an opportunist zone was very obvious, extending for 1.5–2 km from the outfall. Beyond this a transition zone extends for more than 3 km.

This pattern of faunal transition along a gradient of organic enrichment may also occur along similar gradients in time (Pearson & Rosenberg 1978). With increased organic enrichment, the faunal zones succeed each other from 'normal' through transition and opportunist zones and eventually to abiotic

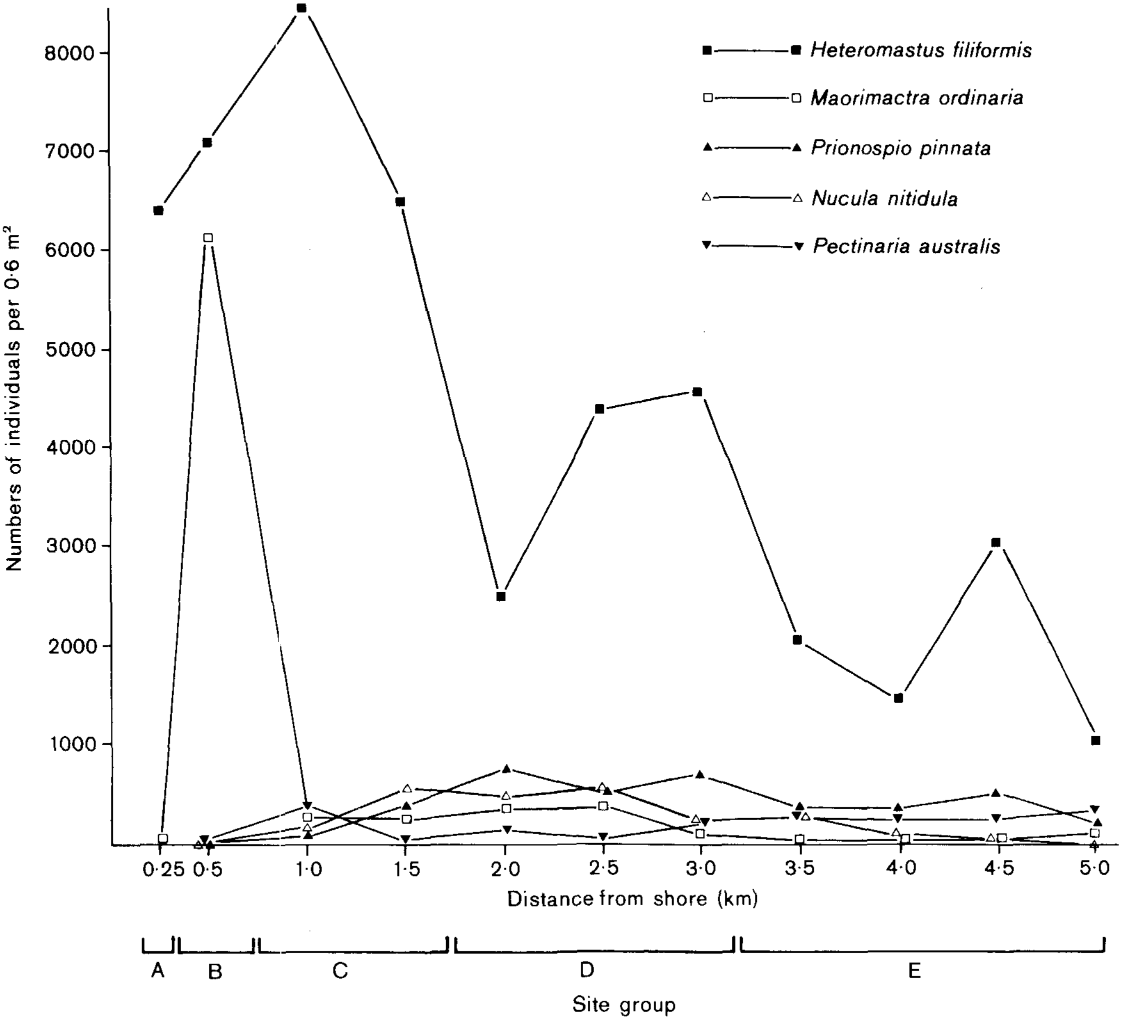

Fig. 10 Distribution of the 5 most abundant species among the stations and site groups.

when the rate of organic input is sufficiently high. As this occurs, the extent and distance from the source of each faunal zone will change, becoming further away with increased inputs (Rosenberg 1976). The reverse succession will occur following reduction or cessation of the input. This idea has been extended as a proposed measure of the degree of the effects of pollution in time and space (Leppäkoski 1975, Pearson & Rosenberg 1978). The magnitude of the effects of pollution may be assessed by determining the position of the PO relative to the discharge point (Pearson & Rosenberg 1978).

For a given organic input, however, the distance from the outfall to the PO will vary with local hydrographic characteristics. In particular, the effects of organic input will be more severe and more extensive at sheltered sites than at more exposed sites. Water movement is the principal factor controlling deposition of organic material. With little water movement, oxygen renewal is slow and, with the increased BOD of accumulated organic matter, very low oxygen concentrations in the sediments and the overlying water will develop (Pearson & Rosenberg 1978). The distance to the PO point was about 1100 m in Saltkällefjord, a long,

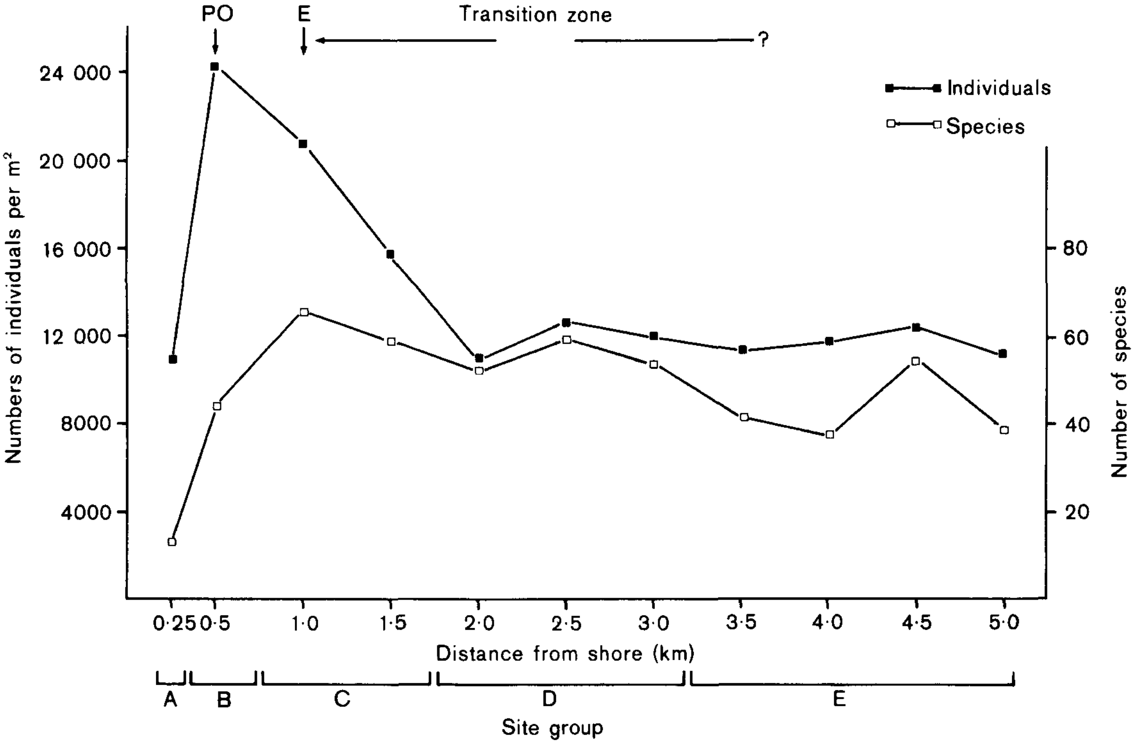

Fig. 11 Faunal density and number of species at each station and site group showing peak of opportunistic species (PO), ecotone point (E), and transition zone.

narrow, deep inlet, at the peak of pollution (1965) (Leppäkoski 1968, 1975, Rosenberg 1972, 1976). At Cortiou, near Marseille, and in Hawke Bay, both relatively exposed sites, the PO points were 200 m and 500 m respectively from the outfalls (Bellan & Bellan-Santini 1972).

Community structure

Diversity measurements have been used increasingly to estimate the relative complexity of faunas in relation to pollution. The Shannon-Wiener index is widely used and is the most useful, especially when considered along with a measure of equitability or evenness (Pielou 1969). Generally, there is a decrease in both the diversity and evenness indexes with greater simplification of the benthos resulting from organic enrichment (Boesch 1972, Pearson & Rosenberg 1978). Thus these indexes effectively summarise the overall changes with time at one site or spatially along a gradient. Comparisons of the effects of organic pollution on benthos from different localities using these indexes can only be made subjectively because of the considerable between-habitat variations and the effects of different sampling methods (Boesch 1972).

The Shannon-Wiener diversity index and Pielou's evenness index increased in successive site groups from the highly polluted inshore site group A to the more normal site group E. Diversity at site group A was extremely low at 0.1442. When this value, along with the very low evenness value of 0.058, is compared with the same values for site group E ($H' = 2.58$, $J' = 0.69$), it is obvious that the fauna at site group A has altered drastically in response to the organic enrichment. An overwhelming numerical dominance of *H. filiformis* is responsible for these extremely low diversity and evenness values at site group A; this species contributed 96% of individuals at this site group and the remaining 4% of individuals was spread among 11 species. At site group E, by comparison, *H. filiformis* still dominated but constituted only 26.5% of the fauna, with 51 species making up the remainder. Further offshore, beyond site group E where there was less organic enrichment, both diversity and evenness increased predictably as *H. filiformis* became less abundant and the distribution of individuals among species became more even.

Pollution-indicator species

Although the concept of pollution-indicator species is not generally applicable to the sea because of the large range of environments and species, the common occurrence of some ubiquitous species in polluted areas has led to their being regarded as indicative of organically enriched habitats (Pearson & Rosenberg 1978). Members of the Capitellidae, especially *Capitella capitata*, are generally held in this context. Pearson & Rosenberg (1978) reviewed species associated with various degrees of pollution, and it is informative to consider the more abundant species from Hawke Bay in terms of pollution-indicator species.

Heteromastus filiformis, a small capitellid polychaete, dominated all site groups in Hawke Bay and constituted 80–90% of individuals in the opportunist zone. Its opportunistic characteristics and behaviour in polluted environments are well documented (Filce 1959, Dean & Haskin 1964, O'Connor 1972, Rosenberg 1976, Pearson & Rosenberg 1978). In unpolluted environments *H. filiformis* is often among the more widespread and abundant members of the benthos (Boesch 1973, Buchanan & Warwick 1974, Whitlach 1977, Cadée 1979) with maximum densities of between 300 and 1128 per square metre. Cadée (1979) observed a maximum density of 9300 per square metre after an unusually heavy juvenile settlement. Densities reported from polluted situations typically range from about 600 to 7000 per square metre (Linke 1939, Rosenberg 1972, 1976) and up to 109 570 per square metre following gross organic enrichment by drifting macroscopic algae (Watling 1975). Densities in Hawke Bay were quite high (6090–37 310 per square metre) compared with those reported for *H. filiformis* elsewhere.

Although *H. filiformis* has been regarded as a transitory species more typical of less extreme pollution, or as a secondary coloniser following pollution or enrichment abatement (Dean & Haskin 1964, Rosenberg 1972, 1973, 1976, Watling 1975, Pearson & Rosenberg 1978), its overall dominance in Hawke Bay, and especially its very high densities so close to the sewage outfall, imply that it may be the equivalent of *Capitella capitata* in some situations. Like *C. capitata, H. filiformis* is a nonselective deposit feeder (Rosenberg 1973, Watling 1975) tolerant of anaerobic conditions (O'Connor 1972). It is a 'conveyor-belt feeder', living vertically in the sediment, feeding indiscriminately on smaller sediment particles 10–30 cm below the sediment surface (Schäfer 1952, Cadée 1979) and depositing copious quantities of faecal pellets on the sediment surface. At densities of 100 or 1000 per square metre, the average amount of sediment reworked was about 110 ml per square metre per day, which is equivalent to a 4 cm sediment layer brought to the surface each year (Cadée 1979). Very large amounts of sediment must be reworked by *H. filiformis* in Hawke Bay, especially at site group C where its mean density was 13 090 per square metre. With such intensive reworking, *H. filiformis* also most certainly altered the nature of the sediment and indirectly influenced the composition of the benthos.

The second apparently opportunistic species found in abundance close to the outfall in Hawke Bay was the bivalve *Maorimactra ordinaria*. Mature individuals of this suspension feeder attain a length of about 13 mm. Although little is known of its biology, this typically open-coast species is tolerant of considerable organic enrichment, but perhaps only where wave action maintains aerobic conditions. Indeed, the mean density of 10 210 individuals per square metre in site group B implies that this bivalve may settle preferentially close to sources of organic enrichment. Thus *M. ordinaria* may prove to be an important pollution indicator species on more open coasts around New Zealand.

In Hawke Bay, *Prionospio pinnata* is the dominant species of the transition zone after *H. filiformis* beyond the PO point in site groups D and E. This polychaete has been reported frequently in environments polluted by sewage (Pearson & Rosenberg 1978). It has been described variously as pollution tolerant, a ubiquitous co-dominant with *H. filiformis* (Boesch 1973), and important in the secondary assemblage (transition fauna) after decline of the initial opportunists (Watling 1975). Two other species of *Prionospio* have also been considered characteristic of transition faunas beyond the peak of opportunists: *P. cirrifera* (Leppäkoski 1971, Grassle & Grassle 1974, Pearson 1975, Rosenberg 1976) and *P. heterobranchia* (Grassle & Grassle 1974).

The fourth most abundant animal in Hawke Bay, a small deposit-feeding bivalve, *Nucula nitidula*, also appears to belong to the transition fauna. Its maximum density of 765 per square metre was recorded immediately beyond the PO point in site group C, whereafter densities declined to zero at Stn 10 (site group E). Species of *Nucula* are common in the benthos of most shallow water sediments (Powell 1937, Boesch 1973, Buchanan & Warwick 1974, Lie 1974, Grange 1979) at densities of up to 367 per square metre (Warwick & Davies 1977), but usually they are scarce in polluted waters. In Saltkällefjord, *Nucula tenius* was present only 8 years after pollution abatement, and then only at the outermost station where its density was 148 per square metre (Rosenberg 1976). These observations suggest that although *Nucula* species generally are intolerant of organic enrichment, *N. nitidula* not only tolerates moderate pollution, but may also be an important component of the transition zone fauna in some enriched environments.

Several other species found in Hawke Bay are either often associated with organic enrichment or belong to families or genera that contain species frequently found in polluted environments. Some such species (*Eteone* sp., *Glycera* sp., *Nephthys* sp.) are quite infrequent here, and others (*Scoloplos* sp., *Lumbrinereis magalhaensis, Glycinde trifida,* and *Goniada* sp.) are of minor significance only.

Distance from the shore

In addition to following a gradient of organic enrichment, the sampling stations in Hawke Bay followed a parallel complex gradient of distance from the shore. As Hughes & Thomas (1971) pointed out, "distance from the shore" embodies several environmental effects which may act separately over different parts of a transect, or they may overlap. In the present study, organic enrichment varied with distance from shore and induced a nearshore zone of opportunists, an ecotone point, and a wider transition zone. Within the first and the last of these zones, our analysis distinguished additional faunal zones, probably resulting from the intensity of distance from shore effects.

Within the study area, wave motion probably has the most significant effect on the benthos directly and indirectly, both by redistributing organic material from the outfall and through its influence on the sediments. The effects of wave motion on the bottom were most pronounced to about 10 m depth, the approximate boundary between site groups C and D, and where the sediments changed from sands at shallower stations to silts and clays at deeper stations.

In their studies of the subtidal (6–30 m) infaunal communities of a high-energy beach off Monterey, California, Oliver et al. (1980) distinguished 2 general zones, the width and depth of which appeared to be determined primarily by wave-induced substrate motion. A shallow crustacean zone (< 14 m) was occupied by small, mobile, deposit-feeding peracarid and ostracod crustaceans. No crustacean-dominated zone was present in Hawke Bay, but crustaceans were more or less uniformly distributed along the transect. Off Monterey, soft-bodied polychaetes dominated the deeper zone and the number of sessile and semi-sessile suspension or selective deposit feeders and commensal animals increased with depth. Polychaetes dominated at all depths in Hawke Bay, although their domination in the shallow site groups A and B was attributable to a single species, *Heteromastus filiformis,* whose presence was induced by the organic enrichment.

In False Bay, South Africa, Field (1971) recognised a 'turbulent zone' to 23 m depth divided into 2 sub-zones. The first, 2–8 m, was dominated by amphipods, bivalves, and mysids, and the second, 16–23 m, by amphipods, cumaceans, polychaetes, and an anemone. In Lamberts Bay, South Africa, Christie (1976) recognised an 'inshore surf zone' at 0 – 1 m, an 'offshore surf zone' at 3–5 m, and an 'outer turbulent zone' at 10–33 m. Indicator species of the offshore surf zone were 2 polychaetes. The outer turbulent zone had many indicator species, including non-burrowing and shallow-burrowing crustaceans (especially amphipods), 2 polychaetes, and a delicate cnidarian.

No generalised picture is apparent from these studies. At best we can distinguish an offshore surf zone and an outer turbulent zone, although these zones are not obvious in Hawke Bay, possibly because the effects of organic input on the benthos are more pronounced.

One striking feature of the Hawke Bay benthos profile is the occurrence of appreciable numbers of 2 holothurians, *Heterothyone ocnoides* and *Paracaudina chilensis.* Both species have their highest density (293 and 147 per square metre respectively) at Stns A3, B3, and C3 in site group C at a depth of 8–10 m (Fig. 12). A few *Heterothyone* were found in site groups D and E, with high numbers of *Paracaudina* in both these site groups. The numbers declined rapidly towards the end of the transect and they were virtually absent at Stns A10, B10, and C10 at 17 m depth. From observations made elsewhere in New Zealand, a band of these 2 holothurians appears to be a common feature of the turbulent zone off exposed sand beaches (Knox et al. 1978). Such a holothurian band is not present in the 4 comparative transects from widely separated geographic regions (Day et al. 1971, Field 1971, Christie 1976, Oliver et al. 1980). *Paracaudina* reaches a length of 160 mm and *Heterothyone* 59 mm; consequently their total biomass can be high. *Paracaudina* has been recorded to a depth of 990 m, but *Heterothyone* is restricted to less than 50 m depth. In the latter species the body is U-shaped and it is presumably restricted to the surface sediments.

Trophic structure

The distribution patterns of the infaunal soft-bottom assemblages have been attributed in large part to the relationship between sediment grain sizes, bottom stability, and particular trophic or feeding types after Sanders (1958, 1960). In Buzzards Bay,

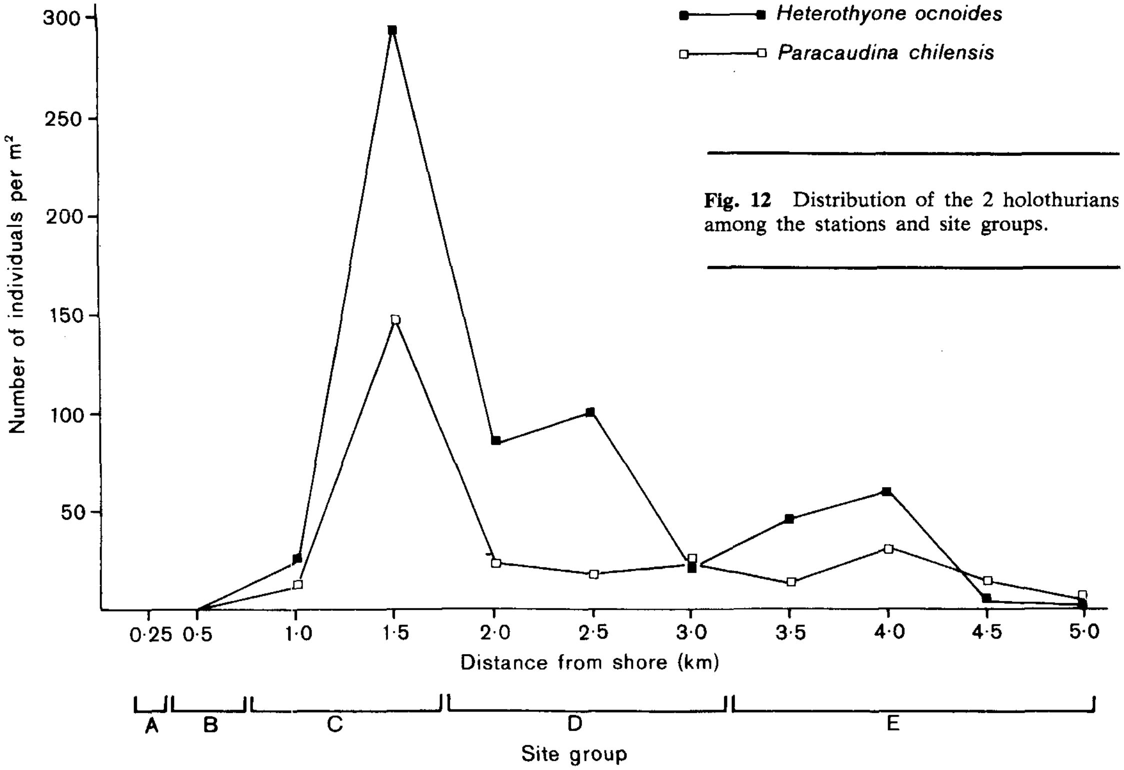

Fig. 12 Distribution of the 2 holothurians among the stations and site groups.

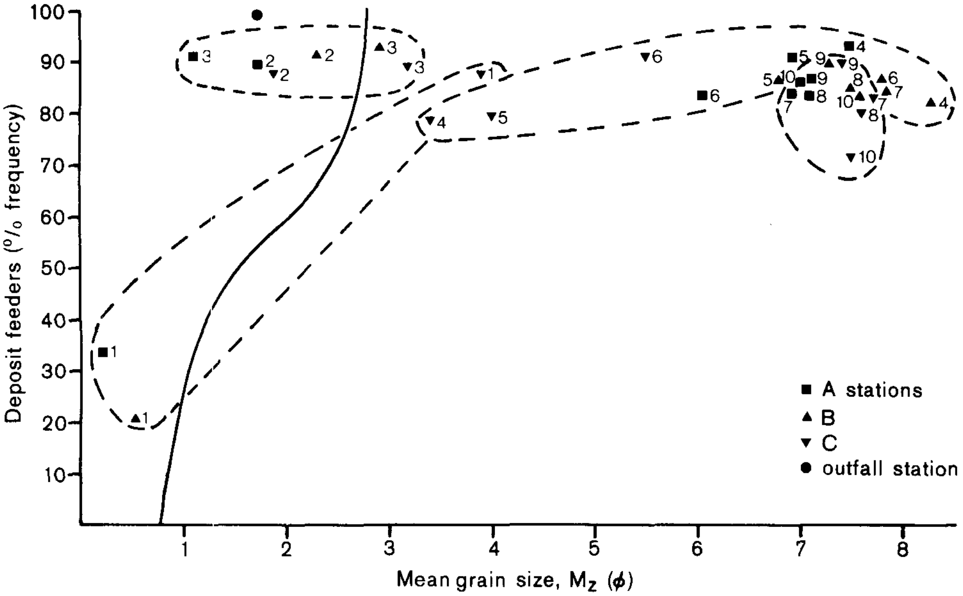

Fig. 13 Percentage of deposit-feeding individuals compared with mean grain size of sediment at each station. Solid line, Grange's (1977) curve for the relationship between frequency of deposit-feeders and mean grain size; broken lines encircle stations of each site group.

Massachusetts, detailed studies have shown that the proportion of deposit-feeders is greatest on unstable mud bottoms, whereas the suspension feeders are largely restricted to muddy sands (Rhoads & Young 1970, Rhoads 1973). Although subsequent work has shown that suspension feeders are not so closely linked with grain size, the initial observations of Sanders (1958, 1960) have been confirmed by many workers (Lie 1968, Nichols 1970, Bloom et al. 1972, Boesch 1973, Rhoads 1974).

Deposit-feeders formed the greatest proportion (40%) of species included in the analysis, and included many of the more abundant organisms. The frequency of deposit-feeders at each station did not vary with mean grain size (Fig. 13), but it is notable that stations of each site group tend to be grouped with respect to mean grain size and the frequency of deposit-feeders. Grange (1977) reported a clear relationship between mean and modal grain sizes and the percentage of deposit-feeders in the intertidal estuarine benthos of Manukau Harbour, Auckland. He found a steady increase in the percentage of deposit-feeders with decreasing grain size (increasing ϕ). In Hawke Bay, however, stations fell into 2 distinct groups: 2 stations (Al, Bl) with few (20–35%) deposit-feeders and the remaining stations with 71–99% deposit-feeders. Further, in the present study deposit-feeders dominated (> 70%) at all stations with mean grain sizes finer than 1.0 ϕ (0.5 mm diameter), whereas in Manukau Harbour the frequency of deposit-feeders did not exceed 70% with grain sizes coarser than 2.0 ϕ (0.25 mm). Thus in the organically enriched environment of Hawke Bay, deposit-feeders dominated at all stations with fine sediments and there was no tendency for domination to increase with finer sediments. This was probably a direct result of the high level of enrichment where all sediments fine enough for deposit-feeders to burrow and feed were inhabited to near capacity. Here the critical maximum sediment size for deposit-feeders seems to be about 1.0 ϕ, and the maximum frequency of deposit-feeders was at a mean sediment size of 1.73 ϕ. Stations with sediments coarser than 1.0 ϕ were dominated by the suspension feeding bivalve *Maorimactra ordinaria.*

The sediments of the study area (Fig. 2) were very patchy, with an irregular transition from sands inshore to fine silt and clay offshore. By comparison, there were 5 distinct faunal zones parallel to the shore and increasing in width with distance offshore. These zones did not correspond directly to any sediment parameter, but were considered to be determined principally by a gradient of organic input and the complex effect of distance from shore.

ACKNOWLEDGMENTS

This study was made possible by a research contract from the Hastings City Council, and this support is gratefully acknowledged. We are deeply indebted to Dr J. K. Lowry, Mr P. M. Sagar, Mr P. Ensor, and Ms L. A. Bolton for assistance with field work and sorting of samples. Special thanks are due to Mr Knut Jensen, skipper of *Jenco II*, for his skill and enthusiastic help. Mr A. R. Thompson and Mr R. Hall (Hastings City Council engineers) are thanked for their careful position-fixing and general help. Drs A. N. Baker and F. Climo (National Museum of New Zealand, Wellington) generously confirmed and corrected our identifications of echinoderms and molluscs. Dr N S. Jones checked identifications of Cumacea. Mr David Hain (Division of Computing Research, CSIRO, Sydney) is gratefully acknowledged for performing the classifications.

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